AVAILABLE ABC BRIDGE SYSTEMS FOR SHORT SPAN BRIDGES - COURSE MODULE

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# Contents

**DISCLAIMER** .................................................................................................................. II

**CONTENTS** ..................................................................................................................... III

**LIST OF FIGURES** ............................................................................................................ X

**LIST OF TABLES** ................................................................................................................ XX

**ACKNOWLEDGMENTS** .................................................................................................... XXI

**CHAPTER 1. INTRODUCTION TO ABC – OUTLINE OF THE COURSE** .......................... 22
  1.1. Abstract ......................................................................................................................... 22
  1.2. Background .................................................................................................................... 22
  1.3. Objectives of the Course ............................................................................................... 25
  1.4. ABC – Definitions and descriptions ............................................................................ 25
   1.4.1. Benefits of ABC ....................................................................................................... 26
   1.4.2. Applications: ........................................................................................................... 26
   1.4.3. ABC Bridge Components ....................................................................................... 28
  1.5. Short Span Classification ............................................................................................ 28
  1.6. Outline of the course ................................................................................................... 30

**CHAPTER 2. TYPES OF ELEMENTS AND SUBSYSTEMS** .............................................. 33
  2.1 Abstract ......................................................................................................................... 33
  2.2 Prefabricated Bridge Elements and Systems (PBES) for Conventional Bridges ......... 33
   2.2.1 Elements: .................................................................................................................. 33
   2.2.2 Systems: .................................................................................................................... 34
   2.2.2.1 Superstructure Systems ....................................................................................... 34
   2.2.2.2 Superstructure/Substructure Systems ................................................................. 34
   2.2.2.3 Total Bridge Systems .......................................................................................... 34
   2.2.3 Superstructure Elements and Systems..................................................................... 34
   2.2.3.1 Deck Panels ........................................................................................................ 34
   2.2.3.1.1 Concrete Deck Panels ..................................................................................... 35
   2.2.3.1.2 Open Grid Decks ............................................................................................. 36
   2.2.3.1.3 Prefabricated Timber ...................................................................................... 36
   2.2.3.1.4 Hybrid Decks .................................................................................................. 36
   2.2.3.1.5 Exodermic Decks ............................................................................................ 37
   2.2.3.1.6 Steel Orthotropic Decks ............................................................................... 39
   2.2.3.1.7 Aluminum Orthotropic Decks ....................................................................... 40
   2.2.3.1.8 Fiber Reinforced Polymer (FRP) Bridge Decks ............................................ 40
   2.2.3.2 Girders: ................................................................................................................ 41
   2.2.3.2.1 Decked slab girder (DS) .................................................................................. 43
   2.2.3.2.2 Decked U-girder (DU) ..................................................................................... 44
   2.2.3.2.3 Precast slab/deck beams ............................................................................... 44
   2.2.3.2.4 Rolled Beam using W-shapes .......................................................................... 45
   2.2.3.2.5 Inverted-T Precast Slab .................................................................................. 46
   2.2.3.2.6 Box Beam ........................................................................................................ 47
   2.2.3.2.7 Double-Tee and Decked Bulb-Tee Girders ..................................................... 48
   2.2.3.2.8 NEXT F Beam ................................................................................................ 49
CHAPTER 3. JOINTS AND CONNECTIONS ................................................. 90
3.1. Abstract......................................................................................................................................... 90
3.1. Joints and Connections.................................................................................................................. 90
3.1.1. Typical ABC Connection Types: ................................................................................................. 91
3.1.1.1. Steel Elements: ....................................................................................................................... 92
3.1.1.1.1. Bolted: ................................................................................................................................. 92
3.1.1.1.2. Welded: ............................................................................................................................... 92
3.1.1.1.3. Cast-in-Place Diaphragms to Connect Steel Girders: ....................................................... 92
3.1.1.2. Concrete Elements: ............................................................................................................... 93
3.1.1.2.1. Grouted Reinforcing Splice Couplers: .............................................................................. 93
3.1.1.2.2. Using Grouted Post-Tensioning (PT) Ducts: ................................................................. 94
3.1.1.2.3. Grouted Voids: ................................................................................................................ 94
3.1.1.2.4. Traditional Post-tensioning (PT): ..................................................................................... 95
3.1.1.2.5. Welded connections: ......................................................................................................... 95
3.1.1.2.6. Cast-in-place Concrete Closure Pours: ............................................................................ 95
3.1.2. Superstructure element connections ............................................................................................ 96
3.1.2.1. Deck Connections ................................................................................................................. 96
3.1.2.1.1. Closure Joint: Type 1 ......................................................................................................... 98
3.1.2.1.2. Closure Joint: Type 2 ......................................................................................................... 98
3.1.2.1.3. Closure Joint: Type 3 ......................................................................................................... 99
3.1.2.1.4. Closure Joint: Type 4 ......................................................................................................... 99
3.1.2.1.5. Closure Joint: Type 5 ........................................................................................................ 100
3.1.2.1.6. Longitudinal Post Tensioning with Grouted Shear Key: ..................................................... 101
3.1.2.1.7. Mechanical Connections: ............................................................................................... 102
3.1.2.1.8. UHPC with Straight Bar .................................................................................................... 103
3.1.2.1.9. Conventional Concrete with Hooped or Straight Bars: ...................................................... 103
3.1.2.2. Expansion Joints and Link Slabs ............................................................................................ 106
3.1.2.3. Connection between deck/superstructure and substructure .................................................. 106
3.1.2.3.1. Simple for Dead Load Continuous for Live Load (SDCL): ............................................. 107
3.1.2.3.2. Integral and semi-integral abutment................................................................................ 108
3.1.2.4. Precast Concrete Bridge Barriers Connections: ................................................................ 111
3.1.2.4.1. Florida DOT Precast Concrete Bridge Barriers Connections: .................................. 112
3.1.2.4.2. Ryerson University Precast Concrete Bridge Barriers Connection: ................................ 113
3.1.2.4.3. Clampcrete Precast Concrete Bridge Barriers Connection: ........................................ 113
3.1.2.4.4. Texas Transportation Institute Precast Concrete Bridge Barriers Connections: .......... 114
3.1.2.4.5. Iowa State University ABC Railing Connection ............................................................. 114
3.1.2.4.5.1 Barrier-to-deck connection using inclined reinforcing bars: ...................................... 114
3.1.2.4.5.2 Barrier-to-deck connection using a U-shaped reinforcing bars: .................................. 115
3.1.2.4.5.3 Barrier to Barrier connection ....................................................................................... 115
3.1.3. Substructure element connections ............................................................................................. 116
3.1.3.1. Cap beam connection to column ............................................................................................ 116
3.1.3.1.1. Connection inside the Pier Cap- Grouted Sleeve: .............................................................. 116
3.1.3.1.2. Connection inside the Pier Cap- Grouted Pocket: ............................................................ 118
3.1.3.1.3. Connection along the Columns- UHPC Column Segments: ............................................ 119
3.1.3.1.4. Connection between column segments: ......................................................................... 120
3.1.3.1.5. Connection along the Column- Grouted Sleeve: .............................................................. 120
5.2.3. Damage inspections: ................................................................. 158
5.2.4. In-Depth inspections: ............................................................. 158
5.2.5. Fracture Critical inspections: .................................................. 158
5.2.6. Underwater inspections: ......................................................... 158
5.2.7. Special inspections: ............................................................... 158
5.3. Inspection Equipment ............................................................... 158
5.4. Bridge Inspection Forms ........................................................... 160
5.5. Non-Destructive Testing ........................................................... 163
5.5.1. Audio-Visual Methods: .......................................................... 164
5.5.2. Acoustic-Seismic Methods: .................................................... 165
5.5.3. Impact Echo Testing (IE) ........................................................ 166
5.5.4. Ground Penetrating Radar (GPR) .......................................... 167
5.5.5. Ultrasonic Testing (UT) .......................................................... 167
5.5.6. Infrared Thermography Testing (IR) ........................................ 168
5.5.7. Impulse Response Testing (IRT) ............................................. 169
5.5.8. Radiographic Testing (RT) ...................................................... 169
5.5.9. Magnetic Flux Leakage Testing (MFL) ...................................... 170
5.5.10. NDT methods most applicable to concrete bridge elements ...... 170
5.5.11. NDT methods specifically applicable to steel elements .......... 171
5.5.11.1. Penetrant Testing (PT) ...................................................... 171
5.5.11.2. Eddy Current Testing (ET) ............................................... 172
5.5.11.3. Magnetic Particle Testing (MT) ......................................... 172
5.6. Other methods ........................................................................ 173
5.7. Evaluation of substructure for reuse ......................................... 175
5.7.1. Field Testing and inspection of concrete elements .................. 177
5.7.2. Field Testing and inspection of steel elements ....................... 178
5.8. Performance of ABC technologies to date .................................. 178
5.8.1. Defects and Anomalies in concrete bridges ......................... 178
5.8.2. Damage Sequence ............................................................... 180
5.8.3. Defects and Anomalies specific to ABC bridges .................... 181
5.8.3.1. Full-Depth Deck Panel: Transverse connections with welded tie plates ... 181
5.8.3.2. Full-Depth Deck Panel: Transverse Connections with Longitudinal Post-Tensioning .......................................................... 182
5.8.3.3. Full-Depth Deck Panel: Transverse Connections with Dowel Bar Pockets ... 182
5.8.3.4. Full-Depth Deck Panel: Deck Panels with Shear Connector Pockets ........ 183
5.8.3.5. Full-Depth Deck Panel: Connections with reinforced UHPC ........ 183
5.8.3.6. Precast concrete Parapets .................................................... 183
5.8.3.7. Connection of Approach Slabs to Bridge Decks ................... 183
5.8.3.8. Precast Concrete Abutments with Vertical Thread-Bar Connections .... 183
5.8.3.9. Precast Concrete Pier Elements ............................................ 183
5.8.3.10. Geosynthetic Reinforced Soil Integrated Bridge System (GRS-IBS) ...... 183
5.8.3.11. Precast Adjacent Box Beams (side-by-side box beams) ............ 183
5.8.3.12. Other investigations for performance of side-by-side box girders and full-depth deck panel systems; causes and methods to decrease premature deterioration: ... 183
5.8.4. Defects and anomalies in Steel Bridges .................................. 185
5.8.4.1. Pitting Corrosion .............................................................. 185
5.8.4.2. Galvanic Corrosion ................................................................. 186
5.8.4.3. Crevice Corrosion ................................................................. 186
5.8.4.4. Stress Corrosion ................................................................. 187
5.8.4.5. Corrosion Fatigue ................................................................. 187
5.8.4.6. Performance of corroded bridges ........................................... 187
5.8.4.7. Performance of fatigue cracks ................................................ 188
5.8.5. Performance related to Construction Methods ............................ 191
5.9. Further performance research ..................................................... 191

CHAPTER 6. DECISION MAKING PROCESS ........................................... 192

6.1. Abstract ...................................................................................... 192
6.2. Decision making for a new bridge construction ............................... 192
6.3. Decision Making Tools developed by different State DOTs. ............... 195
6.3.1. Utah DOT ............................................................................. 195
6.3.2. Oregon DOT ......................................................................... 197
6.3.3. Connecticut DOT ................................................................. 197
6.3.4. Wisconsin DOT ..................................................................... 203
6.3.5. Minnesota DOT ..................................................................... 205
6.3.5.1. Stage 1 ........................................................................... 205
6.3.5.2. Stage 2 ........................................................................... 205
6.3.5.3. Stage 3 ........................................................................... 205
6.3.6. Iowa DOT .............................................................................. 209
6.3.7. Colorado DOT ....................................................................... 211
6.3.8. Washington DOT .................................................................... 213
6.4. Major Parameters Affecting selection of ABC bridge elements and systems in general ............................................................. 214
6.4.1. Time Constraint ....................................................................... 214
6.4.2. Risk and Cost of the project ...................................................... 214
6.4.3. Environmental considerations ................................................. 214
6.4.4. Geometric Considerations ....................................................... 215
6.4.5. Site Condition and Accessibility ............................................... 215
6.4.6. Design Constraints and Considerations ..................................... 215
6.4.7. Compatibility between Superstructure and Substructure, and between Substructure and Foundation ........................................... 215
6.5. Determination of appropriate ABC methods and type of superstructure ................................................................. 216
6.5.1. Considerations for superstructure system and elements selection ................................................................. 219
6.5.2. Suitability of Substructure Types with Respect to Superstructure and Bridge Configuration .................................................. 222
6.6. Available Selection and Design Considerations for Substructure ........ 223
6.6.1. Selection of Substructure Elements and Systems ....................... 225
6.6.2. Parameters affecting the selection of bridge elements and construction methods in general 225
6.6.2.1. Compatibility of Substructure with Superstructure and Bridge Configuration 225
6.6.2.2. Compatibility of Substructure with Foundation ....................... 225
6.6.3. Parameters Specific to Substructure ........................................... 226
6.6.4. Selection of Substructure based on Compatibility with Superstructure and Substructure-specific Parameters ........................................... 226
6.6.5. Suitability of Substructure Types with Respect to Foundation .................. 227
6.6.6. Considerations for substructure system and elements selection ............... 234
6.7. Selection and Design Considerations for Foundation .................................. 235
6.8. Life Cycle Cost Analysis as a tool for decision making ............................... 241
6.8.1. Basic steps in LCCA ............................................................................. 242
6.9. Decision Making for Replacement, Reuse, Or Retrofitting/ Strengthening of Existing Foundations and Substructures ...................................................... 242
6.10. How to use the decision-making guide provided in this chapter: .................... 246

CHAPTER 7. NEW DEVELOPMENTS ..................................................................... 248

7.1. Abstract ........................................................................................................ 248
7.2. New Systems .................................................................................................. 248
7.3. New Technologies .......................................................................................... 251
7.4. Inspection, Evaluation and Performance ....................................................... 251
7.5. Planning, Contracting, and Implementation .................................................. 252
7.6. Materials ........................................................................................................ 253
7.7. Guidelines, Synthesis, and Course Modules .................................................... 254

REFERENCES ...................................................................................................... 256
List of Figures

Figure 1.1 Examples of culverts and buried bridges .................................................................23
Figure 1.2 Other elements and methods for short-span bridges ..............................................24
Figure 1.3 Other elements and methods for short-span bridges ..............................................24
Figure 1.4 ABC Bridge Components ..........................................................................................29
Figure 1.5 ABC Bridge Elements ...............................................................................................30
Figure 2.1 Lightweight precast deck panel [13] ........................................................................37
Figure 2.2 Open grid deck panel [13] .........................................................................................38
Figure 2.3 Timber deck panels [7] ..............................................................................................38
Figure 2.4 Exodermic deck panel [7] .........................................................................................39
Figure 2.5 Orthotropic Steel Deck Bridge [17] .........................................................................39
Figure 2.6 Orthotropic deck [13] ...............................................................................................40
Figure 2.7 FRP deck panel [7] ....................................................................................................40
Figure 2.8 FRP bridge deck and superstructure applications (Aboutaha 2001) [17] ..................41
Figure 2.9 Steel girder [19] ........................................................................................................41
Figure 2.10 Different shape of precast girders [18] ....................................................................42
Figure 2.11 Decked slab girder [20] ...........................................................................................44
Figure 2.12 A sample decked U girder: top widths 15 feet 0 inch, 9 feet 10 inches, or 7 feet 3 inches [20] ..................................................................................................................44
Figure 2.13 Typical Florida Slab Beam (FSB) Section [5] ...........................................................45
Figure 2.14 Axtel UT rolled-beam bridge (https://www.shortspansteelbridges.org/gallery/images/rolled-beam-bridge) .................................................................45
Figure 2.15 Inverted-tee Beams (www.fhwa.dot.gov/bridge/prefab/slab.cfm) [7] ......................46
Figure 2.16 Decked bulb-tee shape compared to adjacent box beam configuration Grace et al [5] ........................................................................................................................................46
Figure 2.17 Texas Adjacent Box Beam [7] ..................................................................................47
Figure 2.18 Traditional (a) adjacent and (b) spread configuration for 28-inch depth box beams [21] ........................................................................................................................................47
Figure 2.19 Double-tee Bridge Profile Typical Transverse Section [14] ......................................48
Figure 2.20 Decked Bulb-tee Cross Section [14] .......................................................................48
Figure 2.21 Full-depth Top Flange NEXT Beam [7] ....................................................................49
Figure 2.22 NEXT D beam span lengths [5] ..............................................................................50
Figure 2.23 Precast channel beam cross section and longitudinal section [22] .........................50
Figure 2.24 Voided Slab Bridge Deck
Figure 2. 25 Modular steel superstructure system [13]……………………………………………………………52
Figure 2. 26 Modular Beams with Decks [13]…………………………………………………………………………52
Figure 2. 27 Modular orthotropic superstructure system [13]………………………………………………………53
Figure 2. 28 Modular steel folded plate girder [24]……………………………………………………………………53
Figure 2. 29 Fabrication of folded plate girder using a press break machine [24]……………………………………54
Figure 2. 30 Conceptual view of modular press-brake-formed tub girder system [25], [27]………………54
Figure 2. 31 Modular double tee superstructure system [13]………………………………………………………55
Figure 2. 32 Laminated timber deck system [13]………………………………………………………………………55
Figure 2. 33 Prefabricated deck panel with a barrier (Utah DOT) [13]………………………………………………56
Figure 2. 34 3D model of prefabricated deck panel with barrier lab set-up at Iowa State University [30]…………56
Figure 2. 35 Bridge bearing [13]……………………………………………………………………………………………57
Figure 2. 36 Substructure elements…………………………………………………………………………………………58
Figure 2. 37 Prefabricated pier bent [13]……………………………………………………………………………………58
Figure 2. 38 Wall Pier [13]……………………………………………………………………………………………………59
Figure 2. 39 Semi-integral abutment [13]……………………………………………………………………………………60
Figure 2. 40 Prefabricated integral abutment [13]………………………………………………………………………60
Figure 2. 41 Prefabricated cantilever abutment [13]……………………………………………………………………61
Figure 2. 42 Prefabricated cantilever wing wall [13]……………………………………………………………………61
Figure 2. 43 Precast Pier Cap [36]…………………………………………………………………………………………62
Figure 2. 44 Rectangular pier cap [37]……………………………………………………………………………………62
Figure 2. 45 Inverted-tee pier cap [37]……………………………………………………………………………………63
Figure 2. 46 Inverted-tee pier cap [38]……………………………………………………………………………………63
Figure 2. 47 Buried Bridge Structure Geometry [39]……………………………………………………………………64
Figure 2. 48 Rectangular (box) buried bridge [39]………………………………………………………………………65
Figure 2. 49 Three-sided buried bridge [39]………………………………………………………………………………66
Figure 2. 50 Arch System [39]……………………………………………………………………………………………66
Figure 2. 51 Arch buried bridge [39]………………………………………………………………………………………67
Figure 2. 52 Corrugated Metal Arch buried bridges [39]………………………………………………………………67
Figure 2. 53 High Profile Arch buried bridges [39]……………………………………………………………………68
Figure 2. 54 Example of metal corrugated box [39]……………………………………………………………………68
Figure 2. 55 Twin Concrete Pipe Culvert [1]………………………………………………………………………………69
Figure 2. 56 Round Arch Culvert [1]..........................................................................................................................69
Figure 2. 57 Pipe Arch Culvert [1]..............................................................................................................................70
Figure 2. 58 Pipe Arch Culvert [1]..............................................................................................................................70
Figure 2. 59 Concrete Box Culvert [1].........................................................................................................................71
Figure 2. 60 Metal Box Culvert [1]..............................................................................................................................71
Figure 2. 61 Multiple Cell Concrete Culvert [1]..............................................................................................................72
Figure 2. 62 Three-sided frame culvert [1]..................................................................................................................72
Figure 2. 63 Precast spread footing as bridge foundation [13].......................................................................................74
Figure 2. 64 Driven pile (prestressed concrete) as bridge foundation [41].................................................................75
Figure 2. 65 Box caisson example (https://www.slideshare.net/Tarique048/caisson-foundationppt)....................76
Figure 2. 66 Caisson Construction for Greenville Bridge (http://www.massman.net/project/greenville-bridge).........76
Figure 2. 67 Shapes of open box caissons [47]...........................................................................................................77
Figure 2. 68 Brooklyn caisson (https://www.structuremag.org/?p=10604)...............................................................77
Figure 2. 69 Continuous flight Auger pile as bridge foundation [13].................................................................78
Figure 2. 70 Prefabricated pile cap footing [13].............................................................................................................78
Figure 2. 71 Precast concrete pier box cofferdam [13].................................................................................................79
Figure 2. 72 EPS Geofoam Embankment (Source ACH Foam Technologies).........................................................81
Figure 2. 73 Typical Section of a GRS/IBS Bridge abutment [13]...............................................................................82
Figure 2. 74 Typical Mechanically Stabilized Earth Systems (MSE) Wall Details [13].................................................83
Figure 2. 75 Drawings for Solid Slab with P.T, Double T (FLET), and FDOT PSU [51].............................................84
Figure 2. 76 Drawings for Type II Box Beam, Texas Box Beam, and Minnesota Flat Slab [51].............................85
Figure 2. 77 Truncated FIB, Super T Beam, and AASHTO Type II [51].......................................................................86
Figure 2. 78 Definitions of Terms for Survey [51]........................................................................................................87
Figure 3. 1 Prefabricated Bridge Connections Example [2]..........................................................................................91
Figure 3. 2 Prefabricated Bridge Connections [2]........................................................................................................91
Figure 3. 3 Example of bolted connections from Ohio’s Muskingum County Bridge [5].................................92
Figure 3. 4 Construction sequence for SDCL Bridge Systems [7]............................................................................93
Figure 3. 5 Grouted Reinforcing Splice Coupler [2]..................................................................................................93
Figure 3. 6 Grouted Reinforcement PT Duct Layout [2].............................................................................................94
Figure 3. 7 Grouted Placement [2].............................................................................................................................94
Figure 3. 38 Commonly used concrete bridge barrier profile shapes [27]................................. 112
Figure 3. 39 Through-deck bolting detail developed by Florida DOT [27]................................. 112
Figure 3. 40 Adhesive-bonded anchor detail [27]........................................................................ 113
Figure 3. 41 Ryerson barrier-to-deck slab connection details [27].............................................. 113
Figure 3. 42 Clampcrete barrier system [27].............................................................................. 114
Figure 3. 43 X-bolt connection concept [27]................................................................................ 114
Figure 3. 44 Inclined bar connection between precast barrier and deck [27]............................... 115
Figure 3. 45 U-bar connection between precast barrier and deck [27]........................................ 115
Figure 3. 46 Plan view of the barrier-to-barrier connection [27].................................................... 116
Figure 3. 47 Column to cap beam connection using grouted sleeve method [28]....................... 117
Figure 3. 48 (a) precast footing with two circular pockets; (b) cap beam pocket construction; (c) cap beam pocket-view from underneath; (d) inserting the columns into the footing pockets; (e) placing cap beam on the columns [28]........ 118
Figure 3. 49 Precast cap beam and cast-in-place column using grouted pocket [2]................. 119
Figure 3. 50 a) Seismic and b) non-seismic detail of UHPC connection of precast column and precast cap beam [30]............................................................... 119
Figure 3. 51 Column to column connection [2].......................................................................... 120
Figure 3. 52 Grouted Splice Sleeve [1]........................................................................................ 120
Figure 3. 53 Pile to Cap Connection [2]...................................................................................... 121
Figure 3. 54 Connection Details of Cap Beam Segments [2]....................................................... 121
Figure 3. 55 Proposed ER Connection [31]................................................................................ 122
Figure 3. 56 Grouted sleeve connection between footing and column [2].............................. 123
Figure 3. 57 Cast-in-place footing to precast column connection using mechanical couplers [2].............................................................................................................. 124
Figure 3. 58 Mechanical Reinforcing Bar Couplers [32].......................................................... 125
Figure 3. 59 (a) Fully penetrated pocket connection; (b) Partial penetrated pocket connection [34]..................................................................................................................... 125
Figure 3. 60 Pouring high strength grout in the gap between precast column and footing [35]............................................................................................................................... 125
Figure 3. 61 (a) precast footing with central pocket; (b) precast column with UHPC in the plastic hinge; (c) inserting column into the pocket; (d) filling the gap by UHPC [28].................................................................................................................... 126
Figure 3. 62 Pocket connection of footing and column [36]....................................................... 127
Figure 3. 63 Closure pour connection in abutment [37]............................................................ 127
Figure 3. 64 Precast abutment stem to precast footing connection [2, 38]............................ 128
Figure 3. 65 Grouted couplers connection in prefabricated abutment [38].......................... 128
Figure 3. 66 Abutment connection [2]............................................................................. 129
Figure 3. 67 Precast integral abutment connection to steel pile [2]................................. 129
Figure 3. 68 Precast integral abutment connection to steel pile [2]................................. 129
Figure 3. 69 Pile Connection Plate Detail [2].................................................................... 130
Figure 3. 70 Steel bar dowels connection in abutment [37]............................................ 130
Figure 3. 71 Adjacent abutment segments connection [2].............................................. 131
Figure 3. 72 Precast Arch Connection [2]....................................................................... 131
Figure 3. 73 Connection of Adjacent Precast Arch Units [2].......................................... 132
Figure 3. 74 Example of spandrel wall to arch connection [2]........................................ 132
Figure 3. 75 Precast arch to precast wingwall connection [2]......................................... 133
Figure 3. 76 Precast footing to arch connection [2]......................................................... 133
Figure 3. 77 Precast footing to precast footing connection [2]......................................... 134
Figure 3. 78 Details of Precast footing to subgrade Connection [2]................................. 134
Figure 3. 79 Precast concrete footing to precast concrete footing connection [2]........... 135
Figure 3. 80 Installation of a precast concrete footing with grouted shear connection on  
  concrete sub-footing [2]............................................................................................. 135
Figure 3. 81 Connection between precast concrete footing and steel pile with uplift [2]... 136
Figure 3. 82 Connection details between concrete square pile and pile cap [2].............. 136
Figure 3. 83 Pile Cap Connection using Extended Reinforcing Steel [20]...................... 137
Figure 3. 84 Pile Cap Connection using Embedded Pile [20]......................................... 137
Figure 3. 85 Connection of Pier Column to Large Diameter Drilled Shaft (Source:  
  Washington State DOT Bridge Design Manual) [2]............................................... 138
Figure 3. 86 Connection between concrete square piles using splice [2]....................... 138
Figure 3. 87 Various types of pile splicing [41]............................................................... 139
Figure 4. 1 SPMTs configuration [3]............................................................................... 141
Figure 4. 2 SPMTs bridge move [7]................................................................................ 142
Figure 4. 3 Use of SPMTs for “MemFix4” project [8]....................................................... 142
Figure 4. 4 SPMTs with gantry system [9]....................................................................... 143
Figure 4. 5 Longitudinal launching construction method [10]....................................... 144
Figure 4. 6 Lateral bridge sliding [11].............................................................................. 145
Figure 4. 7 Hose Configuration and Hydraulic Pump Unit [12]...................................... 145
Figure 4. 8 Slide-in of Larpenteur Avenue Bridge [8]..................................................... 145

xv
Figure 4. 9 Slide-in of State Route 121 over I-70 in Indiana [8] .................................................. 146
Figure 4. 10 Folded Steel Plate Girder installation [13]. ................................................................. 146
Figure 4. 11 Truck crane booms and jibs [14]. ................................................................................ 147
Figure 4. 12 Installation of beam using a crawler crane [14]. ............................................................. 147
Figure 4. 13 The modular decked beams delivered by truck [15]. ..................................................... 148
Figure 4. 14 Installation of Fiber Reinforced Polymer decks with the use of a forklift [16] ...................................... 148
Figure 4. 15 Transportation of main span by SPMTs to the barges [17]. ............................................. 149
Figure 4. 16 Skid Jacks used to locate bridge into strand jack lifting frames (Respectively) [17] ................................................................. 149
Figure 4. 17 Vertical axis pivot [3]. ................................................................................................... 150
Figure 4. 18 Longitudinal gantry bridge placement [18] ................................................................. 150
Figure 4. 19 Transverse gantry bridge placement [3]. ................................................................. 151
Figure 4. 20 Transportation of spans from eastbound to westbound [19] ........................................ 151
Figure 4. 21 Transportation of girders in the eastbound bridge [20]. ............................................... 152
Figure 5. 1 Example of Florida Structural Inventory and Appraisal Sheet [2] .................. 154
Figure 5. 2 Tools for cleaning [2]. .................................................................................................. 159
Figure 5. 3 Tool for inspections [2]. ................................................................................................. 159
Figure 5. 4 Tools for Visual Aid [2]. .................................................................................................. 160
Figure 5. 5 Tools for Measuring [2]. ................................................................................................ 160
Figure 5. 6 Element Level example inspection form [2]. ................................................................. 161
Figure 5. 7 Load Rating Summary Sheet example [2] ..................................................................... 162
Figure 5. 8 Chain drag equipment (left) and hammer sounding tools (right) [3]. ...................... 164
Figure 5. 9 Formation and detection of AE Signals ........................................................................ 165
Figure 5. 10 Flowchart-NDT methods suitable for each type of defect in ABC deck closure joints in order of priority [1] ................................................................. 166
Figure 5. 11 A scheme of an IE method set-up [9] ........................................................................... 166
Figure 5. 12 Example of GPR for bridge deck inspection [10] ..................................................... 167
Figure 5. 13 The defects are read from the screen [13] .................................................................. 168
Figure 5. 14 Infrared Thermal Imaging; Use of IRT camera (left) and a thermal image (right) [18] ................................................................................................................................. 168
Figure 5. 15 A principle of Impulse Response Testing (IRT) set-up for slab evaluation [19] .......... 169
Figure 5. 16 The defects are read from the screen [20] .................................................................. 169
Figure 5. 17 Schematic layout of Magnetic Flux Leakage testing method [22] ...................... 170
Figure 5. 18 Statistical representation of NDT methods most applicable to detect delamination (Left), and to detect corrosion (Right) [1] ......................................................... 170
Figure 5. 19 Statistical representation of NDT methods most applicable to detect cracks (Left), and to detect voids (Right) [1] ................................................................. 171
Figure 5. 20 Different types of penetrating fluid used for nondestructive evaluation [23] ........ 171
Figure 5. 21 Schematic of the ET method [24] .................................................................. 172
Figure 5. 22 Example of MT principle [25] ...................................................................... 172
Figure 5. 23 Some robots collaborating with the operator for bridge inspection [26]............ 173
Figure 5. 24 Multitask robot for NDT inspection on bridge concrete deck [27]...................... 174
Figure 5. 25 Drone used for bridge inspection by Minnesota Department of Transportation [29] ........................................................................................................ 175
Figure 5. 26 DAA GPR platform in action, including AVA antenna and synchronized IMU/GPS [3] .................................................................................................................. 175
Figure 5. 27 Keg Creek Bridge full view [3] ...................................................................... 175
Figure 5. 28 Keg Creek Bridge GPR data [3] ...................................................................... 175
Figure 5. 29 Durability and residual service life assessment of bridge substructure [30] ...... 176
Figure 5. 30 Damage Sequence Tree (DST) for ABC closure joints [1] .............................. 181
Figure 5. 31 Typical joint leakage at deck panels (I-84 WB over Weber Canyon with welded-tie connections from 2009 inspection) [46]. ....................................................... 181
Figure 5. 32 Typical transverse cracking in the overlay which worsened from 2013 to 2016 [50]. .................................................................................................................... 182
Figure 5. 33 Cracks with efflorescence in parapet over the deck panel joint and Poorly bonded grout in shear pocket [50]. ................................................................. 182
Figure 5. 34 Shrinkage crack in the blockout type of ABC closure joint [53] ...................... 184
Figure 5. 35 Longitudine deck cracking of ABC closure joint [52] ...................................... 184
Figure 5. 36 Pitting of girder web and bottom flange [62] .................................................. 186
Figure 5. 37 Crevice corrosion between concrete haunch and steel beam [62]...................... 186
Figure 5. 38 Typical locations of corrosion on a steel girder bridge [63]. ............................ 187
Figure 5. 39 Corrosion of bottom flange and web near supports [65] ................................. 188
Figure 5. 40 Deck Plate Crack [69]. .................................................................................. 189
Figure 5. 41 Cracks in the longitudinal weld trough-deck plate [69] ................................. 189
Figure 5. 42 Crack in the stiffener splice joint [69] ............................................................. 190
Figure 5. 43 Fatigue crack trough – cross beam connection [69] ........................................ 190
Figure 6. 1 Flowchart for High-Level decision on whether a prefabricated bridge should
Figure 6. 30 Flowchart for selection of substructure system [184]. .......................................................... 229

Figure 6. 31 Flowchart for selection of substructure elements for pier and abutment system [184]. .................................................................................................................. 230

Figure 6. 32 Flowchart for selection of substructure elements for buried bridges [184] .......... 231

Figure 6. 33 Flowchart for selection of substructure elements for culverts ............................................................ 232

Figure 6. 34 Flowchart for selection of substructures with respect to foundation type [184]. .................................................................................................................. 233

Figure 6. 35 Situations to select deep foundation [19] ......................................................................................... 237

Figure 6. 36 Flowchart for the selection of foundation for new bridges [24] ................................. 238

Figure 6. 37 Flowchart for the selection of foundation based on types of soils [24] .......... 239

Figure 6. 38 Decision method for reuse of deep foundations [28] ................................................................. 244

Figure 6. 39 Reusing of foundation and substructure [184] ........................................................................ 245
List of Tables

Table 2. 1 Types of ABC deck panel systems alternative to concrete deck panels ..........35
Table 2. 2 Prefabricated Deck panel systems [7] ..................................................35
Table 2. 4 Summarizes different types of girders with potential for use in ABC short span
bridges. For completeness we included the result to up to 100 ft. ..........................42
Table 2. 5 Attributes of Trapezoidal Box Girders (Source: Badie et al. 1999) [14] .............51
Table 2. 6 Buried Bridge Geometry [39] .................................................................64
Table 2. 7 Bridge Foundation Systems, Equipment, and Ground Improvement Methods
for Accelerated Construction on Poor Subgrades .................................................80
Table 2. 8 Survey results [51] ..............................................................................87
Table 2. 9 Survey average results for rating of various systems. ..............................88
Table 3. 1 Different types of closure joints [64] ....................................................97
Table 3. 2 Different connections of cap beam and column .....................................117
Table 3. 3 Different connections of column and footing ........................................123
Table 3. 4 Abutment systems connections ...........................................................127
Table 5. 1 Nondestructive methods for inspections of ABC structures [3] .......... 163
Table 5. 2 Preliminary assessment procedure [30] .................................................176
Table 5. 3 Field testing related to concrete elements [30] .......................................177
Table 5. 4 Durability tests of concrete elements [30] .......................................... 177
Table 5. 5 NDT technologies for concrete elements [30] ......................................178
Table 5. 6 NDT technologies for steel members ..................................................178
Table 5. 7 Examples of defects and anomalies in bridge superstructure [37], [38], [39],
[40], [41], [42], [43], [44], [45] ........................................................................ 179
Table 6. 1 Superstructure system selection considerations .................................220
Table 6. 2 Substructure system selection considerations .......................................234
Table 6. 3 Foundation types based on soil conditions (Modified from Bowles [22]) [23] .... 240
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CHAPTER 1. INTRODUCTION TO ABC – OUTLINE OF THE COURSE

1.1. Abstract
With the use of prefabricated bridge elements and systems, Accelerated Bridge Construction (ABC) promises significant reduction in on-site construction time and traffic interruptions. It also improves the life cycle cost by better control over schedule, and normally by the higher quality of elements resulting in better life-cycle performance. ABC is especially beneficial for short-span bridges that are more receptive of standardized prefabricated elements. In most such cases, the entire span of the bridge can be covered using prefabricated deck elements, modular decks, or systems encompassing the entire bridge width. Furthermore, the substructures in these bridges could avoid special treatment and can be accommodated by prefabricated elements. For shorter spans, prefabrication of the entire bridge consisting of substructure and superstructure is also an option. Various construction methods ranging from installation using customary cranes to the use of Self-Propelled Modular Transport (SPMT) units for moving the entire superstructure, or the use of slide-in methods can be employed for construction of the short span ABC bridges. There are various definitions as what span length constitutes short span. Some define bridges with a span of 20-45 ft. as short-span (FDOT), others span of up to 70 ft., and some attribute spans as long as 100 ft. The proposed course module will introduce the ABC concept and review its applications to short-span bridge construction. It will categorize and describe short-span bridges based on various factors such as access, topographic and geographic conditions, roadway functional category, span length, elements and systems, time constraints, and construction methods. Design and detailing of the bridge and joints will also be discussed in the course. Performance of these bridges will be reviewed based on the information available in the literature. Decision-making on the use of ABC in general and type of elements, systems, and construction method will be briefly discussed in this course. Further, the course will cover new and ongoing developments that can affect the future of ABC for short-span bridges. Inspection of short-span bridges will also be one of topics discussed in this course.

This report subscribes to a definition of short span bridges which will help to distinguish better the limitation in selection of ABC components as well as a better explanation for the scope of work by parties performing the project.

1.2. Background
The main goal of ABC is to use the advantages of prefabrication to the extent possible for reducing on-site construction activities and impact on mobility. In this, short-span bridges represent an ideal case basically allowing implementation of a wide variety of ABC solutions and methods. There are various definitions as what span length constitutes short span. Some define bridges with a span of 20-45 ft. as short-span (FDOT), others span of up to 70 ft., and some attribute spans as long as 100 ft. Solutions ranging from prefabrication at element and member level to pre-construction of the entire bridge can be employed for short-span bridges. Structures over 20 ft. in span are normally called “bridges”, while structures with a span less than 20 ft. in span are called culverts even if they directly support the traffic. It should however be noted that some structures with spans of longer than 20 ft. are designed hydraulically and structurally as culverts [1]. Often, culverts with span longer than 20 ft. are designed accounting for the support from surrounding soil. Such
structures for which the need for static soil-structure interaction is identified, are called “buried bridges.” Span in such structures can reach up to 100-ft spans requiring safety and design considerations as conventional bridges [2]. Many of the culverts and buried structures are constructed using ABC methods and as such, these types of bridges are covered among ABC short-span bridges in this report. Some examples culverts and buried structures are shown in Figure 1.1. Figure 1.2 shows other ABC elements and methods.

Figure 1.1 Examples of culverts and buried bridges
The type of elements and construction method will depend on many parameters such as access, topographic and geographic conditions, roadway functional category, span length, elements and systems, and the time constraints. Accordingly, it is essential to make available to the users all element types, subsystems and systems available to choose for a short-span ABC bridge. Identifying the components and defining clearly their advantages, applications and limitations will help the selection. In most instances, span length is the most significant factor in determining the form and cost of a bridge. Design and detailing of the bridge, and especially the establishment of integrity between elements at the site using cast-in-place closure and other in-situ joints represents some challenges. Accordingly, ABC connections and joints play an important role and their application and limitations need to be understood. The prevalent defects observed in bridge decks using ABC have been cracks (Figure 1.3) accompanied usually with efflorescence and leakage. This type of defect has persisted for a specific type of ABC construction that uses side-by-side box precast concrete beams. Based on the reported survey, most of these problems were observed in the connections between deck panels and between deck panels and piers or abutments. Therefore, inspection and performance evaluation of joints, particularly closure joints, should be emphasized for short-span bridges.
Decision-making on the use of ABC in general and the type of elements, systems and construction methods in specific is essential for an effective project initiation, management and contractual aspects.

A concerted review of the application of ABC methods including important aspects of construction, detailing, performance and inspection, and decision making need to be communicated to stakeholders in the form of educational course modules. This project attempts to generate and compile materials for a course module material in relation with short-span ABC bridges.

1.3. Objectives of the Course

The primary objective of development of this course is to provide a general knowledge about the application of ABC for short-span bridges covering various aspects of decision-making, construction methods, available elements and systems, performance and inspection, design, detailing and connections.

1.4. ABC – Definitions and descriptions

Accelerated Bridge Construction (ABC) is a construction type that reduces the onsite construction time. To achieve the ABC mission, new and innovative materials, design, and construction methods are implemented in designing and construction of new bridges as well as in the replacement and rehabilitation of existing bridges. To reduce the onsite construction time, the prefabricated bridge elements and systems (PBES) is using in the construction of bridges. The prefabricated bridge elements are constructed offsite. In preparing the prefabricated elements, the construction, reinforcement placement, concrete placement, and concrete curing are conducted offsite. In this case, the construction of bridge components is in a high control condition which leads to improving the quality, safety, and durability of bridge elements. More specific, the offsite elements construction are not weather related to cause a delay in the bridge construction and also have no or little impact on traffic flow in comparing with conventional construction methods [3].

Conventional bridge construction is an onsite construction method which is highly dependent on weather condition that makes bridge construction time-consuming. The most disadvantage of this construction method is its effect on reducing traffic flow. To provide enough location for construction, a detour or temporary structure may be needed to reduce the impact of construction on traffic flow. Also, a remote site location is needed as a supporting location for the onsite construction. In fact, the onsite construction may reduce the transportation network mobility and safety. Therefore, the ABC method is more economical and safer than conventional construction method [3].

Conventional construction methods involve onsite activities that are time consuming and weather dependent [4]. An example could be Cast-in-place (CIP) deck which increases construction times and on-site labor activities [5]. For the case of ABC any cast-in-place concrete or overlay placement operation should be performed in a manner that reduces the impacts to mobility. This may require work that is performed under “Fast Track Contracting” methods with incentive/disincentive clauses, nighttime or off-peak hour timeframes, or work done entirely off line. Innovative materials may be needed to expedite placement times such as the use of rapid-set/early-strength-gain materials or ultra-high-performance concrete (UHPC) in closure pours [4].
Moreover, with ABC technology it is common that small closure pours will be required to complete some connections.

One of the key features of precast concrete construction, when compared to cast-in-place construction is the lack of restraint during curing. Individual elements are allowed to cure in a relatively unrestrained condition. The only restraint is the friction between the elements and the forms. In cast-in-place concrete construction, the casting of fresh concrete against previously placed elements leads to a build-up of internal stresses during curing, which often leads to cracking in the concrete. The most common form of this type of cracking is transverse cracking in bridge decks caused by restraint of the girders. Prefabricated concrete elements are placed after shrinkage has occurred; therefore, the potential for shrinkage cracking is eliminated. This will have a significant impact on the long-term durability of the elements [4].

A benefit of precast concrete is that the elements are cast in an un-restrained condition. In cast-in-place construction, concrete is often placed against previously cast concrete. Precast elements and precast bridge deck panels in particular are allowed to cure and shrink in an unrestrained condition, thereby reducing, and in most cases, eliminating shrinkage cracking. The reduction in cracking eliminates one avenue for water infiltration and long-term deterioration of the concrete [4].

1.4.1. Benefits of ABC

ABC technology has strived to create an advantage over the conventional construction methods. Even though traveling public are impacted by any methods of construction, the impact is significantly reduced due to the reduced onsite construction activities from ABC methods. Furthermore, during planning stage, any potential limitation can be accounted for to avoid the inactivity and assure quick progress. The most common benefits are categorized as followed:

- Reducing disruption to traffic and avoiding congestion
- Better safety for public and workers
- Achieving higher quality control for precast elements
- Reducing life-cycle costs and maintenance
- Decreasing environmental impacts
- Better control over cost and schedule (reduce weather dependency)
- Better constructability

1.4.2. Applications:

ABC can be applied to different types of bridge projects:

- Construction of new bridge

Even though the application of ABC appears to be more reasonable for existing bridges it can also offer a variety of benefits when it comes to new construction. A significant advantage for the new bridge construction is that designers have the facility to decide from a pool of options and choose the best suitable system for execution of the project. Common applicability of ABC for new construction can refer where existing construction limitations are forced by regulatory agencies for environmentally sensitive habitats. For this case ABC can be implemented and can decrease the impact to the sensitive habitat by significantly reducing the amount of construction time.
Moreover, if the bridge is a new structure over an existing roadway, the impacts to the lower roadway may still warrant an ABC approach in order to minimize the impacts to the vehicles below [4]. ABC methods also increase the safety at work by reducing the construction time. Furthermore, weather variability will be much less of a problem for construction of new bridges using ABC method when compared to conventional methods of construction.

- Repair-Rehabilitation

A common application of ABC is to reduce traffic impacts. The safety of the traveling public and the flow of the transportation network are directly impacted by on-site construction-related activities, therefore reducing construction time will provide for better safety [6]. The national bridge inventory is aging; therefore, many of the bridges in the United States have significant deterioration [4]. ABC can be used for rehabilitation projects by doing the following:

  o Deck Replacement

Conventional construction method for bridge deck is time consuming and labor intensive as it requires extensive on-site activities. For example, for concrete bridges, a temporary formwork is required to hold the reinforcement and wet concrete until a specific strength is reached. By applying ABC approaches and using prefabricated precast deck elements these limitations can be avoided. There are three main types of ABC deck replacement strategies that have been used. Two main types are: partial depth and full-depth. Both types of concrete deck panels can be manufactured off site in a casting yard, allowed to cure, and transported to the site when needed [7]. Some other examples of prefabricated deck panels are open grid deck, concrete/steel hybrid deck, fiber-reinforced polymer deck, and timber deck panels.

Another main type of ABC deck replacement strategy is by using stay-in-place deck forms. These forms consist of corrugated metal panels that are designed to support the reinforcing steel and the wet concrete of the deck. The benefit to this method of deck construction is that it eliminates the need to strip the forms after the concrete is cured. The disadvantage to this system is that it still requires the placement of reinforcing steel, casting of concrete and curing of concrete, which does not result in a significant time savings during construction. Also, future visual inspection of the underside of the deck is not possible [4].

  o Superstructure Replacement

The use of a prefabricated superstructure reduces the time it takes to construct or replace a bridge's superstructure. This provides for a faster process than using cast-in-place concrete and faster than using girders with slabs placed on top (FHWA, 2011). ABC techniques are particularly well suited for superstructure replacement projects, since the normally time-consuming process of building foundations and substructures is not required [4]. SPMT and skidding/sliding technologies can be used to removed and install entire superstructures, they can be built offsite and placed into new position in a reduced time frame. Other ways are to construct the modular bridge segments or by using a combinations of different prefabricated bridge elements.

  o Substructure Replacement

While prefabricated superstructure elements reduce overall project construction time, there are significant opportunities to reduce construction time through the use of prefabricated substructure elements and application of ABC methods. In most cases, prefabricated substructure elements are designed to emulate cast-in-place concrete [6]. Selection of the type of elements will depend on
time constraints, risks and costs to the project, environmental and geometric considerations, site conditions and accessibility, design constraints, and more importantly, compatibility with the superstructure and foundation. An example is the possibility to remove old pier columns and caps and replace them with prefabricated pier elements if the footings and foundations are in sound condition and structurally adequate. Closure pours at the base of the columns can be used to connect the old footings to the new pier elements. If an existing pier is supported on a spread footing, it is possible to build the new pier alongside the existing bridge on rails and jack it into place in a similar fashion to lateral superstructure [4].

- Replacement of existing bridges

Replacements of entire bridges and construction of new bridges differs from deck replacement and superstructure replacement projects in that there is also a need to replace the substructures and foundations, and more importantly, there is normally an existing traffic crossing the existing bridge. This adds a level of complexity to the project; however, ABC methods still offer advantageous options [4]. For the case of replacing an existing bridge most of the time traffic needs to be accommodated in order to proceed with the replacing. Application of ABC can help minimize impacts to the existing traffic by either building a bridge around the traffic or creating a detour for that purpose. ABC can help in several different replacement strategies and as many construction stages may be needed for the construction it can help reduce the time duration for each. Construction site safety also improves significantly with the use of ABC methods.

1.4.3. ABC Bridge Components

ABC components can be divided into superstructure, substructure, and foundation subsystems (Figure 1.4). Superstructure refers to deck and girders and everything above the deck [4]. The substructure refers to elements that hold the superstructure like piers, abutments, and wing walls, basically, everything below the superstructure bearing and above the foundation. Foundation is a part of substructure that transfers loads from the bridge to the earth and strata, it can be shallow or deep, and includes footings, pile caps, piles, etc. An overview of ABC bridge elements are shown in Figure 1.5. Culverts and buried bridges can be categorized as bridge systems or subsystems since they normally combine superstructure with substructure (3-sided box or arch) or represent the entire structure (box culverts). The ABC bridge elements and components are connected to each other using joints and connections which normally establishes in-situ [8], [9] (Figure 1.2). A more detailed definition, classification and uses of these components for short-span bridges will be covered in Chapter II.

1.5. Short Span Classification

This report covers ABC Bridge Systems for short span Bridges. In most instances, the span length is the most significant factor in determining the form and cost of a bridge. This report subscribes to a definition of short span bridges delimited with span lengths of up to 70 ft and maximum prefabricated bridge module weight equal to 90,000 lb. [10]. This definition helps to distinguish better the limitation in selection of ABC components as well as a better explanation for the scope of work for the project. Within this range of span length, structures with span of less than 20 ft are called culverts. Culverts, many of them surrounded with soil, are normally used for allowing water
to flow under the road, rail, or similar, and are designed with hydraulic considerations. There are also “buried bridges” that are short-span bridges, span of greater than 20 ft, that are constructed with the use of box or three-sided culverts and prefabricated arches and are supported and interact with the surrounding soil. The course will cover briefly the culverts and will review culverts and arch structures classified as “buried bridges.” However, the emphasis in this course will be on other type of bridge using prefabricated bridge elements and systems (PBES) that cover the upper range of the spans (closer to 70 ft), and include such superstructure elements as decked girders, modular superstructure, and similar.

Moreover, the number of spans, span range and weight should be such that it allows an easy transportation of entire elements. Lighter sections make shipping and erection easier. For instance, the longitudinal gantry frame method of installation is limited to relatively short span bridges because the size of the frame needs to be more than twice the length of the modules being installed [4]. Moreover, use of lower capacity smaller cranes become possible. Single short span bridges are more common than multiple or continuous spans.

When selecting types of prefabricated elements and systems the decision will be influenced by the span length of the bridge. Therefore, certain types and configuration of prefabricated elements will be more suitable for short span, along with the corresponding construction method. A more detailed approach for the type of bridge components based on span length is introduced in Chapter II.

Figure 1. 4 ABC Bridge Components
1.6. **Outline of the course**

It is envisioned that the course will be developed in several modules progressing from introduction and outline to various modules on specific topics. Each topic is presented here in this report as a chapter. The chapters corresponding to topics/modules are as follows:

- **Chapter 1 - Introduction to ABC for short-span bridges and Outline of the course**

  This chapter, presented in the section above, introduces the motivation for the course, introduction to short-span ABC bridges and background, objectives, and breakdown and brief description of the chapters/modules of the course.

- **Chapter 2 - Types of elements and subsystems**

  This report subscribes to a definition of short span bridges delimited with span lengths up to 70 ft and maximum prefabricated bridge module weight equal to 90,000 lb. [10].

  Availability of different element types and subsystems are limitless, each fitting certain purpose and objective mostly dependent upon the construction method to be used for bridge erection. In addition to parameters influencing selection of the construction methods, e.g.; availability of space, accessibility, roadway functional category, and condition under the bridge, factors such as time constraint, risk and cost, environmental considerations, design constraint and compatibility among superstructure, substructure and foundation as well as availability will determine the type of elements and subsystems to be used for construction of an ABC bridge. This chapter will introduce and discuss the available elements and subsystems for short-span ABC bridges.
Chapter 3 - Joints and connections

This chapter will deal with identifying the type of joints and connections between the superstructure, substructure, and foundation, and between their prefabricated elements as it applies to short-span bridges. Regardless of the type of prefabricated elements to be used in construction of ABC bridges, the elements, systems and subsystems need to be made integral with the use of joints and connections established in situ. ABC connections and joints play an important role and their application and limitations need to be understood. To effectively design a bridge system that resists design loads the components must be connected successfully. These connections are expected to perform equally to a conventional connection as they are planned to be emulative. Commonly, Ultra-High-Performance Concrete (UHPC), Self-consolidating Concrete (SCC), and other high- and normal-strength, fast-setting, early strength concrete mixes are used within the joints to accelerate the casting and curing process, and to decrease the potential defects. However, precautionary measures should be taken to minimize maintenance problems and improve durability.

Chapter 4 - Construction methods

Main benefit of application of ABC technologies is to have the possibility of prefabricating the elements and systems of the bridge under controlled weather conditions and to install them onsite in less time that conventional construction.

In order for taking advantage of this method, the use of innovative structural placement and construction methods should be considered for all ABC bridge projects. Using any of the construction methods, the elements or systems could be moved in minutes or hours which will implicitly lessen the traffic disruption, increase work safety, constructability and improve contractor options to move new prefabricated bridges into position.

This is considered an important feature of ABC as using innovative structural placement and construction methods will improve safety, quality, and reduce the construction time. In this chapter construction methods applicable to short span bridges will be discussed.

Chapter 5 - Inspection and performance

Prefabricated elements and systems are expected to have better quality and performance due to their construction in controlled environment and under stricter quality control than cast-in-place elements. Therefore, most performance issues in relation with ABC bridges will focus on the joints and connections that are established in situ. Cast-in-place joints may introduce a potential for weak link within Accelerated Bridge Construction (ABC) structures. The quality of the joints, expected to become serviceable quickly, depends on the concrete mix design, reinforcement and enclosure details, and is influenced by placement and curing procedure [11]. Despite the efforts to prevent weaknesses in these critical elements, potential exists that defects or anomalies are left in the joints during construction or develop later during the life of the structure [11].

In this module, a review of performance of ABC short-span bridges with an emphasis on joints will be carried out. Moreover, information on performance of general ABC construction and summary of deterioration patterns will be discussed. Additionally, inspection methods and means applicable to ABC short-span bridges will be explored. Based on the reported surveys, most of these problems have been observed in the connections between deck panels and between deck panels and piers or abutments. Therefore, inspection and performance evaluation of joints, particularly closure joints, should be emphasized for short-span bridges.
Chapter 6 - Decision making process

Decision-making on the use of ABC in general and the type of elements, systems and construction methods in specific is essential for an effective project initiation, management and contractual aspects.

After a decision has been made to use ABC in construction of a new bridge or replacement/rehabilitation of an existing bridge, a decision as to what ABC technology is appropriate for a site need to be taken. Several ABC technologies can be found to be appropriate at a site. This will mean that the project planners need to decide which technique fit better into particular project for which multiple methods are identified. Moreover, further investigation for each option and major contributing factors will affect in the final decision. In some cases, however, one method of ABC will stand up as the most appropriate for a project site which will make the decision-making process easier.

This module will introduce available decision-making methods applicable to ABC short-span bridges. This will include decisions on the use of ABC as an alternative to conventional method, selection of construction method most applicable, and determination of type of elements and subsystems, as well as selection of the type of inspection required.

Chapter 7 - New developments

For this module new and ongoing developments that can affect the future of Accelerated Bridge Construction will be discussed with a focus on short-span bridges.
CHAPTER 2. TYPES OF ELEMENTS AND SUBSYSTEMS

2.1 Abstract

As the choice of bridge structure is affected by many contextual factors it is important to provide a proper guidance to designers and bridge owners on the selection of type of elements and subsystems. Accordingly, it is essential to make available to the users all element types, subsystems and systems for a short-span ABC bridge. Identifying the components and defining clearly their advantages, applications and limitations will help the selection.

Often, the span length is the most significant factor in determining the type, design and details of a bridge. Traditionally, structures crossing span length of less than 20 ft have been called culverts that are often used for hydraulic crossings. This report subscribes to a definition of short span bridges delimited with span lengths up to 70 ft and maximum prefabricated bridge module weight equal to 90,000 lb. Hence, information of available components shall first consider their use for the range of span length identified.

Many element types and subsystems are available, each fitting certain purpose and objective mostly dependent upon the construction method to be used for the bridge erection. In addition to parameters influencing selection of the construction methods, e.g.; availability of space, accessibility, roadway functional category, and condition under the bridge, factors such as time constraint, risk and cost, environmental considerations, design constraint and compatibility among superstructure, substructure and foundation as well as availability will determine the type of elements and subsystems to be used for construction of an ABC bridge.

As an alternative to traditional bridges, buried bridges can sometime offer economic solution, especially for hydraulic and minor road crossings. A buried bridge is a buried structure supporting a roadway that relies on the support from the soil-structure-interaction. The design and installation of buried bridges have evolved over the years to accommodate longer spans inclusive of the range for short-span bridges. Since major segments, sometimes the entire superstructure and substructure, are prefabricated away from site and installed in place, they certainly qualify as ABC bridges.

This chapter identifies elements, subsystems and systems available for the use in short-span ABC bridges and includes information for facilitating their selection for a specific bridge project. The process of decision making is the subject of a later chapter. This chapter includes both PBES for traditional bridges and buried bridges alternatives. For completeness, culverts are also reviewed briefly.

2.2 Prefabricated Bridge Elements and Systems (PBES) for Conventional Bridges

Prefabricated bridge elements and systems (PBES) are structural components of a bridge that are built either off-site or adjacent to the site, in a manner to reduce the on-site construction time and mobility impact that can adversely affect the traveling public. Because of their versatility, PBES can be used to address many common site and constructability issues. Use of PBES has demonstrated proven benefits to agency owners, contractors, and the traveling public [10].

2.2.1 Elements:

Prefabricated elements consist of a single structural component of a bridge and are one category in PBES. Their use reduces the onsite construction time that is needed to build a similar structural
component using conventional construction methods. An element is typically built in a prefabrication shop and in a repeatable manner to reduce the costs. Because of a controlled environment in the prefabrication plant, the influence of weather-related impacts can be eliminated and improvements in quality and durability can be better accomplished [13].

2.2.2 Systems:
Prefabricated Systems are another category for PBES that comprise of an entire superstructure, superstructure and substructure, or a total bridge that is built in a modular manner such to allow traffic operations to resume after placement. Prefabricated systems can be rolled, launched, slid, lifted, or otherwise transported into place, having the deck and preferably the parapets in place such that minimal construction phase is required after placement [13].

2.2.2.1 Superstructure Systems
Superstructure Systems include deck and primary supporting members integrated. In this case, mobility disruptions occur only during placement. These systems are normally rolled, launched, slid, lifted, or transported in place, onto existing or new substructures (abutments and/or piers) [13].

2.2.2.2 Superstructure/Substructure Systems
Superstructure/Substructure Systems may include the interior piers or abutments, and are normally slid, lifted, or transported into place onto new or existing substructures [13].

2.2.2.3 Total Bridge Systems
Total Bridge Systems include the entire superstructure and substructures (both abutments and piers) that are made integral. Total bridge systems typically require unique designs, high-performance materials, and well-designed placement methods [13].

2.2.3 Superstructure Elements and Systems
The superstructure refers to all parts above the bridge bearing and provide horizontal span and rideable surface. These elements carry loads from the deck span and provide the riding surface [14]. Superstructure includes girder and deck slab, miscellaneous elements, barriers, and railing.

2.2.3.1 Deck Panels
The deck elements contain road lanes, walkway, and sidewalks. The conventional construction method requires deck forming and curing of concrete. This method can provide a smooth riding surface. However, this type of bridge deck construction is quite time-consuming. Therefore, the prefabrication of deck elements can significantly reduce the bridge construction time. The deck panel systems consist full-depth precast concrete deck, partial-depth precast concrete deck, open grid deck, concrete/steel hybrid deck, fiber reinforced polymer (FRP) deck, and timber deck panel. (Error! Reference source not found.) summarizes different prefabricated deck systems and their installation times according to the Florida Department of Transportation [7]. Alternatives to the
full and partial-depth concrete deck panel systems, i.e., open grid panels, fiber reinforced polymer (FRP) panel, timber deck, and steel/concrete hybrid deck panel systems are lightweight and can facilitate the shipping of the panels and are appropriate for moveable bridges. Error! Reference source not found. describes some deck panel systems as alternative to concrete deck panels that can be applicable to short span bridges alternative to the full-depth or partial-depth concrete deck panels.

2.2.3.1.1 Concrete Deck Panels

Cast-in-place concrete decks that use stay-in-place forms can also be categorized within the ABC methods because it reduces the construction time by eliminating time for form removal and, depending on the form support type, reduces the need for scaffolding and form installation.

### Table 2. 2 Prefabricated Deck panel systems [7].

<table>
<thead>
<tr>
<th>Deck panel system</th>
<th>Installation time (days/span)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-depth precast concrete deck panel</td>
<td>2</td>
</tr>
<tr>
<td>Partial-depth precast concrete deck panel</td>
<td>7</td>
</tr>
<tr>
<td>Open grid deck panel</td>
<td>1</td>
</tr>
<tr>
<td>Concrete/steel hybrid deck panel</td>
<td>2</td>
</tr>
<tr>
<td>FRP deck panel</td>
<td>2</td>
</tr>
</tbody>
</table>
In full-depth precast deck panel application, the construction time of the bridge reduces more significantly [13] than the partial-deck or stay-in-place forms (Figure 2.1). In this case, however, the shipping of panels may introduce issues that can be addressed by constructing the panels near the bridge site. Restressing or post-tensioning may be needed in the full-depth deck construction. The deck panels are designed as one-way slabs, and longitudinal post-tensioned bars may be used to integrate them. Also, blockout connections are used to attach the beam to the deck panel. Application of the blockouts is for establishing composite action between slab and girders [13].

The partial-depth precast concrete panels that are also used as “concrete framework” have 3.5 to 4-inches thickness. After placement of the partial deck panels on the top of the beams, a layer of concrete is cast on top of the panels to build the full depth of the deck [15].

2.2.3.1.2 Open Grid Decks

In open grid decks, the grid is filled partially with concrete (Figure 2.2). However, there is a concern about the durability of this system [7].

2.2.3.1.3 Prefabricated Timber

Prefabricated timber beams and panels are normally fabricated using glue laminating process that involves gluing nominal dimension lumber side-by-side to create a solid panel. The elements are normally pressure treated before being laminated together, or pressure treatment can be applied after fabrication. The glue used for bridge application should be water proof [13]. In timber deck systems, bolting or post-tensioning is used to connect the glue-laminated deck panels to each other and provide deck span (Figure 2.3). Most timber bridges are used on low volume roadways, but they could be applicable to higher volume roads too [13]. Figure 2.3 shows an example of timber deck panels.

Timber deck panels have been used in two ways:

• Installed on top of beams (glue laminated wood beams or steel beams) by the way of installing laminated timber decks on top of timber or steel beams. The panels span transversely from beam to beam [13].

• Installed as adjacent-deck-slab superstructure for short span bridges by the way of laying laminated deck spans comprised of adjacent timber elements side to form a solid panel. They can be used to span the entire length of the bridge [13].

The design of some of the deck systems described here is covered in AASHTO LRFD structural specification [16].

2.2.3.1.4 Hybrid Decks

Hybrid decks can be made of partially filled grid decks or exodermic decks. In the former, the upper portion of the steel grid is filled with concrete (Figure 2.4).
2.2.3.1.5 Exodermic Decks

These are similar to steel grid, but the concrete is placed over the grid with a connection of concrete to the steel grid that is similar to a full-depth precast concrete deck.
Figure 2. 2 Open grid deck panel [13].

Figure 2. 3 Timber deck panels [7].
2.2.3.1.6 Steel Orthotropic Decks

Orthotropic steel plate can be utilized for distribution of deck traffic loads and for stiffening the supporting slender plate elements in compression. This system (Figure 2.5) consists generally of a flat, thin steel plate, stiffened by a series of closely-spaced longitudinal ribs at right angles or orthogonal to intermediate floor beams, and are typically made integral with the supporting bridge superstructure as a common top flange to beams and girders. This results in cost savings in the deck structure. The orthotropic steel bridge normally results in a nearly all-steel superstructure [17].

Orthotropic construction has good potential for use in short- to medium-span girder bridges. Although the system has not been used more extensively for economic reasons, its light weight makes becomes beneficial for improving load rating during a deck replacement and for instances
where replacement of the bridge may have been the only other alternative [17]. Orthotropic steel deck systems have been known to include details that are sensitive to fatigue damages.

### 2.2.3.1.7 Aluminum Orthotropic Decks

The aluminum orthotropic deck system (Figure 2.6) configuration is similar to the steel orthotropic deck described above, where the use of aluminum instead of steel provides a corrosion resistance advantage resulting in lower maintenance costs since it does not need periodic painting. The additional cost associated with aluminum has often deterred its use in the United States. Other factors to consider include differences in thermal expansion coefficients, reactions with dissimilar materials, lower modulus of elasticity and lower fatigue strength of the material, and difference in welding processes and characteristics [17].

![Figure 2.6 Orthotropic deck [13].](image1)

### 2.2.3.1.8 Fiber Reinforced Polymer (FRP) Bridge Decks

Fiber reinforced polymer (FRP) bridge decks and superstructure systems present newer technology. FRP which can be constructed using different types of fibers (Figure 2.7) [7]. FRP decks have been used successfully for short-span bridges and for deck replacement. The principal advantages of FRP are resistance to corrosion under the same conditions as steel materials and its light weight. Its potential has shown promise for deck replacement (Figure 2.8), especially if total load capacity is relatively low [17].

![Figure 2.7 FRP deck panel [7].](image2)
2.2.3.2 Girders:

The girders carry the slab loads and transfer loads to the substructure and foundation. The term girder sometimes is used interchangeably with beam. Girders can be constructed from different materials, most commonly from steel or concrete.

Steel girders are configured in different shapes (Figure 2.9). Their main advantage is in their light weight that is advantageous for shipping when compared to concrete. The long-term maintenance and corrosion resistance of steel girders can however be an issue. To address corrosion issue, weathering steel girders are introduces that require no painting and therefore less maintenance [13]. The steel beam pre-topped with concrete slab can be used as modular superstructure for replacement and construction of superstructure.

Precast prestressed concrete beam is another type of girder element. The AASHTO and precast/prestressed concrete institute (PCI) have developed standardized precast girders shape [18]. These girders include I-beam, U-beam, Single and Double-tee beam, rectangular beam, voided slab beam, and box-shape beam (Figure 2.10). Among others, the box girders and decked girders are the two shapes of girders commonly used in the ABC bridge construction [13].
Figure 2. 10 Different shape of precast girders [18].

Table 2. 3 Summarizes different types of girders with potential for use in ABC short span bridges. For completeness we included the result to up to 100 ft.
## 2.2.3.2.1 Decked slab girder (DS)

A variety of decked slab girders have been developed. For example, the Colorado Department of Transportation (CDOT) has developed a decked slab girder with a very shallow section suitable
for short spans. These girders are simple to fabricate and are well-suited to GRS-IBS (Geosynthetic Reinforced Soil-Integrated System) systems. The girder lengths are limited by factors such as ultimate strength of concrete and deflection under service load. When compared to deeper girder types, these girders may be expensive to construct due to the volume of materials required for the deeper spans. Simple spans up to 56 feet are feasible. Longer non-standard spans become feasible if the stiffness contribution of rails is accounted for [20]. Figure 2.11 shows the decked slab girder for the 15-foot width.

![Decked Slab Girder](image)

Figure 2.11 Decked slab girder [20].

### 2.2.3.2.2 Decked U-girder (DU)

Decked U-girder is another type of girder the Colorado Department of Transportation (CDOT) has developed with a shallow that offers an efficient structure suitable for short- to medium-length spans of up to 144 feet (Figure 2.12). Their standard section has 5-inch thick web. A thicker 7 1/2-inch web is used when increasing shear capacity for longer spans or shallow sections is required [20]. The useable span length is limited by section weight. More efficiency if provided by this system for span lengths from 30 feet to 96 feet. Fabrication of this system is likely to be more labor intensive and time consuming than the other recommended types [20].

![Decked U Girder](image)

Figure 2.12 A sample decked U girder: top widths 15 feet 0 inch, 9 feet 10 inches, or 7 feet 3 inches [20].

### 2.2.3.2.3 Precast slab/deck beams

Other states also have their standards for Precast slab/deck beams. These are defined as adjacent slab beam bridges, a common superstructure type for short-span bridges applicable to 30- to 60-ft span lengths. Alabama's prestressed slab units is one example which uses post-tensioning after the beams are placed side by side. Another example is Florida Department of Transportation's (FDOT's) Prestressed Slab Units (PSUs) that are joined with longitudinal shear keys and require no post-tensioning and [7]. The Florida Slab Beam (FSB) initially were limited to off-system bridges with low average daily traffic (ADT) and low average daily truck traffic (ADTT). Three
FSB section depths are currently available (12, 15, and 18 inches) for spans ranging from 30 feet to 60 feet [5]. Typical Florida Slab Beam (FSB) section details are shown in Figure 2.13.

![Typical Florida Slab Beam (FSB) Section](https://www.shortspansteelbridges.org/gallery/images/rolled-beam-bridge)

**Figure 2. 13 Typical Florida Slab Beam (FSB) Section [5].**

### 2.2.3.2.4 Rolled Beam using W-shapes

Currently, composite multi-girder subsystems, plate girders or tub girders, that use rolled beams are the most common steel bridge superstructures (Figure 2.14). These systems can be single or multi span, straight or curved, or can also be skewed. For shorter spans up to about 100 ft for simple spans and up to about 120 ft for continuous spans, rolled beam superstructures using W-shapes can be utilized [17].

![Axtel UT rolled-beam bridge](https://www.shortspansteelbridges.org/gallery/images/rolled-beam-bridge)

**Figure 2. 14 Axtel UT rolled-beam bridge**

2.2.3.2.5 Inverted-T Precast Slab

Inverted-T precast slab (Figure 2.15) that provides a formwork for the cast-in-place concrete deck, is also suitable for short-span bridges where there are clearance issues. Additional time required to place and cure the cast-in-place concrete deck can be seen as an issue with this system. Reflective deck cracking is also a concern similar to that observed for adjacent box-beam bridge decks [14].

![Figure 2. 15 Inverted-tee Beams](www.fhwa.dot.gov/bridge/prefab/slab.cfm) [7].

Decked bulb tee is another standardized section from the inverted-tee family that is intended to behave like a series of adjacent box beams, while attempting to avoid the difficulties associated with precasting voided sections and issues with the inspection. The adjacent box beam and pre-topped inverted tee systems are compared in Figure 2.16 [5].

![Figure 2. 16 Decked bulb-tee shape compared to adjacent box beam configuration](Grace et al [5].)
2.2.3.2.6 Box Beam

Box beams with either a square or rectangular shape, usually come with depth greater than 17 inches. They can be arranged as adjacent or spread, used typically for short and medium span bridges. Adjacent box beams have practical span lengths that range 40 to 130 feet and spread box beams have practical span lengths that range up to 130 feet [1].

State of Texas has developed a set of standards for prefabricated prestressed concrete box beam that are appropriate for off-system bridges. They are placed adjacent to each other to achieve the desired roadway width [7]. Figure 2.17 shows an example of Texas Adjacent Box Beam

![Figure 2.17 Texas Adjacent Box Beam](image)

One of the disadvantages attributed to this system is the longitudinal joints between the boxes where leakage and durability becomes a concern. To address these issues, post-tensioning can be used to connect the boxes transversely and provide compression across the joints [7]. However, it has been shown that reflective cracking can develop even under post-tensioning [14]. Adjacent box beams (Figure 2.18 a) have practical span lengths in the range from 40 to 130 feet, while spread box beams (Figure 2.18 b) have practical span lengths that range up to 130 feet [1].

![Figure 2.18 Traditional (a) adjacent and (b) spread configuration for 28-inch depth box beams](image)
2.2.3.2.7 Double-Tee and Decked Bulb-Tee Girders

The standard double-tee girder system (Figure 2.19), originally developed for building and parking structure, has been available for a long time (PCI committee 1983). The limiting factor in the prestressed girder design is the web thickness. Further, due to limited flange thickness, developing a moment connection detail at the flange with two layers of reinforcement has been difficult. Standard double-tee sections require a cast-in-place concrete deck. The use of these girders is limited to short-span bridges with low-traffic volume (Bergeron et al. 2005; Chung et al. 2008; Li 2010) [7].

Decked bulb-tee sections (Figure 2.20) were developed (Shah et al. 2006; PCI 2011) to address the limitations of double-tee system. Larger web thickness of decked bulb-tee sections accommodates post-tensioning to develop continuity details over the supports. This system is suitable for short-to-medium span bridges. As for any other system, durability performance is a concern. The increased flange thickness of the decked bulb-tee section is also suitable for developing durable flexure-shear transfer connection details (Graybeal 2010a; UDOT 2010b; CPMP 2011; Culmo 2011) [7].
Bulb-tee beams can be distinguished by their "T" shapes, with a bulb-shaped section (similar to the bottom flange of an I-beam) at the bottom of the vertical leg of the tee. This girder-deck system can be used for spans as long as 200 feet [1].

2.2.3.2.8 NEXT F Beam

The NEXT F beam system requires an 8 in. thick cast-in-place concrete deck on the typical 4.5 in. thick flange. As with any prefabricated system, joint durability is a concern. However, durability may improve by the use of flexure-shear transfer connections [14].

2.2.3.2.9 NEXT D Beam

The NEXT D beam (Figure 2.21) is appropriate for use in short-span bridges on low-volume roads where there is a less durability concern with the longitudinal joint. Because the top flange is intended to act as a structural deck, a closure pour between members is require as the longitudinal connection in the form of a shear key and headed reinforcing bars that extend from the flanges. To contain the concrete for the closure pour, removable formwork has to be used, and it has to also accommodate differential camber of the beams. The parapets have to be either precast onto the beam during fabrication or must be cast-in-place on site after installation because the top flange is being used as a riding surface. The use of lightweight concrete on the full-depth, top flange section can significantly reduce the self-weight of the beam, and thus reducing the shipping costs [7]. Both the NEXT F and D beams are suitable for short and up to short-to-medium span bridges with a cast-in-place deck.

These beams are available in four different depths (28-inch, 32-inch, 36-inch, and 40-inch), two different widths (96-inch and 120-inch) and are recommended for spans between 20 feet and 80 feet. Because it is a standardized bridge girder, Precast/Prestressed Concrete Institute Northeast (PCINE) has predesigned sections depending on the span length for each beam group, as shown in Figure 2.22 [5].

Figure 2.21 Full-depth Top Flange NEXT Beam [7].
Figure 2. 22 NEXT D beam span lengths [5].

2.2.3.2.10 Channel beams
Channel beams can be precast or cast-in-place. These (Figure 2.23) are formed in the shape of a "C" and placed legs down when erected. They function as both superstructure and deck and are typically used for shorter span bridges [1].

Figure 2. 23 Precast channel beam cross section and longitudinal section [22].

2.2.3.2.11 I-beams
Distinguished by their "I" shape, I-beams function as superstructure members and support the deck. This type of beam can be used for spans as long as 150 feet [1]. Figure 2.9 has an example of I beams.
2.2.3.2.12 Voided slabs

Distinguished by their rectangular shape and their interior voids, voided slabs (Figure 2.24), are generally precast units supported by the substructure. The interior voids are used to reduce the dead load. Voided slabs can be used for spans up to 60 feet [1].

![Figure 2.24 Voided Slab Bridge Deck](https://www.sciencedirect.com/science/article/pii/S0965997810000505)

2.2.3.2.13 Trapezoidal Box Girder

This system was developed in 1998 for bridges up to short-to-medium spans. The girder was developed in two cross-sections: (1) a closed trapezoidal box and (2) an open section requiring a cast-in-place concrete deck.

Considering the difficulty in the casting of a closed trapezoidal box section, an open-top is preferred (Badie et al. 1999). The features of an open-top trapezoidal box girder are shown in (Table 2.4). Based on the data currently available, this section has not been specified for any project [14].

Table 2.4 Attributes of Trapezoidal Box Girders (Source: Badie et al. 1999) [14].

<table>
<thead>
<tr>
<th></th>
<th>Depth range (in.)</th>
<th>Spans up to (ft)</th>
<th>28 day concrete strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trapezoidal box</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(totally closed)</td>
<td>23.5 – 31.5</td>
<td>~95</td>
<td>7,500</td>
</tr>
<tr>
<td><strong>Trapezoidal box</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(open-top)</td>
<td>20 – 28</td>
<td>~86</td>
<td>9,000</td>
</tr>
</tbody>
</table>

2.2.3.3 Modular Superstructure System

The modular superstructure system is created when deck panels, girders, and their connections together are fabricated integrally. In this system, the panels can be connected to each other at the edges using grouted shear connector pockets (shear keys) [13]. A low shrinkage pour should be used to prevent transverse cracking. The limitation in the dimension of the modular systems is controlled by their heavy weight affecting their shipping. Therefore, the modular steel system is more preferable than their counterpart modular precast concrete systems due to its lightweight.
2.2.3.3.1 Modular Steel Girder Superstructure systems

Modular Steel systems can be made of topped multi-beams unit, modular steel folded plate girder system, or orthotropic steel deck system. Steel modules offer advantages over other modular systems as it reduces shipping weight of the modules [13]. The modular superstructure elements and systems are suitable for short-span bridges (i.e., 20 ft to 60 ft) [14].

2.2.3.3.1.1 Modular Steel Beams with an Integral Concrete Deck:

Modular Steel Decked Beams (e.g., using steel I-beams) are made by casting the concrete onto beams at an off-site location typically with two beams in order to facilitate shipping and handling (Figure 2.25). A single beam decked element is also an option [23]. These prefabricated modular steel beam elements are then shipped to the site and lifted into place (Figure 2.26). After placement, the joints between the deck portions of the modular steel beam elements are established with closure pours. Feasibility of pre-cambering the beams offers advantage for steel beams through which the vertical profile required by the roadway can be achieved easier. Doing this with precast concrete beams is more difficult. Steel decked beam elements are relatively wide and can lead to increased shipping and handling weight. This can limit their practical use for short and moderate span bridges [23].

Figure 2.25 Modular steel superstructure system [13].

Figure 2.26 Modular Beams with Decks [13].
2.2.3.3.1.2 Steel beam with orthotropic steel deck system

Another modular steel system is the steel T beam with orthotropic steel deck system that can be single span orthotropic with the running of ribs on the deck span or orthotropic T beam. In orthotropic T beam system, steel girders and a portion of the orthotropic deck are using together as shown in Figure 2.27. The disadvantage of the orthotropic system is its high cost. A standardized method and technique in the construction of the modular orthotropic system is being developed by the FHWA to reduce its cost [13].

![Figure 2.27 Modular orthotropic superstructure system [13].](image)

2.2.3.3.1.3 Modular Folded Plate Girder Bridge System (FPGBS)

The modular steel folded plate girder can be used for short span bridges with a maximum span of 60 feet (Figure 2.28). This system has a tub section that is built by bending a flat plate. The advantage of this system is its stability that doesn’t require the external or local frames against lateral bucking and similar [24].

![Figure 2.28 Modular steel folded plate girder [24].](image)
Folded Plate Girder Bridge System (FPGBS), offers an economical solution for many of the nation's bridges with maximum span lengths up to 60 ft. The system consists of a series of standard shapes that are built by bending flat plates into inverted tub sections using a press break. Figure 2.29 shows a fabrication process for a typical folded plate girder [24].

![Fabrication of folded plate girder using a press break machine](image)

**Figure 2. 29 Fabrication of folded plate girder using a press break machine [24].**

FPGBS have many advantages for both steel fabricators and bridge owners. Folded plate girders suitable for different span lengths differ only by their cross-sectional dimensions [24]. The Folded Plate Girder Bridge Systems (FPGBS) can be constructed using conventional construction techniques as well as using principles of Accelerated Bridge Construction (ABC) [24]. FPGBS is constructed by using prefabricated, pre-topped elements, where each unit consists of a folded plate girder with deck cast on the top. Several (usually four) of these units (pre-topped folded plate girder) could then be transported to the field, placed side by side and joined together to complete the bridge construction [24]. Figure 2.28 is a Pre-topped folded plate girder unit.

### 2.2.3.3.1.4 Press-Brake-Formed Tub Girders

The press-brake-formed tub girder system consists of modular shallow trapezoidal boxes fabricated from cold bent structural steel plate (Figure 2.30). Steel shapes are available in either hot-dipped galvanized or weathering steel options [25]. The fabrication of a composite folded plate girder module starts with a single steel plate of the desired thickness that is strategically bent into a structural shape. The plate is then cold formed into a U shape with a press brake, with each bend occurring along the plate’s longitudinal axis [26]. Once the plate has been formed, shear studs are then welded to the top flanges. A reinforced concrete deck is then cast on the girder in the fabrication shop and allowed to cure, becoming a composite modular unit. Modules are then longitudinally joined using Ultra-High-Performance Concrete (UHPC) [25].

![Conceptual view of modular press-brake-formed tub girder system](image)

**Figure 2. 30 Conceptual view of modular press-brake-formed tub girder system [25],[27]**
Press-brake-formed tub girders are versatile for multiple-deck options. They can be used for both tangent and skewed configurations, as well as simple and continuous spans. They are recommended for single spans up to 60 feet or less [28].

### 2.2.3.3.2 Modular Precast Concrete Superstructure Systems

Double tees and decked bulb tees comprise the modular precast concrete superstructure systems. Double tee modular system includes two girders connected with a deck slab as shown in Figure 2.31. The adjacent beams connect to each other using the shear key connection for the double tee modular superstructure. Bulb tee system consists of a girder with an extended top flange. In this system, the connection of two adjacent bulb tees is established using the welded tab connection. This type of connection limits the use of this system to low volume roads due to the low durability of the connection [13].

![Figure 2.31 Modular double tee superstructure system [13].](image)

### 2.2.3.3.3 Timber Element Systems

Modular timber elements system is another type of modular superstructure system (Figure 2.32). In this system, all the elements are prefabricated, and laminated girder deck system is installed on the top of timber or steel beam. The laminated deck spans are basically comprised of adjacent timber elements that are laid side by side to form a solid wood panel. These panels can be used to span the entire length of the bridge. The laminations can be made with sawn lumber laid on edge, or glue laminated wood panels. The connection between laminations can be made with spikes, bolts or transverse post-tensioning [13].

![Figure 2.32 Laminated timber deck system [13].](image)
2.2.3.4 Barriers and railing

The barriers for ABC bridges can be designed and constructed with prefabricated deck, cast in place, or attached to the deck using fasteners such as bolts (Figure 2.33). The FHWA provided a manual that defines the barrier and railing requirements for bridges [29]. This manual requires crash testing for barriers. To this date, there is no crash tested prefabricated barrier available [13]. A prefabricated railing system has been developed recently by Iowa State University researchers as part of ABC-UTC projects that are verified with static/push-over testing. Next phase of this research project aims at verification through crash testing (Figure 2.34) [30].

![Figure 2.33 Prefabricated deck panel with a barrier (Utah DOT) [13].](image1)

![Figure 2.34 3D model of prefabricated deck panel with barrier lab set-up at Iowa State University [30].](image2)
2.2.3.5 Miscellaneous elements

Miscellaneous elements of the superstructure include the drainage assembly, lightning, expansion joints, bridge bearing, and deck overlay or riding surface of the bridge. The deck overlay or wearing surface can be surface of the bridge without any overlay or can be overlaid with asphalt pavement. The drainage assembly can be preinstalled on the prefabricated deck elements or established the same way as conventional bridges [31].

In the ABC bridges using prefabricated girders and deck, bridge bearing is placed between girder and cap beam to adjust the elevation of girder and deck, and to provide proper, durable and uniform seating for the girders (Figure 2.35). This is normally not the case for conventional bridges for which the gap between the top of girder and the deck (deck haunch) is used to elevation adjustment [13].

For accommodating changes due to temperature variation and preventing the premature deterioration or overloading of the bridge, deck expansion joints are necessary [32]. Expansion joints are not used for the case of integral abutments where super- and substructure become monolithic [12]. Expansion joints can be categorized into two groups [12]. One includes joints within the deck overlay and consists asphaltic plug material and epoxy header with glands or seals. The other includes the embedded joints into the deck. The embedded joints experience large movements and contain modular expansion joints, armored seals, or finger joints. The concern about the expansion joints is that they deteriorate rapidly and need high maintenance requirements. To address this issue, link slab has been introduced to eliminate the use of expansion joints in the ABC projects [33]. The practical recommendation and guideline to use the link slab in the ABC projects is in development and will be available shortly through ABC-UTC.

Figure 2.35 Bridge bearing [13].
2.2.4 Substructure

Substructure elements transfer vertical and horizontal loads from superstructure into the foundation. Piers, pier cap, abutments, culvert, wing walls, and retaining walls are the substructure elements (Figure 2.36) [13].

![Figure 2. 36 Substructure elements](image)

2.2.4.1 Piers

Piers are vertical elements that support deck span at intermediate points and typically consist of pier columns and pier caps. This element transfers loads to the foundation and resists horizontal loads using its shear resistance mechanism. Piers that consist of more than one column are called pier bent (Figure 2.37) [13]. To connect pier cap and column, various types of connections are used, one is grouted splice reinforcing bar couplers. When the pier is affected by the errant vehicles or is adjacent to the railroad, the wall piers may be used instead of the pier (Figure 2.38) [13]. The integrity of piers connection to the pier cap and footing is very essential, especially in the seismic region because they should resist the majority of shear and seismic loads.

![Figure 2. 37 Prefabricated pier bent](image)
2.2.4.2 Abutments

Abutments are elements that sustain the superstructure live and dead load, retain the earth or embankment lateral pressure, and resist sliding and overturning due to the embankment. Abutments consist of walls, wing-walls, and abutment cap. In fact, abutments play both pier and retaining wall function. Abutments are constructed at the beginning or end of the bridge span where the superstructure rests on land [13]. Although the abutments can be constructed integrally or semi-integrally with the superstructure or built as a conventional free-standing abutment, integrally or semi-integrally construction of abutment is more popular.

Construction of abutments integrally with the superstructure has two significant advantages in comparing to the conventional free-standing abutment construction. Integrally and semi-integrally abutments have no deck joints and transfer embankment soil force to the superstructure [13]. In the fully integral abutment, the abutment connection to the superstructure is a full moment connection. However, in semi-integral abutment which a portion of the abutment is constructed with the superstructure, the pin connection is used to allow the rotation of superstructure in respect to the substructure (Figure 2.39) [13]. In this construction type, the abutment is supported on a row of column. An example of the integral abutment is shown in (Figure 2.40). This abutment configuration was constructed based on Utah DOT and several other states specification for the integral abutment. The corrugated void connection was used in this abutment. To create the voids in the abutment stem, the corrugated steel pipe was used. Recently, a research project as a part of ABC-UTC project has been introduced to investigate the constructability of abutment details and evaluate the strength and durability of abutment connections [34]. This project can facilitate the use of abutments in the ABC project by providing a detailed document for the construction of abutments.

Other types of prefabricated abutments are cantilever and spill-through abutments (Figure 2.41). These abutments constructed separately from superstructure and retain the soil pressure and superstructure loads. In the cantilever abutment, wall stem connects to the footing using different connections like grouted splice couplers. To attach the wall to the abutment cap, the reinforcing bar cage which is cast into the corrugated voids can be used [13]. The corrugated steel pipes can be used to create the voids and also reduce the abutment elements weight. When a large void is
erected in the cantilever stem, it is called spill-through abutment. The erection of this void can reduce the soil pressure on the abutment significantly.

The retaining wall and wing wall are the abutment extension to maintain the earth pressure in the approach embankment (Figure 2.42). These walls are constructed at the abutment and are designed to resist earth pressure from backfill, surcharge from the live load, and hydrostatic load from saturated soil. If these walls are not constructed, the earth stays in natural angle response [13].

Figure 2. 39 Semi-integral abutment [13].

Figure 2. 40 Prefabricated integral abutment [13].
Figure 2. 41 Prefabricated cantilever abutment [13].

Figure 2. 42 Prefabricated cantilever wing wall [13].
2.2.4.3 Pier cap

Pier caps provide enough space for sitting of girders to transfer loads from superstructure to substructure and distribute the loads from bearing to piers (Figure 2.43) [13]. The cast-in-place and the precast pocket connections are typically used to connect the columns to the cap. Other connection types have also been used for this purpose. Cap beams can be designed according to the displacement-based or force-based method using AASTO LRFD bridge design specification. A linear elastic behavior for cap beams during the earthquake is necessary according to the specification [35].

![Figure 2.43 Precast Pier Cap [36].](image)

There are two main types of pier cap including rectangular pier cap and inverted-tee pier cap. However, the precast rectangular pier cap is used widely [12]. Rectangular pier cap is typically used when there is a precast girder or steel girder that can sit directly on the top of the pier cap (Figure 2.44). The connection of pier cap to the pier can be fixed, pined, or isolated. The inverted-tee pier cap can be used when there are precast girders (Figure 2.45, 2.46). However, there is a challenge with the seismic behavior of the tee edges to satisfy the required demand that should be considered in the seismic regions [37].

![Figure 2.44 Rectangular pier cap [37].](image)
2.3 Buried Bridges (20 ft< Span < 70ft)

A buried bridge is a buried structure supporting a roadway that relies its support from the soil-structure-interaction with a bridge length greater than 20 feet [2]. The design and analysis methods consider the static soil-structure interaction and that gives the reason of the use of the term buried. As these structures have a span length that exceed 20 ft and in some cases approach 100-foot span therefore the term bridge is utilized. As the same case for conventional bridges, buried bridges can be used for new bridges, existing bridges and bridge reparation [2]. Buried bridges can be used for
a variety of reasons, including but not limited to remote site access, aquatic crossings, pedestrian tunnels, temporary detours, and it can support heavy live loading for trucks, mine vehicles, etc. [2]

Implementation of Accelerated Bridge Construction is possible with buried bridges as installation can be done in a relatively short time (days) basis reducing onsite manpower and expertise for installation. Additionally, accelerated design and installation process can be also guaranteed with availability of many standard designs, rapid shop fabrication and minimum material shipment needed. This type of bridge can improve environmental characteristics and sustainability as onsite material can be used for backfilling. Maintenance decreases as there is no bridge deck and no expansion joint. Reuse of existing foundations are possible and foundation settlement tolerance is increased.

In order to select buried bridge geometry, evaluation of durability, and adequate soil-structure interaction parameters are considered through the evaluation of the function and site constraints for the design. Size of the structure can be defined by rise and span (Figure 2.47) and different types can be determined by the hydraulic opening or clearance envelope. Length on the other hand, can be determined by the roadway width, end treatments or waterway placement [2]. These different types of geometry can be classified into reinforced concrete and corrugated metal geometry as they are in Table 2.6.

![Figure 2. 47 Buried Bridge Structure Geometry [39].](image)

<table>
<thead>
<tr>
<th>SHAPES</th>
<th>RANGE OF SIZES</th>
<th>COMMON USES</th>
</tr>
</thead>
<tbody>
<tr>
<td>RECTANGULAR (RCK)</td>
<td>Span 8 ft to 48 ft</td>
<td>Culverts and short-span bridges.</td>
</tr>
<tr>
<td>THREE-SIDED</td>
<td>Span 8 ft to 48 ft</td>
<td>Culverts and short-span bridges.</td>
</tr>
<tr>
<td>ARCH</td>
<td>Span 15 ft to 102 ft</td>
<td>Culverts and short-span bridges for low, wide waterway enclosures, aesthetic bridges</td>
</tr>
<tr>
<td>ARCH</td>
<td>Span 10 ft to 53 ft</td>
<td>Culverts and short-span bridges</td>
</tr>
<tr>
<td>CORRUGATED METAL</td>
<td>Span Rise x Span to 82 ft x 42 ft</td>
<td>Culverts and short-span bridges, low clearance waterway, aesthetic bridges</td>
</tr>
<tr>
<td></td>
<td>Span 20 ft to 83 ft</td>
<td>Culverts and short-span bridges, culverts, barriers, aesthetic bridges</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Culverts and short-span bridges, guardrail, aesthetic bridges</td>
</tr>
</tbody>
</table>

Table 2. 5 Buried Bridge Geometry [39].
2.3.1 Reinforced Concrete

Use of plant precasting of standardized sections is another way in which accelerated bridge construction can be implemented. Several manufacturers have developed precast concrete box, three-sided, and arch systems. These systems can be filled with onsite or granular backfill. Sometimes, these structures can be slid under existing bridges without interrupting existing roadway. Voids between both structures can then be filled with or without removal of existing bridges [13].

2.3.1.1 Rectangular (Box):
- Span range of 8 ft to 48 ft,
- Common uses: culverts and short span bridges

A variety of sizes, depths and for different live loads are offered in precast concrete box buried bridges. The speed of construction is one of the major advantages when using a precast concrete box [1]. An example of a rectangular (box) buried bridge can be seen in Figure 2.48.

![Figure 2.48 Rectangular (box) buried bridge](image)

2.3.1.2 Three-Sided:
- Span range of 8 ft to 48 ft,
- Common uses: culverts and short span bridges

Three-sided structure was created by a change in the design of the box culvert by removing the floor slab, this was done so it could comply with some environmental restrictions. Therefore, this type of design is used when there is limitation with hydraulic and environmental challenges in some states [40]. Figure 2.49 is an example of three-sided buried bridges.
2.3.1.3 Arch:
- Span range of 15 ft to 102 ft,
- common uses: culverts and short span bridges. For low, wide waterway enclosures, aesthetic bridges

Another environmentally friendly, bottomless option is the arch. Depending on the span length arches can come in one or two pieces. As is the case in Figure 2.50 where a longer span is needed the tow piece arch rebar from each element is tied together at midspan [40].
2.3.2 Corrugated Metal

Several corrugated metal plates are bolted together to form these bridge systems [40]. Corrugated Metal Buried bridges are defined below:

2.3.2.1 Arch:

An Arch is a curved-shape structure that works in compression primarily and does not have a floor slab. This type can be effectively used where natural aquatic organism passage is necessary [1]. Figure 2.52 have different examples of arch buried bridge usage.
2.3.2.2 High Profile Arch:

The difference between a regular arch and a high-profile arch is that its high-rise dimensions are for larger flow volumes or where there are clearance requirements that could govern a specific structure selection. This type of structure is available in steel and aluminum and has an elliptical shape [40]. Figure 2.53 possesses many examples of high-profile arch buried bridges.

![High Profile Arch buried bridges](image)

**Figure 2. 53 High Profile Arch buried bridges [39].**

2.3.2.3 Box Shapes

Figure 2.54 is an example of box shapes. It can be observed that is neither arch shaped nor rectangular, but uses a flat top with rounded corners, allowing the metal plates to make the geometric transition [40].

![Example of metal corrugated box](image)

**Figure 2. 54 Example of metal corrugated box [39].**
2.4 Culverts (Span<20ft)

The NBIS bridge length definition included in the *FHWA Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation’s Bridges* states: “A structure including supports erected over a depression or an obstruction, such as water, highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 feet between undercopings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes.”. Therefore, by understanding, those structures that have a span less than 20 feet may be classified as culverts [1]. A brief summary of culverts classification will be covered next, the will be subdivided into Precast Concrete Sections and Metal Culverts Sections.

2.4.1 Circular Shape or Round Arch:

The most common section shape for pipe culverts is the circular. The pipe generally causes some reduction in the stream during low flows volume. This type of culvert is very common and possible drawbacks can be that they are prone to clogging more than any other shapes [1]. Figure 2.55 is an example of a precast circular culvert structure and Figure 2.56 is an example of a round arch culvert.

![Figure 2.55 Twin Concrete Pipe Culvert [1].](image1)

![Figure 2.56 Round Arch Culvert [1].](image2)
2.4.2 Pipe arch and elliptical shapes:

These are often used when the clearance height is limited due to road profile or when due to high flow volume a wider section is needed. They are also prone to clogging as the circular shapes, however they are not as structurally efficient as the circular shape [1]. Figure 2.57 is an example of a pipe arch culvert.

![Figure 2.57 Pipe Arch Culvert [1].](image)

2.4.3 Arch Culverts:

When a natural stream bottom is needed, arch culverts offer a better option to avoid an obstruction in the waterway compared to pipe arches [1]. Figure 2.58 is an example of a pipe arch culvert.

![Figure 2.58 Pipe Arch Culvert [1].](image)
2.4.4 Rectangular cross-section culverts:
This is one of the most common culverts where there is no environmental restriction as the box culvert has a floor slab that supports the whole structure. Dimensions of the box can vary and are determined by structural, hydraulic and geotechnical design criteria \[1\]. Figure 2.59 is an example of a concrete box culvert and Figure 2.60 is an example of a metal box culvert.

![Concrete Box Culvert](image1)

*Figure 2.59 Concrete Box Culvert [1].*

![Metal Box Culvert](image2)

*Figure 2.60 Metal Box Culvert [1].*

2.4.5 Multiple barrels:
For cases where low embankments or wide waterways are needed to obtain an adequate hydraulic capacity the use of multiple barrels (Figure 2.61) substitute the box culvert \[1\].
2.4.6 Three-sided Frame Culverts:

This type of culverts can be made of precast reinforced concrete. The shape is generally similar to a box culvert with the difference of not having a floor slab. These are commonly used where there is the need to provide a passage for the aquatic organism [1]. Figure 2.62 is an example of a three-sided frame culvert.

Figure 2.61 Multiple Cell Concrete Culvert [1].

Figure 2.62 Three-sided frame culvert [1].
2.5 Foundation

The function of a foundation is to transfer load from the abutment, pier, and wing wall to the earth strata [13]. It acts as an interfacing element between the superstructure/substructure and the underlying soil or rock. Selection of proper foundation is important to transfer load to the underlying soil without causing shear failure of soil or damaging settlement of the superstructure [41]. Therefore, it is essential to systematically consider various foundation types and to select the optimum alternative based on the superstructure requirements and the subsurface conditions. When the soil near the surface is adequately stable and can provide enough bearing for the bridge load, spread footings can be used as the bridge foundation. However, when the top soil is not stable enough, deep foundation such as piles should be considered under the footing to transfer the load into the hard strata and thereby provide enough support to the bridge structure. Also, in case of bridge construction in water, the bridge foundations should be deep enough to prevent scouring due to water current. To reduce the amount of construction time and impact on traffic flow, different precast prefabricated elements can be used in the foundation [13]. Different elements of foundation for accelerated construction include, but are not limited to the following:

- Deep foundations
- Prefabricated Spread Footings
- Prefabricated Caps for Caisson or Pile foundation
- Sheet Piling (Steel or Precast Concrete)
- Precast Pier Box Cofferdams

Additionally, embankment systems that may be used for ABC bridges include:

- Geofoam Rapid Embankment
- Geosynthetic Reinforced Soil
- Mechanically Stabilized Earth Retaining Walls

Details of the foundation elements are presented in the following section.

2.5.1 Precast Spread Footing

Spread footing should be considered as bridge foundation if competent soils are available within shallow depth. The width of spread footing is expected to be small and depth of footing should be economically feasible [41]. Shallow spread footings require significantly less time to excavate and place than deep foundations such as drilled or driven piles. If necessary, ground improvement methods can be used to improve the subsurface conditions for shallow spread footing [41]. Generally, spread footings are constructed using cast-in-place methods. However, precast spread footings are also available for bridge foundation. These footings are precast off-site, transported to the construction site and placed on a prepared subgrade and then grouted in place [42]. However, transporting precast concrete footings may be challenging as the size of footings can get quite large for bridge loads [13]. A new hybrid system can be applied which allows the installation of the footing at the speed of precast with the economy of cast-in-place. In such cases, a precast concrete footing is used only under the columns. A continuous footing is then obtained by using a cast-in-place closure pour on extended reinforcing bars from precast concrete footing during the erection of the remaining portions of the bridge [13]. The completed continuous footing is designed to support all other loads. Figure 2.63 presents a schematic of precast spread footing as bridge foundation.
2.5.2 Deep Foundations

Deep foundations are selected when competent soils or rocks cannot be found on the top stratum or if there is a possibility of extensive scour, liquefaction or lateral spread [43]. Deep foundations are one of the most commonly used foundations for bridges by many state agencies [43] - [44].

Different types of deep foundations such as driven piles, micropiles, continuous flight auger (CFA) piles, or caissons are frequently used as bridge foundation [13], [41], [43] - [46]. Generally, a cap is built with the pile foundation to provide a stable platform for supporting substructure. Also, piles can be directly connected to the bent cap for short span bridges. Pile bents are cost effective and can be built quickly since there is no need for a footing. Most pile bents are constructed with precast concrete piles [13].

Driven Piles- Driven piles are the most commonly used deep foundation system for bridge projects. These precast prefabricated foundation elements are installed in the ground using a pile driving hammer. Driven piles such as steel H, pipe, and prestressed concrete piles (Figure 2.64) with various section properties are available to support bridge structures [41].

Caisson is a foundation type in the shape of a box, rectangular or round structure that is normally built on the land and sunk into water to a desired depth, and it is used when bearing capacity is not available near surface. There are three types of caissons: box caissons, open caissons and pneumatic caissons [47].

Caissons- A box caisson (Figure 2.65) is closed at the bottom and open at the top. It can be made of reinforced concrete, timber or steel. The caisson is built on land and later floated or launched to pier site where it is sunk in position. This type of caisson is normally used where loads are not very heavy and bearing stratum is available at shallow depth [47].

Figure 2. 63 Precast spread footing as bridge foundation [13].
An open caisson (Figure 2.66) is a box of metal, timber, masonry or reinforced concrete which is open at the top and bottom. They are also called wells. This type of foundation is mostly used when scour considerations and bearing capacity require foundation of more than 5 to 7 meters of depth. The common shapes are: single circular, twin circular dumb well, double-D, twin hexagonal, twin octagonal, and rectangular (Figure 2.67). Selection of shape depends on the dimension of the base, abutments, cost of sinking, horizontal and vertical loading to which the caisson is subjected and considerations of tilt and shift during sinking [47].

Pneumatic caissons (Figure 2.68) are rarely used today given the safety reasons [46]. They are open at the bottom during construction and closed at the top [47]. In this foundation type, the air pressure is maintained below the caisson during sinking to prevent water flow into the chamber where workers are excavating [46].

Continuous Flight Auger (CFA) - The advantage of using CFA piles is that these piles are drilled and cast in place rather than driven into the ground. The CFA piles (Figure 2.69) are formed by screwing a continuous auger into the ground and then grouting or concreting through the hollow center of the auger. The CFA is suitable for a wide range of cohesive and cohesionless soil conditions. Also, CFA does not produce shocks, vibrations, noise which makes it suitable for construction in urban areas [13, 46].

Micropiles - Micropiles are another type of drilled pile that are generally smaller in diameter (less than 12 inch), reinforced and grouted deep foundation element. Micropiles are typically used for underpinning, seismic retrofitting, and projects with difficult drilling conditions. These types of piles are suitable for places where small size and lightweight is advantageous or required because of the site constrains [41, 46].
Figure 2. 65 Box caisson example (https://www.slideshare.net/Tarique048/caisson-foundationppt)

Figure 2. 66 Caisson Construction for Greenville Bridge (http://www.massman.net/project/greenville-bridge)
Figure 2. 67 Shapes of open box caissons [47].

Figure 2. 68 Brooklyn caisson (https://www.structuremag.org/?p=10604)
2.5.3 Pile Cap Footings

Precast concrete pile caps can be used when steel or concrete piles are left projecting above the ground line to support the superstructure/substructure. Generally, a pile cap is cast-in-place by pouring concrete around the projecting piles to provide support for the superstructure. However, a precast cap with grouted pocket connection can also be used instead of a cast-in-place pile cap. The connection between the cap and the piles is achieved by filling the grout pockets with an epoxy grout \cite{13, 42}. A number of different pile cap connections are detailed in the FHWA Connections Manual \cite{36} to ensure punching shear and moment resistance at the connections. Figure 2.70 presents a sketch of precast concrete pile cap placed on precast concrete piles.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.70.png}
\caption{Prefabricated pile cap footing \cite{13}.}
\end{figure}

2.5.4 Precast Pier Box Cofferdams

In case of bridge construction in water, a precast concrete pier box is used to dewater the area where deep foundation connects to substructure. This structure can sit over the shaft and be sealed
to provide a dry condition during construction of footing. Also, the precast pier box systems can eliminate the need for complicated cofferdams and dewatering systems. This prefabricating system can be floated downstream from the place of cast and set into place to block off water flow for the installation of the pile caps. Also, these can be used as an additional corrosion protection system for the new pier footing when built with high performance concrete. Additionally, significant savings in time and money in the construction of the foundations can be achieved by using the precast concrete pier boxes [13], [42]. Figure 2.71 presents a precast concrete pier box that allows construction of footings in a dry environment.

Figure 2.71 Precast concrete pier box cofferdam [13].

2.5.5 Precast Sheet Piling

Precast concrete sheet pile and cellular steel sheet piles are most commonly used sheet piling systems for foundation construction and excavation support. Standards for precast concrete sheet piling was developed by Florida DOT. Typically, two types of cellular sheet piles are available, namely closed cell sheeting and open cell sheeting [13]. These precast prefabricated elements can be used to accelerate construction of bridge piers and abutments.

A geotechnical engineering scan tour of Europe was organized by FHWA and AAASHTO in June 2002 to evaluate the use of different accelerated bridge construction technologies. Based on the findings from that scan tour, Dumas et al. [48] presented a comparison (Table 2.7) between bridge foundation systems, equipment, and ground improvement methods for poor subgrade. According to Dumas et al. [41], the standard of practice for bridge foundation construction in the U.S. is driven piles or drilled shafts as CFA piles were found to have problem with quality control/quality assurance. An alternative for rapid construction could be the use of CFA piles with automated
computer control and automated QC/QA. Another alternate accelerated method suggested by the scan team was bored cased secant (CSP) piles which can be used for both bridge support and excavation support involving cut situations. Accelerated bridge construction technologies such as Hydro-Mill and vibro-jet sheet pile driving method were found to be useful for rapid construction of bridge foundation.

Table 2.6 Bridge Foundation Systems, Equipment, and Ground Improvement Methods for Accelerated Construction on Poor Subgrades

<table>
<thead>
<tr>
<th>Technology or process</th>
<th>Anticipated accelerated Construction Performance</th>
<th>Related Potential for Accelerated Construction</th>
<th>Applicable conditions for Accelerated Construction</th>
<th>Relative Cost</th>
<th>Improvement in Quality</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous Flight Auger Piles (CFA)</td>
<td>Rapid pile installation for vertical or batter piles</td>
<td>High</td>
<td>Best in weak to medium soil</td>
<td>Medium</td>
<td>Low</td>
<td>Automated control, Not suitable for difficult drilling</td>
</tr>
<tr>
<td>Bored Piling-Cased Secant Pile (CSP)</td>
<td>Rapid Pile installation for vertical piles</td>
<td>High</td>
<td>Cut situations, temporary excavations</td>
<td>Medium</td>
<td>Medium</td>
<td>Casing assists in some soil conditions</td>
</tr>
<tr>
<td>Self-Drilling Hollow Bar Nailing and Miro piling</td>
<td>Self-drilling and grouting for one-step installation</td>
<td>High</td>
<td>Difficult ground for drilling/driving</td>
<td>Low</td>
<td>High</td>
<td>Confined condition with difficult ground for drilling</td>
</tr>
<tr>
<td>Vibro-Jet of Sheet pile Driving</td>
<td>Speeds driving of sheet piles through layered soils</td>
<td>Medium</td>
<td>Same as conventional</td>
<td>Low</td>
<td>Low</td>
<td>Bridge abutments with grouting through vibro-jet pipes</td>
</tr>
<tr>
<td>Hydro-Mill</td>
<td>Rapid excavation of wall with no mess</td>
<td>Medium</td>
<td>Difficult drilling condition, large loads</td>
<td>Medium</td>
<td>High</td>
<td>Difficult drilling conditions, large loads and tight spaces</td>
</tr>
<tr>
<td>Screw piling</td>
<td>Requires 1/3 the time of auger cast piles</td>
<td>Low</td>
<td>Relatively weak soil conditions</td>
<td>Medium</td>
<td>Low</td>
<td>Auto control Depth&lt;100ft Non-artesian</td>
</tr>
</tbody>
</table>

2.5.6 Geofoam Rapid Embankment System

The Geofoam Embankment System (Figure 2.72) constitutes an embankment formed by expanded polystyrene blocks [13]. Given their light weight property they are used for weak sub soils.
Typically, a load distribution slab is built on top of the geofoam and covered with soil [49]. It usage is not predestined for a structural support system; the expanded polystyrene geofoam can also be placed around piles of an integral abutment or behind a conventional abutment [13].

Application of this technology is mainly for but not limited to reducing swell pressure of swell-type soils, reduce lateral earth pressure and reduction of settlement in embankments [49]. Moreover, benefits of this system include the elimination of pre-load settlement times, extremely lightweight material and fast construction [13].

The design considerations for this system is straightforward. Site is leveled, and layer of bedding sand needs to be placed. Geofoam are then placed with bedding sand that will fill the gap between backslope and geofoam. A load distribution slab is placed on top of the geofoam and then a layer of fill over the slab, and finally covered by the pavement [50].

![Figure 2. 72 EPS Geofoam Embankment (Source ACH Foam Technologies)](image_url)

### 2.5.7 Geosynthetic Reinforced Soil (GRS) Integrated Bridge System

GRS refers to an innovative geotechnical system that combines properties of granular soil and geosynthetic material to improve strength and stiffness of a soil mass. GRS systems are somewhat analogous to reinforced concrete. Both plain concrete and soil perform adequately in compression and shear, but lack strength and ductility in tension. The addition of rebar in concrete and geosynthetics in soil improves performance of both materials. GRS systems were shown to have a
beneficial application to short-span bridges in recent years [40]. The GRS needs to be finished with a beam seat or cap to receive the superstructure. Figure 2.73 shows an example of GRS/IBS Bridge abutment.

A recent form of abutment system is the Geosynthetic Reinforced Soil Integrated Bridge System (GRSIBS), which is described in FHWA publication FHWA-HRT-11-027 (Adams et al. 2011). This is a relatively new abutment system that has been used for accelerated bridge construction, and typically for short spans up to about 140 feet. The abutment uses alternating thin layers of compacted fill and geosynthetic reinforcement sheets that combine to form a reinforced soil mass foundation that directly supports the bridge superstructure without the need for piles. The geosynthetic reinforcement is connected into layers of precast facing blocks that are placed with the reinforcement and soil backfill. Once completed, the reinforced soil mass is ready to support the bridge. Traditional abutments are typically concrete construction. When deep foundations are required to support the bent caps, they normally consist of timber, prestressed concrete square, solid round or hollow cylinder piles, CIP concrete drilled shafts, or steel HP or pipe pile sections [17].

![Figure 2.73 Typical Section of a GRS/IBS Bridge abutment](image)

**2.5.8 Mechanically stabilized earth retaining walls**

Mechanically Stabilized Earth (MSE) retaining walls are very common in the U.S. They are comprised of precast concrete panels connected to reinforcing strips that are embedded into the backfill soils. Figure 2.74 shows a cross section of a typical MSE wall. The use of MSE accelerates the construction of walls since the curing of concrete is minimized (footing only) and backfilling and erection of the wall occur in parallel. MSE walls function by engaging the soil mass behind the wall face to form an earth gravity wall system [16].
There are also wall systems that use GRS fabric, wire mesh or natural vegetation in place of the wall panel facings. The construction of these walls can progress rapidly because the system is built while the soil is being placed behind the wall; thereby combining two processes into one [13].

Many states also use MSE walls for abutments; however, the walls typically do not support the bridge. Piles or drilled shafts are installed prior to wall construction. The MSE wall is then typically built in front of the piles with the reinforcing strips placed between the piles. Once complete, a concrete footing is installed on top of the piles, creating two separate structures [16].

2.6 Survey: FDOT Superstructure Types for Short and Medium Spans

This section provides a summary of survey conducted in the state of Florida by the Florida Department of Transportation (FDOT). The purpose of this survey was to assist them in choosing an optimal superstructure section type to serve as an efficient superstructure for bridges with spans between 50 and 80 feet and to evaluate different structural shapes for off-system bridges with spans between 30 and 60 feet. Even though this survey was not done specifically for ABC bridges the compiled information can be useful when applying ABC technologies.

The superstructures types considered for the survey are: Solid Slab with P-T, Double T (FLET), FDOT PSU, Type II Box Beam, Texas Box Beam, Minnesota Flat Slab, Truncated FIB, Super T Beam and AASHTO Type II Beam. Figure 2.75, Figure 2.76, and Figure 2.77 represent the drawings showing the nine superstructure typical sections considered in the survey. This information will provide a practical and useful set of inputs indicating the preference of the end users for the type of elements works best for them.
Figure 2. 75 Drawings for Solid Slab with P.T, Double T (FLET), and FDOT PSU [51].
Figure 2. 76 Drawings for Type II Box Beam, Texas Box Beam, and Minnesota Flat Slab [51].
Figure 2. 77 Truncated FIB, Super T Beam, and AASHTO Type II [51].
The following terms were defined for rating purposes:

<table>
<thead>
<tr>
<th>Definitions of Terms:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban Area:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Rural Area:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Constructability:</td>
</tr>
<tr>
<td>Can the proposed superstructure be easily constructed? Consider fit-up, tolerances, access, equipment needed, etc.</td>
</tr>
<tr>
<td>Speed of Construction: How quickly can the superstructure be constructed?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material Information:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precast Concrete Beams: Concrete Class VI</td>
</tr>
<tr>
<td>Cast-in-Place Concrete: Concrete Class II (Bridge Deck)</td>
</tr>
<tr>
<td>Post-Tensioning Bar:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Grout: Non-Shrink Grout</td>
</tr>
<tr>
<td>Fiber Reinforced Concrete: Concrete Class II (Bridge Deck) with basalt or steel fibers per project specifications</td>
</tr>
</tbody>
</table>

**Figure 2. 78 Definitions of Terms for Survey [51].**

The survey intended to determine what type of superstructures are commonly selected for short and medium spans bridges. The span range was specified for each of the options. The subject was focused on evaluating different types of superstructures by rating each superstructure type from 1=poor to 10=ideal. Table 2.8 shows each response to the survey, top three responses for each reviewer were highlighted in green. Survey was subdivided into evaluation of each superstructure for constructability in Urban and Rural area, and speed of construction. Same rating values for different types of superstructures can be observed, the reason is that the survey was not developed as a ranking. Moreover, each column represents responses for each company that participated in the survey.

**Table 2. 7 Survey results [51].**

<table>
<thead>
<tr>
<th>Superstructure Type</th>
<th>Maximum Span (ft)</th>
<th>Constructability Urban Area</th>
<th>Constructability Rural Area</th>
<th>Speed of Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Slab with P-T</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double T (FLET)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FDOT PSU</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type II Box Beam</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Texas Box Beam</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minnesota Flat Slab</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Truncated FIB</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Super T Beam</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AASHTO Type II Beam</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Of the survey’s recipients some provided feedback. A summary of the responses is provided in Table 2.9.
Table 2.8 Survey average results for rating of various systems.

<table>
<thead>
<tr>
<th>Superstructure Type</th>
<th>Maximum Span (ft)</th>
<th>Constructability</th>
<th>Speed of Construction</th>
<th>Overall Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Urban Area</td>
<td>Rural Area</td>
<td></td>
</tr>
<tr>
<td>Solid Slab with P-T</td>
<td>50</td>
<td>5.40</td>
<td>6.11</td>
<td>6.40</td>
</tr>
<tr>
<td>Double T (FLET)</td>
<td>60</td>
<td>5.91</td>
<td>6.44</td>
<td>6.60</td>
</tr>
<tr>
<td>FDOT PSU</td>
<td>50</td>
<td>7.90</td>
<td>7.33</td>
<td>7.45</td>
</tr>
<tr>
<td>Type II Box Beam</td>
<td>86</td>
<td>5.78</td>
<td>5.88</td>
<td>5.50</td>
</tr>
<tr>
<td>Texas Box Beam</td>
<td>60 (for 20” ht)</td>
<td>6.22</td>
<td>6.38</td>
<td>6.56</td>
</tr>
<tr>
<td>Minnesota Flat Slab</td>
<td>53</td>
<td>6.63</td>
<td>6.00</td>
<td>6.00</td>
</tr>
<tr>
<td>Truncated FIB</td>
<td>63</td>
<td>6.00</td>
<td>6.50</td>
<td>5.75</td>
</tr>
<tr>
<td>Super T Beam</td>
<td>79 (for 30” ht)</td>
<td>6.22</td>
<td>6.50</td>
<td>6.63</td>
</tr>
<tr>
<td>AASHTO Type II Beam</td>
<td>70</td>
<td>6.73</td>
<td>6.67</td>
<td>6.40</td>
</tr>
</tbody>
</table>

In addition, a few comments were provided for each of the superstructure types. A total of 11 individuals contributed with additional comments from the rating process. A summary of their responses is provided. For Solid Slab with P.T (Figure 2.72) some indicated that they had used solid slab with P.T with a topping, and the benefit was that they were able to drive on the slabs immediately after being set. Others found that The PT does help with live load distribution between the slab units, but it complicates future widening and phase construction. Moreover, it has been found that on many of the solid slab with P.T the transverse connections between the slabs beams have failed. The result is the beams are not deflecting equally under traffic load and continual maintenance of the wearing course due to reflective cracking is necessary. Other issue was that Solid Slab with P.T with void slabs produced problems with differential camber between the units. Some suggestions for considering a Solid Slab option is to use closure pours b/w slabs, similar to those shown for Double Tee, and eliminate the P/T. Comments for Double T (FLET) (Figure 2.72) is that some had never used them and other stated that the sections are very heavy and only one piece at a time can be transported. However; they were easy to handle. FDOT PSU (Figure 2.72) advantage is that the FDOT PSU could be driven on, so keyway grout could be poured right out of the ready-mix truck. Some had also used the FDOT PSU beams on several county projects. They typically use 2 layers of steel which requires a little thicker CIP section. This design has successfully locked the individual slab units together and has prevented any cracking from reflecting up to the deck surface. One disadvantage is that they generally had longitudinal cracks through the topping above the shear keys and live load distribution could be questionable in some
cases. For **Type II Box Beam** (Figure 2.73), the recommendation was to use sacrificial form. As for Urban Area, ability to widen in future is needed; which would be the reason why transverse p/t is not preferred. For the **Texas Box Beam** (Figure 2.73) only one individual mentioned that they generally had longitudinal cracks through the topping above the shear keys. Also live load distribution could be questionable in some cases. **Minnesota Flat Slab** (Figure 2.73); for this one they had more confidence in live load distribution due to the stirrups in the blockouts between units. Minnesota flat slab only requires one concrete placement without PT or placement of key or closure concrete which should make it very fast when construction duration is critical. The units are also lighter than the other systems, so they have excellent constructability. **Truncated FIB** (Figure 2.74) it was used on a widening project where vertical clearance was an issue. At the time of the response it was early in the project, but they had run some preliminary analysis and had found that the release stresses can easily control the design and were likely going to need to add some steel near the top of the Tee. Moreover, a few never built any of these because of the need for SIP forms and greater superstructure depth which usually make them less attractive than a flat slab system for shorter spans. For **Super T Beam** (Figure 2.74) recommendation to use sacrificial form. As for Urban Area, ability to widen in future is needed; that’s why transverse p/t is not preferred. Some claimed to have longitudinal crack concerns for Super T. A comparison was made between Super T Beam with the Florida U-beam which is typically only used if there are aesthetic criteria to be met, not because it is economical. They expected this would be similar behavior. For **AASHTO Type II Beam** (Figure 2.74) only one comment was made to express that they had built a lot of these and they had worked [51].
CHAPTER 3. JOINTS AND CONNECTIONS

3.1. Abstract

Regardless of the type of prefabricated elements to be used in construction of ABC (Accelerated Bridge Construction) bridges, the elements, systems and subsystems need to be made integral with the use of joints and connections established in situ. To effectively design a bridge system that resists design loads the components must be connected successfully. These connections are commonly supposed to perform equally to a conventional connection as they are planned to be emulative. Commonly, Ultra-High-Performance Concrete (UHPC), Self-consolidating Concrete (SCC), and other high- and normal-strength, fast-setting, early strength concrete mixes are used to decrease the potential defects. However, precautionary measures should be taken to minimize maintenance problems and improve durability.

Closure pours (joints) can be defined as joints for connecting the bridge deck elements to each other, connecting the bridge deck elements to the substructure, connecting superstructure to substructure as well as substructure elements to each other, and to foundations. Therefore, selection and design of the type of closure joints may depend on type of prefabricated elements.

In some literature, Closure Joint has been defined as joints in the bridge deck, connecting deck slab elements to each other and to the pier or abutment cap. Categorization of closure joints have been established in various ways depending on the application, geometrical features, or structural details.

ABC connections and joints play an important role and their application and limitations need to be understood. This module will deal with identifying the type of joints and connections between the superstructure, substructure, and foundation, and between their prefabricated elements as it applies to short-span bridges.

3.1. Joints and Connections

In an ABC bridge construction, joints and connections are needed to attach the prefabricated elements to each other as well as using between foundation, substructure, and superstructure (Figure 3.1 and Figure 3.2). The design and details of joints and connections in bridges that use prefabricated elements should at a minimum satisfy the same conditions as connections in cast-in-place bridges to provide enough durability and integrity for the structure [52]. Also, performance such as ductility, energy dissipation, strength, stiffness and failure modes need to be comparable to cast-in-place system in seismic region. The main characteristic of emulation design is to provide a substitute connection that emulates the standard lap splice of cast-in-place concrete structures [53]. In other words, “Emulating connection detailing” and design is used to make the precast structural elements behave as they are monolithic [54]. Accordingly, various connection types have been developed and validated for prefabricated elements including welded ties, mechanical couplers, small closure pours, closure joints, socket and pockets, and grouted tubes with reinforcing dowels.
3.1.1. Typical ABC Connection Types:

Prefabricated connections can be categorized into different common types and groups. Depending on what type of elements (material) they connect, ABC joints can be divided into those connecting steel elements and others connecting concrete elements [53]:

Figure 3. 1 Prefabricated Bridge Connections Example [53].

Figure 3. 2 Prefabricated Bridge Connections [53].
3.1.1.1. Steel Elements:

3.1.1.1.1. Bolted:

This process have been used for many years to connect prefabricated bridge elements. It can be used for transverse connection of modular double tee units and also adjacent units diaphragms plates that are joined together by bolt connections [53]. Depending on the type of connection, the process of bolting can be fast or slow. For example, due to a larger number of bolts required, girder splices are slow connections [53]. Figure 3.3 shows and example of a bolted girder [55].

![Figure 3.3 Example of bolted connections from Ohio’s Muskingum County Bridge [56].](image)

3.1.1.1.2. Welded:

Lately, many states have expanded the use of welding and have developed procedures that take into consideration the factors that affect the use of field welding. These factors include lack of certified field welders, concerns with quality of field welds, and time and difficulties with welding in colder environments [53]. This type of connection is preferable for ABC application as connections can be completed quickly. It can be used to connect steel girders to panels, for which, first steel plate is positioned in a specified place on the panel, and then the girder and the panel are welded together.

3.1.1.1.3. Cast-in-Place Diaphragms to Connect Steel Girders:

One of the means to connect steel girders or modular superstructure elements with steel girders at the pier location is the use of cast-in-place closure pours (diaphragms). This configuration, as it pallies to ABC construction, normally creates simple span for dead load and contious span for live load (SDCL). The connection can be established in different ways. Inclusion of top reinforcement in the deck level for transferring negative moments between two girders, and shear studs welded to the top and/or bottom flange of the steel girders are performed in some cases. The use of steel bearing blocks between the bottom flanges of the steel girders over pier has been used as one means for transferring compressive forces in the bottom flanges from negative moment at the pier. Closure pour assures the live load continuity connection and goes to steel member by bearing plates or welded stud shear connectors [53]. Recently, a SDCL joint that in addition to the details discussed above includes horizontal steel ties at the bottom flange level to assure that the joint would perform properly in the seismic application. This system is discussed in more details later in relation with superstructure to substructure connections. These connections have shown to
perform excellent in seismic regions and offer good constructability under bi-axial horizontal seismic loading [57]. Figure 3.4 shows an example of the construction sequence for simple for dead load and continuous for live load (SDCL)

![Figure 3.4 Construction sequence for SDCL Bridge Systems [58].](image)

3.1.1.2. Concrete Elements:

In the following, some of the common types of connection between concrete elements are discussed.

3.1.1.2.1. Grouted Reinforcing Splice Couplers:

Couplers have been developed by various manufacturers that can splice reinforcing steel bars within precast elements. These couplers are in the form of a pipe. Elements are connected by the couplers and then grout is cast in the joint cavities and pumped into couplers to establish the connection. This connection is desirable for substructure as large diameter bars can be spliced in less distance than conventional development lengths. These types of connections can develop 125%, 150% and up to 160% of yield strength of the connected bars [53]. Figure 3.5 shows a grouted Reinforcing Splice Coupler.

![Figure 3.5 Grouted Reinforcing Splice Coupler [53].](image)
3.1.1.2.2. Using Grouted Post-Tensioning (PT) Ducts:

These connections are similar to the grouted reinforcing splice couplers with the difference that the reinforcing bars from one element are inserted into non-structural ducts (post-tensioning duct segments) cast in the receiving element. Because the ducts are non-structural, normally, confinement reinforcement will be required to develop the connection. For seismic areas that require plastic hinging connections, these types of connections are not recommended as they do not have the required ductility to perform in a high seismic zone [53]. Figure 3.6 shows a grouted reinforcement PT duct layout [53].

![Figure 3.6 Grouted Reinforcement PT Duct Layout [53].](image)

3.1.1.2.3. Grouted Voids:

These types of connections are used in connections that transfer little moment between elements, such as pin connections. In contrast to grouted reinforcing splice couplers, the coupler is substituted with a void cast in the element [53]. Figure 3.7 shows an example of grouted placement [53].

![Figure 3.7 Grouted Placement [53].](image)
3.1.1.2.4. **Traditional Post-tensioning (PT):**
Post-tensioning connections between pieces in a segmental box girder bridge is considered the most common type. It can also be used in pier caps, pier columns, and precast concrete bridge decks. Connection of deck elements using post-tensioning combined with grouted shear key is also common [53]. Figure 3.8 shows typical post-tensioning details [53].

![Figure 3. 8 Lateral Post-Tensioning Details [53].](image)

3.1.1.2.5. **Welded connections:**
As stated above, welding can be used to connect precast elements. Normally, welded connection is made after erection using the steel plates that are embedded in the elements [53]. Figure 3.9 Shows details of welded plate connection.

![Figure 3. 9 Lateral Welded Plate Beam Connection Details [53].](image)

3.1.1.2.6. **Cast-in-place Concrete Closure Pours:**
This type of joint is considered one of the simplest connections as only an area is left to pour concrete to allow an effective connection between two precast concrete elements [53]. Figure 3.10 shows examples of various types where cast-in-place concrete closure pours is performed.

95
3.1.2. Superstructure element connections

Joints for connecting the bridge deck elements to each other and to the substructure are generally called closure joints. Selection of the type of closure joints is subject to many different factors. It may depend on functional requirements, type of substructure, environmental conditions, type of material selected for closure joints, type of deck elements, time constraint, necessity for continuity for shear and bending transfer, etc. Figure 3.10 has examples of various types of ABC closure joints. Additionally, use of proper concrete with characteristics such as high- and normal-strength, early strength, fast-setting, Self-Consolidating Concrete (SCC), and Ultra-High-Performance Concrete (UHPC), assure the closure joints are less vulnerable to defects and discontinuities [59].

Figure 3.10 Examples of various types of ABC closure joints [53], [60], [61], [62]

3.1.2.1. Deck Connections

Deck connections are defined as connections joining the deck slab segments to each other and to the girders and diaphragms. Deck connections can be categorized in different ways. Definitions may vary based on the purpose of categorization. Hence, the following descriptions and definitions adopted from different sources may overlap and, in some cases, disagree. However, for
Categorization based on geometric features: According to Mehrabi and Farhangdoust (2019) closure joints can be subdivided into five different types when considering the geometric features and type of anomalies influencing the use of NDT methods for evaluation of these joints [59]. These five groups of closure joints are represented in Table 3.1. The first four joint types in this table are linear joints which are used for connecting deck panels to girders, deck panel to each other, and to abutment/piers longitudinally and transversely (Figure 3.11). Longitudinal joints will be required only where multiple panels are needed across the bridge width. Joints should all be detailed and designed as full moment connections [63]. Finally, the last joint type (Type 5) is mostly used for connecting deck panels to the girders through pocket-type joints called blockouts [59].

<table>
<thead>
<tr>
<th>Group</th>
<th>Sample</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td><img src="image1" alt="Type 1 sample" /></td>
<td><img src="image2" alt="Type 1 symbol" /></td>
</tr>
<tr>
<td>Type 2</td>
<td><img src="image3" alt="Type 2 sample" /></td>
<td><img src="image4" alt="Type 2 symbol" /></td>
</tr>
<tr>
<td>Type 3</td>
<td><img src="image5" alt="Type 3 sample" /></td>
<td><img src="image6" alt="Type 3 symbol" /></td>
</tr>
<tr>
<td>Type 4</td>
<td><img src="image7" alt="Type 4 sample" /></td>
<td><img src="image8" alt="Type 4 symbol" /></td>
</tr>
<tr>
<td>Type 5</td>
<td><img src="image9" alt="Type 5 sample" /></td>
<td><img src="image10" alt="Type 5 symbol" /></td>
</tr>
</tbody>
</table>
The most common closure joints are categorized in the above table are described below [64].

3.1.2.1.1. Closure Joint: Type 1

This type of closure joint is normally used to connect Full-Depth Precast Desks and sometimes for connecting precast beams [53]. This joint may come in different shapes, such as rectangle and diamond-like in order to provide shear transfer. These joints are also known as shear-key or keyway joints and depending on the application are used longitudinally and/or transversely. The shape is prone to debonding, voids and porous grout formed in the corners. Also, sharp corners may contribute onset and propagation of cracks [66]. Figure 3.12 shows an example of Type 1 joint.

3.1.2.1.2. Closure Joint: Type 2

This type of joint is used to connect precast desks to precast concrete beams and Full-Depth Precast Desk to each other. This type of connection is differentiated from others by its near straight sides which allows smoother placement of concrete and decrease the possibilities of creation of voids [53]. For the case when this connection is used to connect the slabs to the girders, shear reinforcement is extended into the joint channel to transfer the horizontal shear. This type of joint is usually cast with self-consolidating non-shrink grout and can also be used to provide negative moment and continuity at the piers [53]. Figure 3.13 shows an example of Type 2 joint.
Figure 3. 13 Type 2 joint [59].

3.1.2.1.3. Closure Joint: Type 3

This linear joint is normally used to join butted decked precast girders, partial depth precast deck panels and sometimes to join steel girder superstructure with P/C Slab longitudinal connections [53]. This joint usually contains longitudinal and transverse reinforcement and may be used in both directions of longitudinal and transverse. Also, for unreinforced joint, post-tensioning can be used [53]. Moreover, where projecting tie bars of panels were bent and used as reinforcement in the connection this type of joint can be used to connect precast PT tub girders to precast deck slabs. Also, it can be used as a partial-depth link slab or transverse joint to provide negative moment and continuity at the piers [53]. Figure 3.14 shows an example of Type 3 Cross Section.

Figure 3. 14 Type 3 Sample Cross Section [59].

3.1.2.1.4. Closure Joint: Type 4

The last linear joint of Table 3.1 is only casted in the longitudinal direction and it refers to those that connect double beams or two prestressed tee beams, and sometimes partial or full depth deck panels. To fill this type of joint a non-shrink cementitious grout is what is normally used. Additionally, a layer of leveling surface is expected to be cast over the deck including this type of joint [59]. Figure 3.15 shows an example of Type 4 Cross Section.
3.1.2.1.5. Closure Joint: Type 5

This type of joint refers to blockouts which are box/rectangular shaped joints. They usually connect steel girders or concrete I-beams to precast full depth decks and are spaced throughout the decking. Usually shear connectors are extended into the blockout void and void is cast using high-early strength concrete. If necessary, adhesive tape can be used to prevent leaking by sealing the bottom of the joint [53]. A layer of leveling surface is expected to be cast over the deck. Care should be taken in installation of jointed elements since deck reinforcement may need to be adjusted for cases where steel reinforcement crosses the joint. Moreover, sometimes the joint can be used in combination with grouted linear shear key joint [59]. Additionally, UHPC joints and grout-filled deck pocket connections between adjacent deck panels are capable of providing structural integrity under earthquake loading [57]. Figure 3.16 shows an example of Type 5 joint.

Figure 3. 15 Type 4 joint [59].

Figure 3. 16 Type 5 joint [59].

Categorization based on mechanical and material aspects: Another way to classify the different types of closure joints is following categorization suggested by Garber and Shahrokhinasab (2019) for several common joints used in practice for joining precast full-depth deck panels. The joints were subdivided into different categories: post-tensioned, mechanical, ultra-high-performance concrete and conventional concrete as shown in Figure 3.17. These types of joints are described in the following.
<table>
<thead>
<tr>
<th>Post-Tensioned</th>
<th><img src="image" alt="Post-Tensioned" /></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td></td>
</tr>
<tr>
<td>Welded</td>
<td><img src="image" alt="Welded" /></td>
</tr>
<tr>
<td>Grouted Dowel</td>
<td><img src="image" alt="Grouted Dowel" /></td>
</tr>
<tr>
<td>Ultra-High Performance Concrete</td>
<td></td>
</tr>
<tr>
<td>Self-Forming w/Straight Bar</td>
<td><img src="image" alt="Self-Forming w/Straight Bar" /></td>
</tr>
<tr>
<td>Headed Bar</td>
<td><img src="image" alt="Headed Bar" /></td>
</tr>
<tr>
<td>Straight Bar</td>
<td><img src="image" alt="Straight Bar" /></td>
</tr>
<tr>
<td>Hooped Bar</td>
<td><img src="image" alt="Hooped Bar" /></td>
</tr>
<tr>
<td>Conventional Concrete</td>
<td></td>
</tr>
<tr>
<td>Hooped Bar</td>
<td><img src="image" alt="Hooped Bar" /></td>
</tr>
<tr>
<td>Straight Bar</td>
<td><img src="image" alt="Straight Bar" /></td>
</tr>
<tr>
<td>Headed Bar</td>
<td><img src="image" alt="Headed Bar" /></td>
</tr>
<tr>
<td>Hooked Bar</td>
<td><img src="image" alt="Hooked Bar" /></td>
</tr>
</tbody>
</table>

Figure 3. 17 Common types of longitudinal and transverse joints in FDPC Deck Panel Database [67].

### 3.1.2.1.6. Longitudinal Post Tensioning with Grouted Shear Key:

Use of non-strands, flat multi-strand tendons and high strength threaded rods is typical for longitudinal post tensioning. Post tensioning usually runs along entire length of the bridge and is located at the mid depth of the panels. This type of connection is the most common transverse joint.
detail that has been used as it is considered a good way to improve durability of the system. Male-to-female (Figure 3.18 b) match-cast joint with epoxy or grout, or female-to-female (Figure 3.18 a) joint with a small grouted section between panels can be used for post tensioned joints [67].

Figure 3. 18 Typical longitudinal PT joints: (a) female-to-female and (b) male-to-female match cast [67].

Blockout joints which are pockets cast in the slab produce the composite behavior between girders and deck panels. Shear studs are extended from the beam into the grouted pockets as seen in Figure 3.19 [65].

Figure 3. 19 Shear pocket used to create composite action between beam and deck [53].

3.1.2.1.7. Mechanical Connections:

The grouted reinforcing dowels placed in slotted connection is one of the options to connect precast deck panels [65]. Results from investigation related to NCHRP project 12-65 showed that development length could be shorter thanks to the confinement given by the steel box containing
the connection. The use of this connection in Live Oak Creek Bridge in Texas is shown in Figure 3.20 [65].

![Figure 3.20 Transverse connection at Live Oak Creek Bridge, Texas [53].](image)

The other option is the use of welded or bar coupler. However, due to corrosion affecting the long-term performance, this type of connection is not used anymore as bridges with welded tie connections can experience leakage between deck panels [65].

### 3.1.2.1.8. UHPC with Straight Bar:
This type of connection can also be used in longitudinal and transverse joints [67]. Many experimental tests have been conducted investigating the bond behavior reinforcing steel encased in UHPC. These investigations have concluded that UHPC can meet the development requirement generally in shorter lengths when compared with normal strength concrete [65]. Therefore, width of closure joints can be reduced in this case. Additionally, durability and long-term performance makes UHPC a supreme alternative for closure joints [68]. An example of closure joint using UHPC is shown in Figure 3.21

![Figure 3.21 Closure joints detail using UHPC [68].](image)

### 3.1.2.1.9. Conventional Concrete with Hooped or Straight Bars:
This type of connection whether with straight or hooped bars can be used for longitudinal and transverse joints. However, it is mostly used in the longitudinal direction as it requires a wide
closure pour. As it has a wider width, the shear studs and reinforcement are easily placed, and the top of girder can be used as base form for the joint. Figure 3.22 shows an example [67].

![Figure 3.22 Schematic of conventional concrete longitudinal joint over girder [67].](image)

Some other definitions for superstructure joints are included in the following. Linear joints can be divided into two types, non-grouted male-female (Figure 3.23) and grouted female-to-female joint (Figure 3.24) [53]. For non-grouted joints, in order to connect the panel and keep them together, a longitudinal post-tensioning bar is used. Before post-tensioning is applied, sealant or epoxy is applied at the interface. For the case of grouted female joints, non-shrink grout is typically used as filler. The performance of this type of connection is considered acceptable if shrinkage or service loads do not produce cracks and leakage does not occur through the joint [69]. Moreover, to resist shear and bending moment and to distribute traffic live load, the longitudinal reinforcement (Figure 3.25) in panels can be doweled or spliced within the joints [53].

![Figure 3.23 Non-grouted panel to panel (male-to-female) joint [63], [65]](image)

![Figure 3.24 Various types of female-to-female joint [69].](image)
Blockouts are pockets left in the precast panels, and they are used to connect the precast panel to concrete girders. Shear studs and/or reinforcement embedded into the pockets transfer shear between two connected elements (Figure 3.26). Composite action between deck and supporting girders can be achieved by the use of shear pockets and shear studs (Figure 3.27) preventing any vertical or horizontal movement [67]. This type of connection is easily accessible, has little deformation and can experience high shear and bending moment. Also, linear closure joints with headed steel studs can establish the connection of precast deck panels to girders and piers [69].

It is also important to mention the use of a leveling device (Figure 3.28) when there is an irregularity due to inconsistency in the panels or supporting members. Leveling is done by
colocating a threaded socket in each panel corner. A bolt is then threaded and wrench to adjust the elevation [69].

![Figure 3. 28 Leveling bolt [70].](image)

It is also important to mention that proper material selection is critical for these connections for the long-term performance of the system. For example, high early strength concrete can develop shrinkage and excessive cracking can occur which will result in gradual deterioration [16]. Also, strength is gained at different rates in different materials. This has to be considered when the connection design anticipates load carrying during material curing time. For example, UHPC requires several days to finally obtain the ultimate strength anticipated for the connection [16]. Fast-setting concrete, high and normal-strength concrete, Ultra-high Performance concrete and Self-Consolidating concrete (SCC) are mixes normally used to fill closure joints [59].

3.1.2.2. Expansion Joints and Link Slabs

Another important component to mention for the superstructure is the expansion joint. Expansion joints are considered one of the most problematic components of simple span bridges. They are known for providing a gap for the deck system and bridge girder to expand, contract, and rotate. These joints can cause durability problems due to the gap as it allows the entrance of corrosive materials and resulting in faster deterioration of the underlying structure. For this problem, one solution is the application of link slabs. They can create a continuous bridge deck system by replacing the expansion joints over the piers and maintaining a simply-supported conditions under the deck. This will effectively eliminate the ingress of corrosion but will be subjected to axial forces and high moments by the service and thermal loading of the supporting girders. Therefore, link slabs must be designed so they can withstand the tensile loads and maintain crack resistance properties to avoid penetration of corrosive materials [71]. Moreover, UHPC joints cast over the piers can be designed to have adequate structural integrity to bear severe earthquake loading [57].

3.1.2.3. Connection between deck/superstructure and substructure

Superstructure can simply sit on the pier or abutment using rollers, rockers, neoprene pads and similar for non-integral pier or abutment type. On the other hand, connections can be established
between superstructure and substructure to accommodate integrity (semi or full). Some of such connections are presented in the following with more covered later in the substructure connection sections.

3.1.2.3.1. Simple for Dead Load Continuous for Live Load (SDCL)

SDCL joint was introduced earlier in this report in relation with superstructure connection. Here, SDCL joint is described in relevance to superstructure to substructure connection. This system is suitable for short and medium span bridges [58]. In SDCL system, girders span from abutment to pier, or from pier to pier. For the superstructure consisting of steel girder and cast-in-place deck, spans are simply-supported when deck is cast. After the deck is cast and cured, the deck reinforcing steel provides continuity for live load and superimposed dead loads. For the case of ABC bridges where modular girder systems consist of steel girder pre-topped with deck slab, the slab dead load is transferred to the modular system as simply supported. After the continuity joint (SDCL) is established between two adjacent spans, the remaining future superimposed dead load and live load are carried by continuous spans. Compressive forces are transferred between the bottom flange through devices such as steel bearing blocks, shear studs, ties and concrete providing continuity for carrying negative moment at the pier location. An example of SDCL joint can be seen in Figure 3.29 [58].

![Figure 3.29 Simple for Dead and Continuous for Live connection detail [58].](image)

This system is appropriate for ABC technologies as individual spans can be built off-site and can be joined over the piers after being transported to the site [58]. This system can have a higher service life as there is no expansion joint or bolts in the connection. The construction process follows the simply supported spans located over the piers, then connected through concrete diaphragm and finally deck becomes continuous for live loads [58].

This system has been proven to be economical for non-seismic application (Figure 3.30). However, new research from Florida International University proposes a connection (Figure 3.31) that performs adequately under seismic forces as well. Experimental work was performed on truncated system in the lab as well as complete two-span bridge specimen on shake tables. After the experimental phase culminated, connection behaved as designed and sufficient ductility was noticed, therefore, connection was proven to perform effectively under high levels of displacements [72].
Integral and semi-integral abutment

Construction of abutments integrally with the superstructure has two significant advantages when comparing to the conventional free-standing abutment construction. Integral and semi-integral abutments have no deck joints and transfer embankment soil force to the superstructure [73]. In the fully integral abutment, the abutment connection to the superstructure is a full moment connection. However, in semi-integral abutment which a portion of the abutment is constructed with the superstructure, a system comparable to pin connection is used to allow the rotation of superstructure in respect to the substructure [73]. Figure 3.32 shows an example of Semi-integral abutment used by the New York State DOT. Moreover, figure 3.33 is an example of a precast integral abutment from Utah DOT. It shows interaction between a variety of elements in the colure pour. Details shows a separate backwall element that can possibly be made integral with the stem if beam depths are not excessive [16]
Recently, a research project was completed as a part of ABC-UTC program that investigated the constructability of abutment details and evaluated the strength and durability of abutment connections [75]. This project has produced a guideline to facilitate the use of integral abutments in the ABC projects. Design details of two integral abutments was provided. Figure 3.34 shows UHPC connection of the specimens tested in this study, and Figure 3.35 shows schematic of
UHPC-joint connection of the integral abutment systems proposed for ABC projects. According to Hosteng and Shafei (2019), the integral abutment connection with the use of UHPC was designed to be used with slide-in-construction. UHPC was chosen due to its high strength, good flowability, and impermeability. For this type of connection, the design would include a mechanical coupler, specifically Dayton Superior D310 Taper-Lock Standard Couplers [76]. The second type of connection can be seen in Figure 3.36 which shows the Grouted reinforcing bar coupler (GRBC) connection tested in the study and Figure 3.37 is a schematic GRBC proposed in the Guideline [76]. The design of this connection includes typical cast-in-place integral abutment and insertion of grouted reinforcing bar couplers. For this type of connection, a slide-in construction is not possible. However, any other alternative as crane or SPMT’s is feasible [76].

![Figure 3.34 Integral Connection: UHPC Connection](image1)

**Figure 3.34 Integral Connection: UHPC Connection [75].**

![Figure 3.35 Plan View of UHPC-Joint specimen](image2)

**Figure 3.35 Plan View of UHPC-Joint specimen [76].**
3.1.2.4.  Precast Concrete Bridge Barriers Connections:

Bridge barrier is an important safety component as its purpose is to shield, redirect and contain vehicles in case of a bridge accident. Iowa State University performed a research to present two connection alternatives between the precast barriers and the deck as part of research performed at ABC-UTC [77]. The literature review they completed showed the following types of connections:
There are three commonly used concrete bridge barrier shapes [77]. Profiles shapes can be seen in Figure 3.38

![Concrete Bridge Barrier Shapes](image)

**Figure 3.38 Commonly used concrete bridge barrier profile shapes [77].**

3.1.2.4.1. **Florida DOT Precast Concrete Bridge Barriers Connections:**

Florida has two types of methods for anchoring barriers to deck. One is the through-deck bolts which is applied in the Type K temporary concrete barrier system. The shape is similar to a F-shape profile and has sloped faces on both sides. Figure 3.39 shows a detail of the Florida DOT configuration [77].

The other technique used is the adhesive-bonded anchor (Figure 3.40). This method consists of drilling a hole into the deck and inserting a threaded bolt. Adhesive is used to secure the bolt [77].

![Through-deck Bolting Detail](image)

**Figure 3.39 Through-deck bolting detail developed by Florida DOT [77].**
3.1.2.4.2. **Ryerson University Precast Concrete Bridge Barriers Connection:**

Using post-tensioned rods inserted through the wall and deck slab is another way for connecting barriers utilizing the previous mentioned through-deck method. In the test conducted by Ryerson University the post-tension rods were anchored by the end plates, nuts and washers. Corrosion and access to exposed hardware is a challenge for this connection. Figure 3.41 shows a detail of the Ryerson University system [77].

![Ryerson barrier-to-deck slab connection details](image)

*Figure 3. 41 Ryerson barrier-to-deck slab connection details [77].*

3.1.2.4.3. **Clampcrete Precast Concrete Bridge Barriers Connection:**

Connection of this type of precast barrier is similar to adhesive-anchored connections. It consists of the barrier connected to the deck by polyester resin anchors that are drilled in. The connection consists of three deformed reinforcement dowels at a minimum. This system can be used for temporary and permanent barriers and it is shown in Figure 3.42 [77].
3.1.2.4.4. Texas Transportation Institute Precast Concrete Bridge Barriers Connections:

Texas transportation performed a study to design a portable concrete traffic barrier. The connection used two threaded rods across the joints and has a profile similar to an F-shape. The connection is called an X-bolt connection and is used for temporary concrete barriers. Figure 3.43 shows a drawing of the X-bolt connection [77].

3.1.2.4.5. Iowa State University ABC Railing Connection

In their research, Iowa State University proposed two new railing systems for Accelerated Bridge Construction. Additionally, a new connection was also introduced between two adjacent prefabricated barriers. All connection details were designed considering factors such as ease of replacement, minimal damage to deck, durability, constructability and cost effectiveness. Structural performance, force distribution and load carrying capacity were examined under different loading options [77].

3.1.2.4.5.1 Barrier-to-deck connection using inclined reinforcing bars:

This system consists of connecting the barrier to the bridge deck with the use of inclined reinforcing steel. A special threaded bar sleeve hardware is used to anchor the bars into the deck. However, this custom made hardware may render the joint less cost effective. The barrier system
is designed to fail at the barrier-to-deck connection interface which will guarantee an easier repair. Figure 3.44 is a schematic illustrating details of this connection [77].

Figure 3.44 Inclined bar connection between precast barrier and deck [77].

3.1.2.4.5.2 Barrier-to-deck connection using a U-shaped reinforcing bars:

This system consists of connection of barrier to bridge deck using a stainless-steel U-shape reinforcing bar. The U-shaped bar is inserted into the precast barrier through the bridge deck under the bridge overhang and then it is grouted. This type of connection was designed to ensure durability and minimize cost. Stainless-steel U-shape is considered to make the connection more durable. Compared to the inclined bar connection, this concept is more cost effective. However, the connection with the U-shape bars is considered more labor intensive, and its potential repair may require replacing a portion of the deck. Figure 3.45 is a schematic illustrating details of this connection [77].

Figure 3.45 U-bar connection between precast barrier and deck [77].

3.1.2.4.5.3 Barrier to Barrier connection

This type of connection utilized headed reinforcement in transverse and longitudinal directions, and it was designed to produce continuity such that the load will be distributed between barriers. It included four double headed ties between barriers and transverse reinforcement utilized to guarantee the confinement in the perpendicular direction. This type of connection did not have any
exposed reinforcement to assure that its durability. Figure 3.46 shows a drawing of this connection detail [77].

![Figure 3.46 Plan view of the barrier-to-barrier connection [77].](image)

3.1.3. Substructure element connections

Within a substructure, joints are used to connect columns, piers, or walls to a cap beam as well as to the footing [53]. While it is easy to access the connections to the pier cap beam for inspection, the connections to the footing can be covered. These connections can experience high shear and bending moment, especially from lateral loading due to the earthquake. Additionally, in the longitudinal direction, it may undergo considerable lateral loading due to high deformation from thermal expansion of the deck slab [53].

3.1.3.1. Cap beam connection to column

Precast cap beam may connect to the cast-in-place column, a precast concrete column, steel pile, or precast concrete pile. There are different methods to join the column to cap beam. The connection of column to cap beam can form in the cap beam or along the column. In another method, the cap beam can be welded to the column. The summary of different methods to connect cap beam and columns are listed in Table 3.2. Moreover, according to NCHRP Project 20-68A three types of ABC columns were identified to perform well under seismic events, natural or man-made events, blasts, loading and other larger forces. First type included column embedded into pockets/sockets cast in an adjacent member such as, footing, cap beam or pile shaft [54]. The second type included grouted couplers connected to footing dowels, embedded into a precast column and subsequently grouted. The third connection type is grouted (corrugated) ducts forming oversized holes in the cap or footing that receives longitudinal bars protruded from a precast column and then filled with grout [54].

3.1.3.1.1. Connection inside the Pier Cap- Grouted Sleeve:

One of the methods for connecting precast pier columns to the prefabricated pier caps are with the use of grouted sleeve (Figure 3.47). In this method, slots or sleeves in the cap receives the extended reinforcing bars from the column.
Table 3. 2 Different connections of cap beam and column

<table>
<thead>
<tr>
<th>Type</th>
<th>Connection method</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formed in cap beam</td>
<td>Grouted sleeve</td>
<td>-Connect precast cap beam to cast-in-place or precast concrete column</td>
</tr>
<tr>
<td></td>
<td>Grouted pocket</td>
<td>-Connect precast cap beam and precast or cast-in-place concrete column</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Connect precast cap beam and steel pile or column</td>
</tr>
<tr>
<td>Formed along the Columns</td>
<td>UHPC column segment</td>
<td>-Connect precast cap beam and precast concrete column</td>
</tr>
<tr>
<td></td>
<td>Grouted sleeve</td>
<td>-Connect precast cap beam and precast concrete column</td>
</tr>
<tr>
<td></td>
<td>Mechanical couplers</td>
<td>-Connect precast column to cap beam</td>
</tr>
<tr>
<td>Other types</td>
<td>Welding</td>
<td>-Connect precast cap beam and steel pile or column</td>
</tr>
<tr>
<td>Cap beam segments</td>
<td>Closure pour</td>
<td>-Connect precast cap beam segments</td>
</tr>
<tr>
<td></td>
<td>Mechanical couplers</td>
<td>-Connect precast cap beam segments to create moment connection</td>
</tr>
</tbody>
</table>

Figure 3. 47 Column to cap beam connection using grouted sleeve method [7].
Moreover, the study developed by the University of Nevada also evaluated the seismic performance of a precast bent with a pocket connection and advanced materials such as ECC (Engineered cementitious composites) and UHPC (Ultra-high-performance concrete). The two columns were connected to a precast cap beam and a precast footing. Shake table results showed the effectiveness of this detail in limiting damage and a good overall performance of the pocket connection [78]. Figure 3.48 shows the construction sequences of the bent model.

![Figure 3.48](image1.jpg)

**Figure 3.48** (a) precast footing with two circular pockets; (b) cap beam pocket construction; (c) cap beam pocket-view from underneath; (d) inserting the columns into the footing pockets; (e) placing cap beam on the columns [78].

### 3.1.3.1.2. Connection inside the Pier Cap-Grouted Pocket:

In another method that can be used to connect precast cap beam and the cast-in-place concrete columns or steel piles and columns, a large oversized pocket in the pier cap is left to receive the column or pile. The pocket is intended to receive the longitudinal bars extended out of column (Figure 3.49) or the entire column section [7].

In this method, after installation of column or pile, the column or pile is inserted into the cap beam pocket and leveled on its position. Then, the grout is poured from the holes on the top of the cap beam. When the pocket is used to insert the entire column section, a thin layer of grout may be used between the cap beam and column to provide a uniform bearing [79]. This method was used
by MnDOT to connect cast-in-place pile and precast cap beam as shown in Figure 3.49. This connection also can be used to connect the pier column to pier cap integrally constructed with superstructure, integral abutments, or semi-integral abutments [53]. This technique can also be used to connect driven steel piles and precast cap beam.

![Figure 3.49 Precast cap beam and cast-in-place column using grouted pocket [53].](image)

### 3.1.3.1.3. Connection along the Columns- UHPC Column Segments:

Another type of connection between the precast column and precast cap beam where connection is formed along the columns has been recently developed under an ABC-UTC project using UHPC at Florida International University. The details of this connection for the seismic and non-seismic region are depicted in Figure 3.50 [80]. In the proposed connection for the seismic region, two layers of UHPC is used. The second layer near the cap beam is used because of the potential for significant stresses in this area. In the non-seismic connection, the two members are joined simply with a layer of UHPC.

![Figure 3.50 a) Seismic and b) non-seismic detail of UHPC connection of precast column and precast cap beam [80].](image)
3.1.3.1.4. **Connection between column segments:**

In some cases, where the height of the columns is long, column segments are prefabricated and connected to each other in the field to make the handling of the prefabricated columns easier. To establish continuity and the required strength, the segments are post-tensioned and grouted in the field (Figure 3.51) [53]. Grouted sleeves, mechanical couplers, and other types of connection can be used between column segments.

![Diagram of column to column connection](image)

*Figure 3. 51 Column to column connection [53].*

3.1.3.1.5. **Connection along the Column- Grouted Sleeve:**

Sleeves can be also left at the top end of precast or cast-in-place columns to receive reinforcing bars projected downward from the cap beam. The connection zone and inside the coupler is then grouted to establish the connection. Figure 3.52 shows an example of grouted splice sleeve.

![Diagram of grouted splice sleeve](image)

*Figure 3. 52 Grouted Splice Sleeve [52].*

3.1.3.1.6. **Welding:**

Connections between column or pile and cap beam can also be established by welding. In this method, a steel plate embedded at the bottom of beam and the top of pile or column are welded to each other [53]. Figure 3.53 shows the welding procedure for a pile to cap connection.
3.1.3.1.7. **Connection of Cap Beam Segments:**

When the width of the bridge deck is large, it is possible to have a cap with large dimension and massive weight that can make problem in their shipping. In this case, the cap beam segments can be constructed with a smaller dimension. Then, the cap beam segments can be connected in the field using cast-in-place closure pour method (Figure 3.54) [53].

![Figure 3. 54 Connection Details of Cap Beam Segments [53].](image-url)
3.1.3.18. CFST Column-to-Precast Cap Beam Connections

Concrete-filled steel tubes (CFSTs) can provide stiffness and strength and allow fast construction. They can be used as piles, piers, and drilled shaft foundations. The use of self-consolidating concrete (SCC) can expedite the concrete placement as it does not require vibration. Stephens et al. (2016) proposed three connections types that minimizes damage in the cap beam and provides excellent ductility under reversed-cyclic loading. Only one of the three proposed connection is further discussed as it was considered the only connection that could offer better benefit for the accelerated construction [81].

3.1.3.18.1 Embedded CFST annular ring (ER) connection

This type of connection develops full ductility and flexural capacity of the concrete filled steel tubes. Annular ring is the transfer mechanism which is welded to the tube ends. It is extended inside and outside providing shear and normal transfer from the tube to the cap beam [81]. Figure 3.55 shows an ER connection.

![Figure 3.55 Proposed ER Connection [81]](image)

3.1.3.2. Footing connection to column:

Another connection in the bridge substructure is the connection between column and footing. A summary of the column to footing connection are listed in Table 3.3. The precast concrete column either may need to connect to the cast-in-place concrete footing or precast concrete footing [53]. To connect the precast concrete column to the cast-in-place footing, two methods can be used.
### Table 3. Different connections of column and footing

<table>
<thead>
<tr>
<th>Type</th>
<th>Connection method</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formed along the column</td>
<td>Grouted sleeve</td>
<td>- Connect precast concrete column and cast-in-place footing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Connect precast column to precast footing</td>
</tr>
<tr>
<td></td>
<td>Mechanical couplers</td>
<td>- Connect cast-in-place footing and precast column</td>
</tr>
<tr>
<td>Formed in footing</td>
<td>Grouted Pocket</td>
<td>- Connect precast column and precast or cast-in-place footing</td>
</tr>
<tr>
<td>Column segments connection</td>
<td>Closure pour</td>
<td>- Connect precast column segments</td>
</tr>
<tr>
<td></td>
<td>Grouted sleeves mechanical couplers</td>
<td></td>
</tr>
</tbody>
</table>

#### 3.1.3.2.1. Connection along the Column, Grouted Sleeve:

In one, the footing is cast with waiting reinforcing bars (dowels) projecting from the footing. Sleeves are incorporated at the lower end of the precast column to receive the bars projecting from the footing. The column is then braced in its position on the top of the footing using temporary supports. Then the grout is poured in the sleeves around the projecting reinforcing bars. This connection is formed in the column and called grouted sleeve connection method (Figure 3.56). Utah DOT used this connection to join the precast column to precast footing.

![Grouted sleeve connection between footing and column](image)

*Figure 3.56 Grouted sleeve connection between footing and column [53].*
3.1.3.2.2. Connection along the Column, Mechanical Couplers:

In another method, mechanical couplers can be used to connect the cast-in-place footing to the precast column. The mechanical coupler details used by Florida DOT is shown in Figure 3.57. When the footing is also prefabricated, the grouted sleeve or splice connection method can be used.

An critical part of designing bridges with precast elements using mechanical connections is to assure adequate resistance to loads and development of at least 125% of yield strength of the connected bar [16]. Connection of prefabricated columns to cap beams or footing can be established by the use of mechanical bar splices [82].

An extensive parametric study was developed by Tazarv et al. (2015) to investigate seismic behavior of connections using mechanical couplers. In general, tension-compression couplers can be categorized as (1) shear screw couplers, (2) headed bar couplers, (3) grouted sleeve couplers, (4) threaded couplers, and (5) swaged couplers [82]. These five types of common mechanical bar splices can be seen in Figure 3.58.

Figure 3.57 Cast-in-place footing to precast column connection using mechanical couplers [53].
3.1.3.2.3. **Connection in the Footing, Grouted Pockets:**

For this type of connection, the longitudinal reinforcement bars projecting from the precast column are embedded into the precast footing pocket and later grout is poured into the remaining space [83]. For this type of connection, a non-shrink or high strength grout is preferred [84]. It can be constructed with full or partial penetration (Figure 3.59) and connection should not experience any significant sliding for any of the options. For the case of the full penetration, axial strength depends on the shear resistance acting in the embedded portion and for partial penetration the side shear and tipping provide the axial load resistance [84].

![Figure 3. 58 Mechanical Reinforcing Bar Couplers [82].](image1)

![Figure 3. 59 (a) Fully penetrated pocket connection; (b) Partial penetrated pocket connection [84].](image2)

Kavianipour et al., (2013) tested precast columns inserted into precast footing with pocket connections and filled with High-strength grout (Figure 3.60). As column and footing were prefabricated, the method saved onsite construction. Embedment length of the column in the footing was 1.5 times the column diameter which according to the study was sufficient to develop full fixity at the base of the columns [78].

![Figure 3. 60 Pouring high strength grout in the gap between precast column and footing [85](image3)
A study carried out by the University of Nevada evaluated the seismic performance of a precast column to precast footing with a square pocket connection. To eliminate permanent drifts, the column was post-tensioned with unbonded CFRP (Carbon fiber reinforced polymer) and in the plastic hinge zone UHPC (Ultra-high-performance Concrete) was used to mitigate the seismic damage. Shake table test and follow-up analysis showed that plastic hinge was formed successfully in the column with no damage to the pocket connection [78]. Figure 3.61 shows the construction sequences of the column model.

![Figure 3.61](image)

*Figure 3.61 (a) precast footing with central pocket; (b) precast column with UHPC in the plastic hinge; (c) inserting column into the pocket; (d) filling the gap by UHPC [78].*

In another study, a synthesis about the behavior and performance of the pocket connection in the seismic region was conducted to define a standardized pocket connection detail. The results showed that full plastic moment occurs in the column. Also, the full precast column or partially prefabricated column (Figure 3.62) can be used to be inserted into the pocket [86].
3.1.3.3. **Abutment and wall systems connections**

Abutment systems including cantilever abutment, spill-through abutment, precast wall, integral and semi-integral abutments are other components of the bridge that can be constructed off-site and connected to each other in the field. The connections that can be used to join the abutment components together are summarized in Table 3.4.

3.1.3.3.1. **Closure pour:**

Cast-in-place closure pour is the connection method that can be used to connect the integral abutments elements and join abutment to superstructure. Figure 3.63 depicts this connection details [87].

**Table 3.4 Abutment systems connections**

<table>
<thead>
<tr>
<th>Connection type</th>
<th>Comment</th>
</tr>
</thead>
</table>
| Closure pour, grouted pockets or sleeves | -Connect abutment elements  
-Connect abutment to superstructure |
| Grouted Sleeve/Splice couplers | -Connect all types of abutment elements |
| **Grouted Pocket Connection** | -Connect abutment stem or cap directly to steel piles or precast concrete piles |
| Welded Plate Connection | Connect steel piles to abutment |
| Steel bar dowels connection | -Connect pile cap and integral abutment |
| Small closure pour | -Connect abutment segments |
| Simple grouted shear key | -Connect abutment cap segments |

![Figure 3.63 Closure pour connection in abutment [87].](image)

3.1.3.3.2. **Grouted Sleeve/Splice couplers:**

Grouted splice couplers can be used to connect precast elements like abutment stem and footing [53]. This connection type has been used by New Hampshire DOT to connect the abutment elements and is shown in Figure 3.64. In the cantilever abutment system, the connection of backwall to abutment stem is also needed (Figure 3.65, 3.66). Backwall is used to support the soil...
behind the beam ends. To connect backwall to abutment stem, the grouted splice couplers connection, same as abutment stem to footing connection, can be used. Also, other types of connections adapting to the existing conditions can be used. Another connection in the cantilever system is precast breastwall (checkwall) to abutment stem. Breastwall in this system is used as a decorative element at the corner of the abutment to connect the end of the beams. To attach precast breastwall to abutment stem, grouted splice couplers or other kind of connections based on the conditions can be used. In another type of abutment system, spill-through abutment, the same type of connections as that used for cantilever abutment can be used [53]. Other connecting methods of the precast wall to the precast footing include grouted shear key and using mechanical connectors. Recently, a study conducted by Iowa State University evaluated durability, strength, and application of grouted couplers in the integral abutments. The grouted reinforcing bar and pile couplers were evaluated, and this connection detail was established [88].

Figure 3. 64 Precast abutment stem to precast footing connection [53], [88]

Figure 3. 65 Grouted couplers connection in prefabricated abutment [88].
3.1.3.3. Grouted Pocket Connection:
In some cases, the abutment stem or cap connect directly to steel piles or precast concrete piles. One way to establish this connection involves a large pocket prefabricated in the precast abutment stem, and the pile is embedded into the pocket and grouted (Figure 3.67, 3.68). This develops an integral abutment detail that transfers bending and shear.

Figure 3. 66 Abutment connection [53].

Figure 3. 67 Precast integral abutment connection to steel pile [53].

Figure 3. 68 Precast integral abutment connection to steel pile [53].
3.1.3.3.4. **Welded Plate Connection:**

To connect the steel piles directly to abutment, steel plates can be anchored in the abutment, and welded to the piles. Figure 3.69 shows a pile connection plate detail. Moreover, welded plate connection can be used for flying wingwalls. Normally, plates are anchored in the elements and then during installations plates are welded together [53].

![Figure 3. 69 Pile Connection Plate Detail [53].](image)

3.1.3.3.5. **Steel bar dowels connection:**

To make the abutment integral with the superstructure, steel bar dowels can be used between the abutment stem and abutment cap that is made integral with the superstructure. Figure 3.70 shows a dowel connection.

![Figure 3. 70 Steel bar dowels connection in abutment [87].](image)

3.1.3.3.6. **Small closure pours:**

In some cases, because of the abutment dimensions and shipping limitations, the abutment cap may be prefabricated in segments [53]. These segments can be attached to each other in the field. To connect them, the match cast and post-tensioning method which is used by Maine DOT or small closure pour technique can be used (Figure 3.71).
3.1.3.4. **Precast Arch Section connections**

Connection between sections of bridge arches are normally designed as continuous connections. For large spans, sometimes a mid-span splice is made between two half-arch pieces at the crown. A temporary connection is established by first bolting the pieces together and a closure pour is made between the pieces to complete the joint. The arch soffit acts as a form for the pour [53]. Figure 3.72 shows an example of a precast arch connection.

3.1.3.4.1. **Precast Arch Segment Connections for culverts and buried bridges:**

Figure 3.73 shows a connection of adjacent precast arch units. This connection helps the spandrel walls to resist the lateral soil forces. On the exterior unit, a structural connection is used. However, the other joints are butted and sealed as mostly precast arch segments do not need a structural connection. They can be butted together and joints are established parallel to the roadway with a waterproofing strip placed over the gap in order to prevent any type of soil to fall through the joints and to guarantee corrosion protection [53].
3.1.3.4.2. **Precast Spandrel Wall to Precast Arch unit**

This type of connection connects a precast arch unit to a precast spandrel wall. One type of connection consists of a spread footing bolted with stainless steel bolts. Another type of connection uses a cast-in place concrete bond beam that connects the spandrel wall to the precast arch. This connection also is used to resist vehicle impacts by resisting overturning [53]. Figure 3.74 shows an example of a bridge with spandrel walls in the corners.

![Example of spandrel wall to arch connection](image)

*Figure 3. 74 Example of spandrel wall to arch connection [53].*
3.1.3.4.3. Precast arch to precast wingwall connection

Connection between precast arch and spandrel wall with a wingwall stem can be established using galvanized steel bolts and plates. The connection is bolted and used during backfilling to guarantee alignment. Overturning forces are resisted by wall anchors cast into stem elements [53]. Figure 3.75 shows an example of a precast arch to a precast wingwall connection.

![Figure 3.75 Precast arch to precast wingwall connection [53].](image)

3.1.3.4.4. Precast Arch Unit to Precast Footing Connection

Arch elements are designed to have pinned connection at the base. To resist lateral shear, the arch is installed into a shallow pocket. To adjust grade and to allow for grouting under the stem, the arch units are set on shims. Figure 3.76 is an example of precast footing to arch connection [53]. Moreover, footing joint is also used to connect wingwall footing to arch footing. Figure 3.77 shows an example of precast concrete footings connections.

![Figure 3.76 Precast footing to arch connection [53].](image)
3.1.4. Foundation connections

Proper connections are required between different precast foundation elements to successfully transfer the load to subgrade soil and resist failure. Connections are required to ensure sufficient joints between precast footing to steel and concrete pile, precast footing to precast footing. Details of different connections in foundation systems are discussed in the following sections.

3.1.4.1. Footing and Pile Systems:

Prefabricated piles are most commonly used for bridges by state DOTs whereas the concept of prefabricated footings is relatively new. The connection between the footing and pile system is important to transfer the load successfully.

3.1.4.1.1. Precast Footing to Subgrade Connections:

The primary problem with the use of precast concrete footing is to properly seat the footing on the subgrade. Settlement or rocking of the foundation may result from inadequate seating on the subgrade. It can be eliminated by placing a flowable concrete or grout under the footing or by using leveling bolts on the corners to lift the footing above the subgrade. In such cases, low grade concrete or flowable fill can be used as this is not a structural element. A sub-footing can also be used to create a level area for footings construction in bedrock [53]. Figure 3.78 presents the connections between precast footing and subgrade materials.

Figure 3. 77 Precast footing to precast footing connection [53].

Figure 3. 78 Details of Precast footing to subgrade Connection [53].
3.1.4.1.2. **Precast Footing to Precast Footing Connections:**

The connection between adjacent footing elements may or may not need to be a structural connection, depending on the design. A simple grouted shear key can be used if there is no structural requirement for the connection. However, a small closure pour connection can be used if a moment connection is required (Figure 3.79). For this purpose, reinforcing bars are extended from footing elements and grout is poured in the formed area created by the two footing elements and the subgrade [53]. Figure 3.80 presents a photograph of installation of a precast concrete footing with grouted shear connection on concrete sub-footing.

![Diagram of precast footing to precast footing connection](image)

*Figure 3. 79 Precast concrete footing to precast concrete footing connection [53].*

![Photograph of installation](image)

*Figure 3. 80 Installation of a precast concrete footing with grouted shear connection on concrete sub-footing [53].*

3.1.4.1.3. **Precast Footing to Steel Pile Connection:**

The connection details for precast concrete pier caps to steel pile mentioned can be used for precast footing to steel pile connections. However, uplift on the piles or moment capacity requirement
may create problems for such connections. The pile end reinforcing steel can be welded and embedded in a closure pour to provide enough uplift capacity for this connection (Figure 3.81). Also, embedment of the pile top by at least 12 inches into the footing will help to achieve adequate moment capacity for this connection [53].

![Figure 3.81 Connection between precast concrete footing and steel pile with uplift [53].](image1)

### 3.1.4.1.4. Precast Footing/Caps to Precast Concrete Piles:

Similar to steel pile connections, several states have developed connection details for precast concrete piles connected to precast concrete pile caps/footing. There are also details developed for integral pile to pile cap connection. For example, Florida DOT has developed a connection for a hollow precast concrete pile to a precast footing to develop full moment capacity of the pile (Figure 3.82). The connection consists of a large blockout in the footing where a reinforcing steel cage is installed between the pile top and the blockout [53].

![Figure 3.82 Connection details between concrete square pile and pile cap [53].](image2)
Another option for the design of the pile cap connection is to project pile reinforcing into a void in the cap that will be filled with closure pour concrete. Figure 3.83 shows the detail used in Iowa. Moreover, Figure 3.84 shows details that have been used in Minnesota and South Carolina, respectively, where the pile is embedded into a pile cap pocket. Depth of embedment follows the agencies’ requirements for cast-in-place construction [16].

![Figure 3.83 Pile Cap Connection using Extended Reinforcing Steel [16].](image1)

![Figure 3.84 Pile Cap Connection using Embedded Pile [16].](image2)

### 3.1.4.1.5. Precast Footing to Cast-in-place Pile or Drilled Shaft Connections:

Till now, no connections between precast footing to cast-in-place piles or drilled shafts connected to precast concrete footings have been developed by any state DOTs. However, the precast footing to concrete pile connection details could be adapted for use with cast-in-place concrete piles or drilled shafts.

### 3.1.4.2. Precast Columns to Drilled Shafts:

The concept with this connection as shown in Figure 3.85 is to have an oversized drilled shaft and after concrete in the drilled shaft is cast to a specific elevation, the column reinforcing is inserted in the shaft space near the shaft reinforcing, and finally connection is completed using a cast-in-place pour. Similar detail can also be adopted for precast concrete column [53].
3.1.4.3. Precast Pile to Precast Pile Connection:

Splicing in precast piles is often required when there are length limits for shipping and transportation; limited headroom, and/or when required capacity is not achieved with existing lengths. Also, to accommodate variations in subsurface conditions, pile lengths for some pile types can be easily adjusted and spliced in the field. According to Bruce and Hebert (1974) the piles splices can be categorized as; Welded splices, Bolted Splices, Mechanical Locking Splices, Connector Ring Splices, Wedge Splices, Sleeve Splices, Dowel Splices, and Post-Tensioned Splices (Figure 3.86) [89]. Many state DOTs have developed standard details for connecting precast driven piles that need to be spliced. Precast concrete pile industry has also developed their standard pile splicing details [90]. Figure 3.87 shows a detail for splicing hollow square prestressed concrete piles use by the Florida DOT as a form of dowel splice connection. These details consist of a reinforced concrete closure pour between pile elements.

Figure 3. 85 Connection of Pier Column to Large Diameter Drilled Shaft (Source: Washington State DOT Bridge Design Manual) [53].

Figure 3. 86 Connection between concrete square piles using splice [53].
Florida Department of Transportation has also used alternative dowel material for epoxy dowel pile splices including Carbon Fiber Reinforced Plastic (CFRP) and Stainless Steel (SS) to prevent corrosion damage especially in the marine environment and splash zones. They are currently investigating the feasibility of using Glass Fiber Reinforce Plastic (GFRP) dowels for pile splices.
CHAPTER 4. CONSTRUCTION METHODS

4. Abstract
Main benefit of application of ABC relates to prefabricating the elements and systems of the bridge under controlled weather conditions and to install them onsite in less time than conventional construction. In order to take advantage of this method, the use of innovative structural placement and construction methods should be considered for all bridge projects. Using any of the construction methods, the elements or systems could be moved in minutes or hours which will implicitly lessen the traffic disruption, increase work safety, and improve constructability and contractor options to move new prefabricated bridges into position.

In this module, construction methods will be discussed in general and those applicable to short span bridges will be emphasized. The applicability of these methods of construction depends on many factors that need to be considered along with engineering judgement for proper planning of the projects.

4.1. Construction Methods
There are many different types of techniques that are used by various agencies to accelerate the bridge construction process. The popular techniques used in general for accelerated bridge construction are [91]

- Use of Self-Propelled Modular Transporters (SPMTs) normally for moving large superstructure systems,
- Use of longitudinal launching for example for when the bridge is above existing highways,
- Sliding or horizontal skidding to move a complete superstructure or super- and substructure system,
- Use of cranes for vertical lifting of prefabricated components,
- Other heavy lifting methods and equipment.

The use of innovative structural placement and construction methods is a key aspect of ABC that improves safety, quality, and reduces the construction time.

This report subscribes to a definition of short span bridges limited to span lengths of up to 70 ft and maximum prefabricated bridge module weight equal to 90,000 lb [10]. While all the above construction methods can be used in general for ABC bridges, the use of cranes for vertical lifting of prefabricated components prevails as the method of choice for short-span bridges. The sliding or horizontal launching, and longitudinal launching, and SPMT methods can also be considered depending on the site and accessibility conditions and other factors discussed later in the decision-making portion of this report. For completeness, all the above construction methods are described in this chapter with reference to specific application example for each method.

The following describes the common construction methods for ABC [53].

4.1.1. Self-Propelled Modular Transporters (SPMT)
The SPMTs is a vehicle that is used to carry, lift, and place heavy loads like bridge elements and systems [92]. They can be differentiated by the number and configuration of the wheel lines
The trailers in this type of vehicles have high capacity and high maneuverability. The typical load capacity of vehicles is approximately 50,000 pounds to 75,000 pounds per axle line. The capacity can be managed when the trailers are interconnected. SPMTs can be configured to accommodate different soil conditions [92].

SPMT can be used for a variety of bridge types. Single span and multi-span bridges have been installed using SPMT. Lifting and moving bridge systems with the use of SPMT may subject the structural members to loading that is different from structural loading on the bridge in service. Therefore, special care should be taken to deal with additional and sometimes reversal loading during SPMT operation. Temporary bracing may be required for truss and arch type superstructure [93].

The use of SPMT has also been associated with additional dynamic loading on the structural system being transported. NCHRP Project 12-98 investigated the dynamic effects a recommended dynamic impact factors for the use of SPMTs [94]. Rotation capacity of these transporters vary from a limited rotation to 360 degrees depending on the manufacturer. SPMT’s can be rotated and moved vertically, transversely, and longitudinally [92]. Superstructure can be built off the site using conventional methods and supported on temporary abutment. It can then be lifted by the SPMT, transported into its final position and lowered to seat on permanent supports/bearings (Figure 4.2) [95]. Depending on geometry of the bridge and travel path, the installation time can vary from 2 hours to 8 hours [92].

![Figure 4.1 SPMTs configuration](image)
“MemFix4”, a project developed by Tennessee DOT in 2018 included rehabilitation program to replace four bridges using ABC. The heaviest unit was six girders wide and 150 feet long. Given the limitation for closure time and the large impact to the Memphis transportation network, reducing disruption to traffic was a critical component of the project. After demolition was completed, the contractor started moving the modular units with SPMTS (Figure 4.3) from the staging area to its final position [97].
SPMTs can also be used in combination with a specially-designed steel truss frame for lifting and transporting as it was the case on the Lewis and Clark Bridge (Figure 4.4). Using this combination of systems allowed removal and replacement of deck modules during overnight operation. The process consisted of using the SPMTs with the truss frame to move the new panels on top of the bridge, then lift the old panel and position the new panel into its position before taking the old panel off the bridge. Total bridge length was 3,900 ft and it was replaced with 103 prefabricated deck panels that were 36 ft wide and 20 ft to 45 ft long. An average of 6.5 hours was used to move each panel [98].

Figure 4.4 SPMTs with gantry system [98]

4.1.2. Longitudinal launching

For places with limited accessibility for cranes and SPMT, superstructure launching have been used as a solution [92]. It is also commonly used where bridges are located over busy waterways or roadways [95]. To implement longitudinal launching, a launching pit is needed behind the abutment for constructing the bridge superstructure. Once the construction is complete, with the use of a sliding or rolling system, the superstructure is jacked out over the spans. Usually, a lightweight launching nose is used to minimize the deflection of cantilevered end of the superstructure during the process of launching. A typical procedure for completion of a longitudinal launch will take days or months depending on the size of the bridge and availability of launching pit [92].

Figure 4.5 shows the longitudinal launching of the I-15 Layton Parkway Bridge span. For this project it was required to limit the construction impacts to the traveling public. Therefore, the superstructure span with a maximum span length of 108.80 feet was constructed behind the abutments. Using large hydraulic rams, the superstructure was then longitudinally launched/slid over its final position [99].
4.1.3. **Horizontal skidding or sliding**

The horizontal skidding or sliding also known as lateral sliding is another construction method for ABC [92]. In contrast with SPMT’s, the bridge is not moved or rotated for substantial distances and sometimes is not lifted by a significant height [95]. In this method, the superstructure is constructed parallel to the bridge placement location on the temporary supports. The temporary supports are located over a railing system. After the new superstructure is completed and the existing bridge is demolished, the new superstructure is moved transversely to its new location [100] (Figure 4.6). Pulling or pushing of the superstructure into its place can be performed using railing, sliding pads or rollers [100]. This method allows the old bridge to function until shortly before the sliding [92]. Ideally, this type of technology is used for bridges located over low-volume roadways and waterways [95].

A lateral slide method was used in Illinois for the replacement of the 115 Gar Creek Bridge. Next to the existing structure, the 82 feet long and 39 feet wide bridge superstructure was built and then rolled into place during a roadway closure window of 72 hours [101]. The hydraulic jack system used can be seen in Figure 4.7.

Other projects that have used this type of construction method are the Larpenteur Ave Bridge in Minnesota and State Route 121 over I-70 in Indiana. The Larpenteur Ave Bridge by Minnesota DOT was constructed in 2014. It consisted of a total bridge length of 187.10 feet and a maximum span length of 91.20 feet. Considering the best value approach and shorter closure time, the contractor proposed the sliding approach as the construction method of choice. Figure 4.8 shows the Larpenteur Avenue Bridge being placed into its final position [97]. Moreover, the State Route 121 over I-70 was a 3-span structure with a total length of 140’-10’’ that was also constructed using the horizontal sliding technique in 2017. Figure 4.9 has two images showing the horizontal sliding taking place [97].
Figure 4. 6 Lateral bridge sliding [100].

Figure 4. 7 Hose Configuration and Hydraulic Pump Unit [101].

Figure 4. 8 Slide-in of Larpenteur Avenue Bridge [97].
4.1.4. Use of cranes and lifts

Cranes of different capacities can be used for vertical lifting and erection of prefabricated elements and systems.

4.1.4.1. The use of conventional cranes

In conventional bridge construction, the primary use for cranes is for the erection of girders. Therefore, in most bridge constructions the cranes are considered an integral part of the operation. Conventional cranes can be used for elements other than girders given the weight limits for the crane. The conventional crane can be used to install and place the prefabricated bridge elements including footings, pier columns, pier cap, girders, and deck panels [92].

Multiple cranes and crane with higher capacity can be used for installation of modular system. Figure 4.10 is an example of the use of conventional cranes for placement of modular systems. Cranes with higher capacities (e.g., 150,000 lbs) can be used for heavier projects [92].

Figure 4. 9 Slide-in of State Route 121 over I-70 in Indiana [97].

Figure 4. 10 Folded Steel Plate Girder installation [56].
Another effective use of the crane is the use of the telescoping boom and jibs on large truck cranes. The reach can be extended by extending the booms equipped with jibs enabling crossing over an obstacle such as the bridge pier (Figure 4.11) [102].

Moreover, a crawler crane can also be used to offer the advantage of moving with the load (Figure 4.12). For instance, when construction shall be operated during traffic off peak window, the crawlers can have the load suspended off the road during peak hours and move back to operation when off-peak hours begin. Crawler cranes can handle soft ground; however, they are susceptible to uneven roads. Often, truck cranes are chosen over crawlers in cases where treatment of the ground is needed [102].
4.1.4.2. **Use of conventional truck**

Conventional trucks are normally used to transport the prefabricated elements and modules from precast plant to the bridge site. For the Wrights Corner Bridge in 2016, the Folded Plate Girder System (FSPGS), a modular girder system, was fabricated offsite and then delivered by truck to the construction site. The maximum span length was 45 feet. Installation of the four elements with the use of cranes was completed in four hours [103] (Figure 4.13).

![Image](image1.png)

*Figure 4. 13 The modular decked beams delivered by truck [103].*

4.1.4.3. **Forklifts**

Another lifting equipment for placement of elements that can be utilized for short span bridges is forklift of various capacity and mechanisms. For instance, for replacement of the deck panels of the Rocks Steel Truss Bridge (122.5 feet long and 33 feet wide single-span), fiber-reinforced polymer (FRP) deck panels was prescribed. Due to limited vertical clearance, a forklift was very advantageous for lifting and installation of the panels. This was possible due light weight of the panels, and that the panels allowed immediate construction loads. Hence, the forklift was able to move onto the new panel to install the next set of panels (Figure 4.14) [104].

![Image](image2.png)

*Figure 4. 14 Installation of Fiber Reinforced Polymer decks with the use of a forklift [104].*
4.1.5. Other heavy lifting equipment and method.

There are several other equipment and techniques to lift the bridge elements and systems [92]. One approach is using a strand jack or climbing jack. Strand jack pulls up the bridge and climbing jack pushes up the bridge. In this case, the bridge is constructed at the ground level, and then lifted up using strand jack or climbing jack. The bridge is transferred to the location for lifting by SPMTs, barges, and similar.

Different methods and equipment can be combined to adapt to unique cases. As it was for the case of the new Hastings Minnesota Bridge. Adjacent to the staging area, the main span, approximately 545’ long, was constructed on land and then moved with self-propelled modular transporters into barges (Figure 4.15). It was then moved to its pre-lifting position using a skid system. The span was later lifted approximately 50 feet with the use of hydraulic strand jacks until its final position connecting it between the piers. Figure 4.16 shows the sequence of pre-lifting position and the use of strand jack lifting frames [105].

![Figure 4.15 Transportation of main span by SPMTs to the barges [105].](image1)

![Figure 4.16 Skid Jacks used to locate bridge into strand jack lifting frames (Respectively) [105].](image2)
Another technique is transverse pivoting which can rotate the bridge to its actual position (Figure 4.17). Moreover, transverse gantry crane or longitudinal gantry crane can be used to place the elements on the bridge. The longitudinal gantry frame method of installation is limited to relatively short span bridges. This is mainly because the frame size needs to be more than twice the length of the modules to be installed [92]. To overcome this limitation, a large overhead longitudinal gantry crane can be used as it was the case for construction of the US 17 Bridge over Tar River (Figure 4.18) with a maximum span length of 121.67 feet. The individual precast cap segments on the piles were erected using the launching gantry [106]. These types of gantry are mostly used for areas where conventional equipment cannot be used [92]. Moreover, Figure 4.19 shows an example of a gantry crane on temporary trestle. This type of gantry can be advantageous as the cranes can be left in place during peak hours without interrupting the traffic [92].

Figure 4.17 Vertical axis pivot [92].

Figure 4.18 Longitudinal gantry bridge placement [106].
A high capacity crane can also be used for transportation of elements in accelerated bridge construction. For the emergency repair of the I-10 Bridge over the Escambia Bay a barge-mounted high-capacity crane and conventional modular transporters on barges were used to repair the bridges. A barge-mounted conventional modular transporter was used to lift the spans from eastbound substructure. The spans were then transported to the westbound bridge (Figure 4.20). The spans were set in place with a barge mounted high capacity ring crane. Some of the spans that were misaligned due to the storms were realigned using the transporters on barge [107].

After repairs were completed in the westbound bridge, the high capacity crane on barge was also used for the eastbound bridge repairs. In this case, the pile caps, precast piles, girders and footing were similar in weight with a maximum of 80 tons each considered within an effective design and planning that assured an efficient use of the high-capacity crane on the barge (Figure 4.21) [108]. The maximum span length in this case was 250 ft.
Figure 4. 21 Transportation of girders in the eastbound bridge [108].
CHAPTER 5. INSPECTION AND PERFORMANCE

5.1. Abstract
Prefabricated elements and systems are expected to have better quality and performance due to their construction in controlled environment and under stricter quality control than cast-in-place elements. As such, ABC bridges are expected to have a better service life and lower maintenance. Despite this advantage, ABC bridges will need to be inspected the same manner as the conventional bridges. To this date, no advantage is given to ABC bridges over the conventional bridges in regards with inspection frequency and extent. On the other hand, most performance issues reported in relation with ABC bridges has focused on the joints and connections that are established in situ. Cast-in-place joints may introduce a potential for weak link within Accelerated Bridge Construction (ABC) structures. The quality of the joints, expected to become serviceable quickly, depends on the concrete mix design, reinforcement and enclosure details, and is influenced by placement and curing procedure [11]. Despite the efforts to prevent weaknesses in these critical elements, potential exists that defects or anomalies are left in the joints during construction or develop later during the life of the structure [11]. Hence, more attention and perhaps special inspection should be applied to joints and connections when inspecting ABC bridges.

As it is for conventional bridges, the inspection of ABC bridges will range from overall visual routine inspection to detailed special inspection for locations with damage or potential for damage. With the proliferation of the use of non-destructive evaluation (NDE) methods, their use is also justified and encouraged for ABC bridges, especially for joints and connections. Furthermore, in tandem with the use of ABC methods for accelerating the construction of bridges, the use of automated, non-contact, and self-operating inspection systems will allow accelerated evaluation and maintenance.

In addition to reviewing inspection and evaluation means and methods, in this module, a review of performance of ABC short-span bridges with an emphasis on joints will also be carried out. A knowledge of potential damages and performance issues will lead to better planning of inspection activities. Moreover, information on performance of general ABC construction and summary of deterioration patterns will be discussed. Based on the reported surveys, most of these problems have been observed in the connections between deck panels and between deck panels and piers or abutments. Therefore, inspection and performance evaluation of joints, particularly closure joints, should be emphasized for short-span bridges.

5.2. Inspection of ABC bridges
In general, inspections should follow AASHTO Manual for Bridge Evaluation (MBE) and National Bridge Inspection Standards (NBIS). Basic activities will include bridge components physical and visual examination, evaluation and examination of approach roadway and waterway beneath structure, if any. Maintaining reliable documentation including member numbering system, proper structure orientation and following inspection requirements are among responsibilities associated with inspection. Bridge type, general conditions and material used in construction influence the procedures to be used for inspecting a bridge [1].

As for any type of inspection, documentation and record-keeping are crucial. Every deficiency must be recorded, and Comprehensive and complete documentation and report should contain the
description of the bridge condition and deficiencies along with adequate information. Maintenance needs and safety problems with the bridge must be identified. Culverts and bridges over waterways must be checked for scour, changes in drainage area, high-water marks, and roadway settlements. For bridges passing over waterways the volume and path of the flow must be inspected [1].

According to AASHTO Manual for Bridge Evaluation, there are 7 different types of inspections that distinguished by the inspection frequency, the requires level and intensity of inspection, details and types of structures. Those are classified as initial, routine, damage, in-depth, fracture critical, underwater, and special inspections. The required intensity of the inspection varies over the useful life of a bridge. The initial inspection for example includes load capacity ratings and detailed Structure Inventory and Appraisal data (SI&A), identification of existing problems and structural conditions is provided [1]. Figure 5.1 shows an example of Florida Structural Inventory and Appraisal Sheet for a sample bridge.

![Figure 5.1 Example of Florida Structural Inventory and Appraisal Sheet [1].](image-url)
Figure 5.1 Example of Florida Structural Inventory and Appraisal Sheet (Continued) [1].
Figure 5. 1: Example of Florida Structural Inventory and Appraisal Sheet (Continued) [1].
5.2.1. Visual Inspection

When a bridge becomes part of the inventory, as well as when a change in configuration of the bridge occurs or there is change in ownership, a visual inspection is performed. The orientation of the bridge and the site is established first, and the direction of flow in waterway and the inventory route is determined. Environmental condition, date and time, and the name and affiliation of the inspection team is also recorded. Visual inspection allows evaluation and close observation of the members. The removal of leaves, dirt, debris and animal waste is sometimes needed to allow the inspection. Superstructure must be inspected thoroughly as it is the primary load carrying members. The substructure elements must be also inspected and checked for settlements and undermining [1].
5.2.2. **Routine inspection**

Routine inspections ensure that structures continue to satisfy service conditions, identify changes from previous recorded conditions, and determine functional and physical conditions of the bridge. The areas determined to be critical to load-carrying capacity must be closely monitored [1].

According to NBIS, intervals between inspections should not exceed 24 months. The frequency of inspection must be established based on traffic, age and deficiencies observed in the bridge. Some bridges may require inspections at intervals less than 24 months, and in contrast, some can be inspected in intervals longer than 24 months by prior approval from FHWA [1].

5.2.3. **Damage inspections:**

When human actions or environmental factors are recognized to be detrimental to a bridge, a damage inspection is scheduled. Based on damage inspection, the necessity of closure of traffic or posting of the bridge for load limit is evaluated and the level, type and extent of repair/remediation action is determined [1].

5.2.4. **In-Depth inspections:**

When routine inspections are not able to identify certain deficiencies, an in-depth inspection is necessary as it is a close-up inspection of members both below or above the water. Non-destructive tests may also be needed in this case to identify the extent of the deficiencies. Depending on the detected damage, the residual capacity of the members must be evaluated [1].

5.2.5. **Fracture Critical inspections:**

This type of inspection is performed in a tension element failure of which may result in failure and collapse of the entire bridge. Non-destructive and visual methods are used for this type of inspection [1].

5.2.6. **Underwater inspections:**

Environmental factors, scour characteristics, age, construction material and condition rating from past inspections are used to determine the level and frequency of underwater structural elements. Intervals should not exceed 60 months according to the NBIS, however, depending on the abovementioned factors, the interval could be longer or shorter. When visual inspection at low-flow water or probing cannot be used for a portion of the bridge substructure and surrounding channel, underwater inspection will be necessary. This type of inspection usually requires diving and other appropriate procedures [1].

5.2.7. **Special inspections:**

With the discretion of the Bridge Owner, a special inspection can be planned to monitor suspected deficiency such as fatigue damage, scour or settlement [1].

5.3. **Inspection Equipment**

Equipment needed for inspection varies with the type of bridge and inspection. A set of standard tools are needed to perform a comprehensive and accurate inspection. There are 7 different basic categories of standard tools which are tools for cleaning, inspection, visual aid, measuring, documentation, access and miscellaneous equipment [1].

Tools for cleaning (Figure 5.2) include wire brush, Wisk broom, flat bladed screwdriver, scrapers and shovel [1].
Figure 5. 2 Tools for cleaning [1].

Tools for inspection (Figure 5.3) include ice pick, pocket knife, timber boring tools, hand brace and bits, plumb bob, chipping hammer with leather holder, chain drag, tool belt with tool pouch and range pole/probe [1].

Figure 5. 3 Tool for inspections [1].

Tools for visual aid (Figure 5.4) include flashlights, binoculars, inspection mirrors, lighted magnifying glass, dye penetrant [1]. Borescopes and video-borescopes can also be used for hard to reach locations.
Tools for measuring (Figure 5.5) include calipers, 25 foot and 100 foot tape, pocket tape, optical crack gauge, thermometer, tiltmeter and protractor, paint film gauge, D-meter, four-foot carpenter’s level, line level and string line and electronic distance meter (EDM) [1]. New measurement tools such as laser distansometers can also be used.

Tools for documentation include notebooks, inspection forms, pencil, clipboards, digital camera, straight edge, center punch, chalk, paint sticks, markers and “P-K” nails. Some common tools for access include boat, ladders, waders and rope. Some bridges may require rigging and special access vehicles such as climbing baskets and under-bridge inspection vehicles. Miscellaneous equipment includes penetrating oils, “C” clamps, wasp and hornet killer, insect repellent, dust masks, first-aid kit, life jackets, coveralls, toilet paper and cell phone [1].

5.4. Bridge Inspection Forms

Forms are used so the inspector can have a checklist of items that need to be reviewed. Standard inspection forms can vary based on bridge owners’ preference and needs. Figure 5.6 shows an example of a bridge inspection form. These forms allow registering numerical conditions, field notes, and appraisal rating by the inspector. Among forms included in the bridge record is load
rating summary sheet that indicates a complete record of load carrying capacity of the bridge (Figure 5.7) [1]. Aside from standard forms, specific features of each bridge may warrant developing customized inspection forms. For ABC short-span bridges that have unique features distinguishing them from conventional bridges, standard inspection forms can be modified, or new forms can be developed that facilitate the inspection in accordance with their features.

![ODOT Bridge Inspection Report Form](image)

*Figure 5. 6 Element Level example inspection form [1].*
Figure 5.7 Load Rating Summary Sheet example [1].
5.5. **Non-Destructive Testing**

The use of Non-destructive Testing (NDT) may be required for detecting and characterizing different bridge deteriorations and defects in the form of cracks, voids, leakage, delamination, corrosion and other damages that are not readily visible. Accordingly, NDT methods can be also used for condition assessment of components of bridges built using Accelerated Bridge Construction (ABC) method. Since they do not require changing or damaging the structure in the course of the inspection the uses of Non-destructive Testing (NDT) methods are usually preferable [11]

There exist several nondestructive methods that can be used for inspection, evaluation, damage detection and quality control purposes for ABC bridges and its components. Although visual inspection is the most common technique for inspection of bridges, it cannot capture damages and defects that are hidden from eye. For ABC projects where cast-in-place joints are used to connect prefabricated elements, nondestructive evaluation may be needed to evaluate their performance and integrity to detect damages as soon as possible in the service life of the bridge to avoid the need for costly repairs for extensive damages [109].

A variety of nondestructive inspection methods can be used for evaluation of the integrity of ABC components. A study developed by Freeseeman et al., 2018, evaluated different types of nondestructive techniques for inspection and quality assurance/quality control purposes. They categorized the methods into five main groups: audio-visual, acoustic-seismic, electro-magnetic, thermal and radiographic [109]. Their review of audio-visual and acoustic-seismic methods are described below, and the remaining of the methods are discussed in more details later in this chapter. Freeseeman et al., 2018, developed a summary of the nondestructive techniques associated with general application for ABC (Table 5.1)

**Table 5.1 Nondestructive methods for inspections of ABC structures [109].**

<table>
<thead>
<tr>
<th>NDE Method</th>
<th>General applications for ABC structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Inspection</td>
<td>Rapid detection of flaws and anomalies on the surface, and inspection of leaks and alignment of connections</td>
</tr>
<tr>
<td>Hammer-Sound and Chain Drag</td>
<td>Detect the area of delaminations and spalls in concrete</td>
</tr>
<tr>
<td>Acoustic Emission (AE)</td>
<td>Leak detection and location, in-process weld monitoring, mechanical property testing and characterization, monitoring of fatigue cracks, fiber fractures, fiber matrix debonding, matrix micro-cracks, and delamination</td>
</tr>
<tr>
<td>Impact Echo (IE)</td>
<td>Detection of delamination, surface opening cracks, ducts, voids, and overlay bonding, and evaluation of the modulus of elasticity, compressive strength, and grouting characteristics</td>
</tr>
<tr>
<td>Ultrasonic Testing (UT)</td>
<td>Inspection of the internal structure of concrete, such as quality and uniformity of concrete, location of reinforcement, as well as defect and anomaly detection. Capabilities depend upon the quantity and type of transducer employed by the device</td>
</tr>
<tr>
<td>Ground Penetrating Radar (GPR)</td>
<td>Location of reinforcement, prestressing strands, cables, voids, cracks, and delaminations in concrete, and estimation of concrete cover depth, density, and moisture content variations</td>
</tr>
<tr>
<td>Infrared (IR) Thermography</td>
<td>Rapidly inspect large surfaces to detect delamination, internal voids, and cracks over bridge decks</td>
</tr>
<tr>
<td>X-ray and Gamma-ray</td>
<td>Visualization of internal characteristics of a component</td>
</tr>
</tbody>
</table>
5.5.1. **Audio-Visual Methods:**

These methods rely on an inspector’s judgement and experience. The visual inspection can be combined with different technologies such as vision from drones [109]. This type of inspection is an initial step to identify flaws and anomalies on the surface components which can later guide the next steps that can be time consuming and costly [110]. This process can be improved by the use of optical instruments, computer-assisted systems, borescopes, and charge coupled devices. Magnetic particle and liquid penetrant test can be also used when defects are difficult to visualize. Advances in visual inspections such as light detection and ranging (LIDAR) formulates 3D representations based on laser return times. A disadvantage of the visual inspections is that only surface discontinuities can be detected without possibility to know the extent of the problems [109].

The most popular audio inspection techniques are chain dragging and leverage hammer sounding. These are used to detect delamination severity in concrete structures. Following stroke of the hammer and drag of the chain, the inspector listens to the final sound and the presence of delamination will provoke a change of sound [109]. Figure 5.8 shows the equipment for both techniques. One disadvantage of the techniques is that they can only be use in horizontal surfaces to detect delamination in concrete bridge decks and cannot be used on asphalt overlays [109].

![Figure 5.8 Chain drag equipment (left) and hammer sounding tools (right) [109].](image)
5.5.2. **Acoustic-Seismic Methods:**

Acoustic emission technique relies on elastic waves transmission. It is normally used to measure fatigue, metallurgical, tensile, and weld properties. It also evaluates friction, wear, spalling, strain rate, initiation and propagation of cracks, corrosion and erosion effects [110]. A highly skilled inspector is needed in order to identify the damage mechanisms using the acoustic emission data [111]. Also, it cannot be applied in large surfaces since small distances are required between the sensors and actuators [109]. Figure 5.9 shows how transducers are used to listen to strain energy produced by fractures [109]. Moreover, Impact echo and ultrasonic tests were also considered in the research by Freeseman et al., 2018.

![Formation and detection of AE Signals](image)

After an extensive literature review of available NDT methods applicable to ABC closure joints, a summary of the most promising methods was introduced by Mehrabi and Farhangdoust (2019). Although their focus was on the deck closure joints, their work applies to ABC bridges using concrete details in general. After reviewing the majority of available NDT methods, they identified the promising methods for use in inspection and health monitoring of ABC as: Impact Echo Testing (IE), Ground Penetrating Radar (GPR), Ultrasonic Testing (UT), Infrared Thermography Testing (IR), Impulse Response Testing (IRT), Radiographic Testing (RT), Magnetic Flux Leakage Testing (MFL) [11]. Furthermore, Mehrabi and Farhangdoust (2019) developed a flowchart (Figure 5.10) to determine which NDT method is most applicable to each of common types of defect/damage. As stated above, their work focused on deck closure joints, however, their conclusions apply to detection of damages in any component of ABC bridge using concrete details.

The most promising NDT methods for detection of damages in concrete ABC bridges are described below in detail.
5.5.3. Impact Echo Testing (IE)

Main defects that can be identified by the Impact Echo (IE) testing are cracks, voids, large delamination and different types of discontinuities. For detection of the damages, IE uses mechanical waves and it has good ability to detect internal damages in the concrete [112]. Figure 5.11 shows a schematic of the IE method. The surface of the concrete component is first impacted by a small impulse hammer or steel ball [113]. Reflected energy wave is then recorded by the use of an accelerometer receiver which is collocated near the impact location [114]. This method may not be applicable to a case where deck overlay exists. Also, the evaluation process is associated with lane closure and use of sparse grid [112].
5.5.4. Ground Penetrating Radar (GPR)

This is one of the most commonly used microwave-based methods, and normally is used to locate the reinforcing bars and other inclusions in reinforced concrete structures [116]. Often, GPR is used in combination with other NDT methods for damage detection (Figure 5.12). GPR is good for deck inspection to detect crack, delamination and voids. In this method, electronic waves are sent through the deck antenna and then are received from internal reflectors. Damage is detected by exploring the wave propagation pattern [117]. It is considered to be user friendly, cost effective and it has a moderate speed of operation [118].

![Image of GPR for bridge deck inspection]

Figure 5. 12 Example of GPR for bridge deck inspection [116]

5.5.5. Ultrasonic Testing (UT)

In this method structural elements are tested using high frequency sound waves, normally above 2 MHz. The monitor indicates distance between surface and any internal defect (Figure 5.13) [119], [120]. This is one of the most common techniques among Pulse Velocity Testing methods that utilizes sound waves at frequencies above audible range to evaluate different types of voids and internal cracks in concrete [121], [122]. This method is not that effective when used with thin elements, complex geometry components brittle materials [123]. Also, as this is a relatively fast
nondestructive evaluation test its cost is moderate and needs a skillful operator to use the machine [118]. The use of ultrasonic testing is not limited to concrete elements. UT are also used routinely for detecting cracks in steel elements.

![Diagram of ultrasonic testing](image)

*Figure 5.13 The defects are read from the screen [119]*

### 5.5.6. Infrared Thermography Testing (IR)

Variation in the emitted infrared radiation from a structural member monitored by an infrared camera is used for detection of damages in structural elements [123]. The method uses difference between infrared radiation rates of the material for detecting voids, cracks and delamination in a structure. Depending on the ambient conditions, the method can work with a heating source (active type) or without the external heating source (passive type) [123]. This method has a high sensibility to contaminants and can be distracted by contaminants on the bridge deck. However, low cost and ease of use are some of the advantages of this method [124]. Figure 5.14 shows an example of infrared thermal image.

![Infrared thermal image](image)

*Figure 5.14 Infrared Thermal Imaging; Use of IRT camera (left) and a thermal image (right) [124]*

168
5.5.7. Impulse Response Testing (IRT)
Impulse response testing is used for damage detection of concrete structural elements by monitoring the stress wave propagation [11]. The concrete surface is struck by a hammer and a stress wave is generated (Figure 5.15). It has been used for detecting cracks, voids, and delamination. Deep foundation evaluation is one of the applications of this method [115]. This method requires a moderate skill for operating, has a moderate speed of testing and is fairly accurate [118].

![Impulse Response Testing (IRT) set-up for slab evaluation](image)

*Figure 5. 15 A principle of Impulse Response Testing (IRT) set-up for slab evaluation [125]*

5.5.8. Radiographic Testing (RT)
Radiographic testing has been used in concrete bridge decks to detect internal defects with the use of X-Ray radiation (Figure 5.16). Structural components are projected on fluorescent screens or photographic films and are evaluated by the different rate of transmitted radiation [126]. It can be applied in different material types and little surface preparation is needed. It is good for detecting internal defects and creating images of defects and discontinuities [11]. Drawback of this method is that a skillful operator is needed, it presents safety risk for users and public, and is expensive [118].

![Radiographic Testing](image)

*Figure 5. 16 The defects are read from the screen [126]*
5.5.9. Magnetic Flux Leakage Testing (MFL)

The magnetic Flux Leakage Testing involves the use of an external magnet to magnetize the steel within the structure in order to detect defects such as loss of cross section, corrosion, and breaks in the embedded steel elements [127]. The operator must be highly experienced, and this method may present some safety risks for the users and public [118]. Moreover, for this method to be effective, the rebar location needs to be known. The inspector would normally need to first use another method to locate the reinforcement and then use this technique for damage detection [123]. Figure 5.17 shows a schematic layout of this testing method.

![Figure 5.17 Schematic layout of Magnetic Flux Leakage testing method](image)

5.5.10. NDT methods most applicable to concrete bridge elements

Mehrabi and Farhangdoust (2019) reviewed a total of 50 literature sources and developed charts that classified the most appropriate/commonly used NDT methods for each damage type in closure joints. There are four charts representing the four common types of defects or damages. Figure 5.18 shows two charts with representation of NDT methods used to detect delamination and corrosion, and Figure 5.19 shows two charts for crack and voids [11]. Most suitable methods for each defect are represented by higher percentages in these charts. These charts can be used by the inspectors and/or bridge owners as a selection guide for the most efficient NDT method applicable to a specific type of damage.

![Figure 5.18 Statistical representation of NDT methods most applicable to detect delamination (Left), and to detect corrosion (Right)](image)
5.5.11. NDT methods specifically applicable to steel elements

In order to evaluate and examine the integrity of ABC components there is a variety of nondestructive inspection methods that can be used. Mehrabi and Farhangdoust (2019) research was focused on NDT methods for field inspection and damage detection mostly applicable to concrete. However, they discussed other NDT methods that have better applicability to Metallic elements mainly Penetrating Testing (PT), Eddy current testing (ET), and Magnetic Particle Testing (MT). Chapter 2 of this report described several ABC elements and systems that use steel elements including orthotropic deck elements and modular superstructure systems. Steel elements are prone to corrosion and corrosion related damages in general. The ABC steel elements, as it is also the case for conventional bridges, contain details that are susceptible to certain types of damages such as fatigue cracking. Hence, inspection methods that are applicable to conventional steel bridges apply also to ABC bridges that use steel elements. Following contains brief description of some of NDT methods applicable to steel structures.

5.5.11.1. Penetrant Testing (PT)

Penetrant testing, also known as Penetrant Flaw Detection (PFD), Liquid Penetrant Inspection (LPI) and Dye Penetrant Inspection (DPI) can be used to detect surface damages, commonly cracks. Although this method is often used for steel elements, it has some applications also for concrete elements. Exceptions for the application of this surface damage detection testing method are porous materials such as wood, cloth, pottery, and unglazed ceramic. Penetrants must be able to enter the discontinuities or defects to form indication, therefore, penetrant testing can detect surface defects. For application of this type of testing, the element needs pre- and post-cleaning. The penetrating fluid is then applied to the element and drawn by capillarity actions into the surface discontinuities. This method is easy to use and interpret, does not have any shape or size limitation for the elements, requires low cost equipment, is easy to use for testing and analyzing [129]. Figure 5.23 shows different types of penetrating fluid used for nondestructive evaluation. Some drawbacks of using PT are temperature dependence, the need for pre- and post-cleaning and preparation of the element surface, and inability of examining internal discontinuities [11].
5.5.11.2. Eddy Current Testing (ET)

One of the common and most practical NDT methods for inspection of steel and aluminum elements is the Eddy Current Testing (ET) that is used for surface and subsurface damage detection. The procedure for this method is an alternating current through a coil that generates an alternating field and introduces Eddy current in the conducting element (Figure 5.24) [130]. The advantages of using ET is that it needs little preparation of the test surface, is capable of precise conductivity measurements, is able to detect defects through several layers, measurement can be automated, and it is easy use. However, some disadvantages of the application are high susceptibility to permeability changes, inability in using for large areas and complex geometries, inability in recognizing and analyzing the internal defects, application limited to conducting elements, and inability to detect defects parallel to the surface [129]

![Eddy Current Testing Schematic](image)

Figure 5. 21 Schematic of the ET method [130]

5.5.11.3. Magnetic Particle Testing (MT)

Surface and sub-surface defects in ferromagnetic materials can be detected by the implementation of Magnetic Particle Testing (MT). In this test, discontinuities disrupt the magnetic flux and magnetic field magnetizes the element defects. By applying the ferromagnetic particles like iron powders, the sub-surface and surface defects are revealed (Figure 5.25) [131]. Some of the advantages of MT evaluation include little or no surface cleaning and preparation (in comparison with PT), high speed of test (in comparison with PT), recognizing the sub-surface and surface discontinuities, ability to test the elements which have a very thin coating, easy to use for testing
and analysing the element, low cost equipment, and high sensitivity [11]. In contrast, some of the disadvantages of MT are shape and size limitation, lower accuracy for the element with coating, inability to detect internal defects and the need for demagnetization after the test [129].

![Figure 5. 22 Example of MT principle [131]](image)

5.6. **Other methods**

Implementation of automation techniques is growing fast for every application and the inspection is not an exception. Automation is about working faster, smarter and more efficiently. The advancements in robotics and automation have allowed implementation of different technologies for inspection. These technologies include the use of unmanned aerial vehicles, robots, and automated visual and non-destructive testing [132]. Application of NDT using robots can be seen in Figure 5.23.

![Figure 5. 23 Some robots collaborating with the operator for bridge inspection [132].](image)

Technological developments have inspired many different researchers to combine different options to automate systems and implement for bridges. Ghasemi et al. (2013) performed a pilot project to collect information on the external and internal condition of bridge decks. A variety of nondestructive evaluation technologies can be deployed simultaneously, and data collection can be carried out automatically. This helps to enhance data interpretation and forms a snapshot of the bridge deck condition. The nondestructive technologies used in this robot were impact echo, ground penetrating radar, global positioning system, electrical resistivity, high-resolution imaging and ultrasonic surface waves. Figure 5.2 shows the multitask robot [133].
In recent years, drone technology has been used in many applications, including in construction industries for application ranging from management to inspection, and evaluations. In the case of ABC technology, the use of drones can help solving problems regarding geometry control, for inspection and surveying/mapping. Drones can be used for on-site and off-site mapping of existing supports and prefabricated elements. Also, uninterrupted and accurate process of mapping and surveying can be provided at all time. Additionally, accurate geometry, condition, and measurement of hard-to-reach areas can be performed using drones [134].

Use of drones for bridge inspection have been implemented by the Minnesota Department of Transportation (Figure 5.25) [135]. A field study was also performed by ADOJAM, LLC, for an ABC bridge in Iowa using an airborne GPR. The airborne craft was equipped with measurement capabilities and integrated sensing and provided a framework for developing a civil infrastructure asset information database. LIDAR was also included in the airborne craft enabling three-dimensional geospatial imaging. Surface cracking and concrete deterioration can be detected with the use of LIDAR, and moisture, subsurface voids and larger cracks can be detected with the radar. Methodology for data fusion and post processing included subsurface GPR measurements, surface LIDAR measurements and IMU/GPS (Inertial measurement unit/global positioning system) (Figure 5.26). Currently, this system is flown by a pilot in command, however, automation is in sight for the future [109].
Figure 5. 25 Drone used for bridge inspection by Minnesota Department of Transportation [135]

Figure 5. 26 DAA GPR platform in action, including AVA antenna and synchronized IMU/GPS [109].

Figure 5.27 shows a full view at the deck level of Keg Creek Bridge captured by the DAA GPR technologies and Figure 5.28 shows an output for GPR system [109].

Figure 5. 27 Keg Creek Bridge full view [109].

Figure 5. 28 Keg Creek Bridge GPR data [109].

5.7. **Evaluation of substructure for reuse**

In most bridge replacement projects, the critical question is whether we can reuse any portion of the existing bridge. This can have significant economical consequence. To be able to evaluate usability, the existing elements need to be evaluated for potential damages that would limit their capacity and utility. Depending on the environmental condition, one or another part of the bridge may suffer most of the damages. In majority of cases, the bridge superstructure is damaged more than substructure. Also, when functional obsolescence is the case, often it relates to inadequate superstructure regarding width, height or other limitations. In this regard, it is often the case that
the question on reuse of the substructure to accommodate the new superstructure arises. In the following, a report issued recently by FHWA on reuse of substructure [136] has been used as reference to describe the evaluation and decision-making process.

For the decision on reusing bridge substructure and/or foundation, one of the critical issues is determining the remaining service life of the substructure or foundation. To define the remaining service life (durability) of the bridge components, an exhaustive bridge evaluation and inspection need to be performed. Bridge elements and components are commonly constructed from reinforced concrete or steel. Remaining service life evaluation and durability of the bridge components can be categorized in three stages (Figure 5.29) [136].

![Figure 5.29 Durability and residual service life assessment of bridge substructure [136]](image)

During the initial evaluation, environmental conditions, previous performance issues, and every concern related to durability of a bridge are investigated. Appropriate plans for further inspections as well as repair type and extension are expected as outcomes of this evaluation. The procedure for this evaluation is summarized in Table 5.2.

**Table 5.2 Preliminary assessment procedure [136]**

<table>
<thead>
<tr>
<th>Evaluation Procedure</th>
<th>Reason/Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Records Review</td>
<td>Review of past inspection history allows for assessment of the time history of</td>
</tr>
<tr>
<td>Environmental Conditions</td>
<td>bridge performance</td>
</tr>
<tr>
<td>Visual/Physical Survey</td>
<td>Document extent of cracking, signs of rust staining or efflorescence, erosion</td>
</tr>
<tr>
<td></td>
<td>of concrete paste, and extent of spalling. Locate delaminated areas using</td>
</tr>
<tr>
<td></td>
<td>hammer sounding and physical methods. Generally, overlaps with integrity</td>
</tr>
<tr>
<td></td>
<td>assessment in finding the current condition of the concrete.</td>
</tr>
</tbody>
</table>

As shown in this table, a visual inspection and review of previous records is required during the preliminary evaluation. Later, after a plan is created and the investigation through testing and inspection is completed, the information necessary to define the bridge condition is gathered. The testing plan, including field and laboratory testing, is tied to the type of the components of the bridge. Different methods can be applied to reinforced concrete or steel elements.
5.7.1. Field Testing and inspection of concrete elements

To determine the condition of the bridge elements, investigation through inspection and testing is required. The structural capacity of a bridge can be defined by developing a test plan with observations, inspections, considering local experiences, environmental and other conditions. In the testing plan, various tests including visual inspections, physical inspection using nondestructive tests (NDTs), or dissection by removing defective portions and performing the tests can be considered.

For reinforced concrete elements, identifying the extent and depth of cracks, extent of carbonation and chloride penetration into the concrete cover and reinforcement’s corrosion is the objective of a durability testing plan. Table 5.3 shows the typical factors in defining the durability of concrete elements [136].

Table 5.3 Field testing related to concrete elements [136]

<table>
<thead>
<tr>
<th>Available Testing</th>
<th>Issue identified during preliminary evaluation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover Measurement</td>
<td>Corrosion, chloride exposure, carbonation</td>
<td>Determine cover thickness important to evaluation of other durability issues.</td>
</tr>
<tr>
<td>Chloride Testing</td>
<td>Exposure to chlorides</td>
<td>Determine profile of chloride diffusion into cover concrete. Initial chloride testing can be limited to surface and depth samples, to ascertain the magnitude of bound and unbound chlorides.</td>
</tr>
<tr>
<td>pH testing</td>
<td>Carbonation</td>
<td>Perform pH testing on extracted cores to determine depth of carbonation penetration.</td>
</tr>
<tr>
<td>Half-cell potentials</td>
<td>Active corrosion</td>
<td>Perform half-cell potential testing in areas of suspected corrosion.</td>
</tr>
<tr>
<td>Electrical Resistivity</td>
<td>Potential for corrosion</td>
<td>Useful for finding areas of corrosion or areas susceptible to corrosion.</td>
</tr>
</tbody>
</table>

The tests to be conducted to evaluate the concrete elements degradation factors are listed in Table 5.4 [136].

Table 5.4 Durability tests of concrete elements [136]

<table>
<thead>
<tr>
<th>Test</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corroded cover depth</td>
<td>Ground Penetration Radar (GPR) Radar reflection, Cover more area, Eddy current detection, less affected by moisture and voids</td>
</tr>
<tr>
<td>Concrete cover delamination</td>
<td>hammer sounding, steel rod off the surface, impact echo, ultrasonic pulse responses, wall climbing robots, infrared thermography Delamination survey, ASTM D4580</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Half-cell Location of corrosion ASTM C876</td>
</tr>
<tr>
<td>Porosity</td>
<td>90-day ponding test AASHTO-T-25</td>
</tr>
<tr>
<td>Chloride ingress</td>
<td>Electrical method ASTM C1202 Acid-soluble test ASTM C1152 Water-soluble test ASTM C1218</td>
</tr>
<tr>
<td>Carbonation Susceptibility</td>
<td>SHRP-S-329 Air permeability CO² ingress resistance phenolphthalein test</td>
</tr>
<tr>
<td>Freeze/Thaw</td>
<td>Petrograph Temperature measurement</td>
</tr>
</tbody>
</table>
Moreover, the most commonly used NDT techniques for concrete elements are summarized in Table 5.5.

*Table 5. 5 NDT technologies for concrete elements [136]*

<table>
<thead>
<tr>
<th>NDT Method</th>
<th>Issues Investigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Penetrating Radar</td>
<td>Rebar layout, voids, cover depth</td>
</tr>
<tr>
<td>Ultrasonic Pulse Velocity and tomography</td>
<td>Location of voids, weak zones, honeycombing, and cracks</td>
</tr>
<tr>
<td>Infrared Thermography</td>
<td>Location of voids and delaminations</td>
</tr>
<tr>
<td>Electrical Resistivity (ER)</td>
<td>Presence of water, chlorides, and salts</td>
</tr>
<tr>
<td>Radiography</td>
<td>Location of voids and condition of tendons and strands</td>
</tr>
<tr>
<td>Rebound Hammer</td>
<td>Surface strength of concrete</td>
</tr>
<tr>
<td>Impact Echo/Ultraseismic/Parallel Seismic</td>
<td>Location of defects and voids in piles</td>
</tr>
</tbody>
</table>

5.7.2. **Field Testing and inspection of steel elements**

According to FHWA report on reuse of substructure, NDT technologies commonly used for steel elements to detect flaws are Dye Penetration Testing (PT), Magnetic Particle Testing (MT), Eddy Current Testing (ECT), Ultrasonic Testing (UT) and Phased Array Ultrasonic Testing (PAUT), and Acoustic Emission (AE) [136]. These technologies are summarized in Table 5.6 according to their usage.

Physical evaluation and inspection are conducted periodically in steel members. When underwater or underground field evaluations are performed, a core may need to be driven in order to directly evaluate exposure of steel members. Caution should be exercised since damage to the foundation could occur during coring and excavation [136]. Steel elements that are below the pier cap or in the water line are specifically susceptible to corrosion. Consequently, periodic inspection should be performed during the service life of the member in order to assess the corrosion rate.

*Table 5. 6 NDT technologies for steel members*

<table>
<thead>
<tr>
<th>NDT Method</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT</td>
<td>Detect cracking and surface flaws</td>
</tr>
<tr>
<td>MT</td>
<td>Detect surface breaking cracks</td>
</tr>
<tr>
<td>ECT</td>
<td>Detect flaws, material, and coating thickness</td>
</tr>
<tr>
<td>UT and PAUT</td>
<td>Detect surface and undersurface flaws</td>
</tr>
<tr>
<td>AE</td>
<td>Monitor cracks growth</td>
</tr>
</tbody>
</table>

5.8. **Performance of ABC technologies to date**

5.8.1. **Defects and Anomalies in concrete bridges.**

Examples and types of defects and anomalies expected in bridges in general (emphasis on concrete bridges) are shown in Table 5.7. In concrete structural elements, defects can include separation
and delamination, voids and/or honeycombing filled with air or water, cracking, corrosion and loss of cross-section of reinforcing bars, roughness, leakage through joints, abnormal appearance, and lack of cohesion or continuity in concrete or similar material [11].

Table 5. 7 Examples of defects and anomalies in bridge superstructure [137], [138], [139], [140], [141], [142], [143], [144], [145]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>![Crack Image]</td>
<td>![Delamination Image]</td>
<td>![Internal Discontinuities Image]</td>
</tr>
<tr>
<td>![Surface Discontinuities Image]</td>
<td>![Corrosion of Reinforcing Bars Image]</td>
<td>![Spalls Image]</td>
</tr>
<tr>
<td>![Honeycombing Image]</td>
<td>![Abnormal Appearance Image]</td>
<td>![Leakage Through the Joints Image]</td>
</tr>
<tr>
<td>![Corrosion of Embedded Steel Plates or Connectors Image]</td>
<td>![Wearing and abrasion Image]</td>
<td>![Loss of Cross-section or Breakage of Reinforcing Bars Image]</td>
</tr>
</tbody>
</table>
Factors such as improper workmanship, design flaws, material defects, mechanical and environmental effects can initiate sequential damages at various stages. For example, many defects reported for concrete elements are possibly affected by workmanship [146]. Workmanship can affect all activities including forming, casting, pumping, curing, concrete mixing, steel fabrication and installation, and material selection [11]. Improper design and detailing can also result in initiation and progress of specific type of damages [147]. Voids, cracks, and delamination can be caused by material deficiency and inappropriate mix design as a result of bleeding, segregation, and high porosity [148, 149]. Another cause for damages is the mechanical effects such as live loads, and abrasion [150]. Also, environmental effects such as temperature variation, moisture, precipitation, freeze and thaw, and other factors can have harmful effects [151].

5.8.2. Damage Sequence

Mehrabi and Farhangdoust (2019) developed a Damage Sequence Tree where ABC joint defects and damages were included at several levels (Figure 5.30). This classification was used to analyze the cause of defects in closure joints, however, these sequences apply almost entirely to concrete elements in general. Determining the damage sequence is critical in identifying the potential cause of the defects. This will facilitate both the selection of the most applicable techniques for inspection and also will lead to better decision of remediation [11].
5.8.3. **Defects and Anomalies specific to ABC bridges**
Utah DOT has been performing periodic inspection and evaluation of ABC technologies in which the performance of each element and technology in various bridges is targeted with the goal of guaranteeing a continuous improvement of quality. Five inspections have been completed between 2009 and 2016. The bridges in their study contained Full Depth Deck Panels with welded tie connections, Full Depth Deck Panels with longitudinal Post-Tensioning, Full Depth Deck Panels with dowel bar pockets, Full Depth Deck Panels with shear connector pockets, Full Depth Deck Panels with UHPC Connections, SPMT Bridge Systems, Lateral and Longitudinal Slide Systems, Precast Approach Slabs, Precast Abutments, Precast Piers and GRS/IBS [152], [153], [154], [155], [156]. Garber and Shahrokhi (2019) organized a summary of the main observations, results and recommendations from Utah inspections as described below [157].

5.8.3.1. **Full-Depth Deck Panel: Transverse connections with welded tie plates**
According to the results of evaluating the performance of ABC technologies, the technique that performed the worst among others was the Full Depth Deck Precast with welded tie connections. Leakage and efflorescence between deck panels was noticed (Figure 5.31). Moreover, over the joint region, reflective cracking was visible (Figure 5.32). It can be seen through inspections between 2013 and 2016 how damage had worsened in the asphalt overlay in time. Figure 5.33 shows an example of one of the observed problems in the full depth precast deck panels with welded tie connection where defect in a poorly grouted shear key between panels is shown [157].

![Figure 5. 31 Typical joint leakage at deck panels (I-84 WB over Weber Canyon with welded-tie connections from 2009 inspection) [152].](image)
Figure 5. 32 Typical transverse cracking in the overlay which worsened from 2013 to 2016 [156].

Figure 5. 33 Cracks with efflorescence in parapet over the deck panel joint and Poorly bonded grout in shear pocket [156].

5.8.3.2. Full-Depth Deck Panel: Transverse Connections with Longitudinal Post-Tensioning

Minor leakage was observed in this connection, and that it is performing well. Use of high-quality grout for the connections and high-quality concrete for the panels was recommended to reduce leakage. Sullivan (2003) stated that one of the causes of appearance of premature deterioration of full-depth deck panel systems is the lack of post-tensioning to secure the tightness of the joints. The measures to lessen the issue is stated as treating the joints with caulking material, grouting the joints with magnesium phosphate and to using a proper shear key connection.

5.8.3.3. Full-Depth Deck Panel: Transverse Connections with Dowel Bar Pockets

Leakage and efflorescence at many joints was noticed. This detail should be used only in positive moment regions as the deterioration for a bridge with 5 years in service is more than expected.
5.8.3.4. Full-Depth Deck Panel: Deck Panels with Shear Connector Pockets

Signs of minor leakage were seen in several bridges. However, compared to a typical cast-in-place concrete bridge deck system, the amount of leakage was less than typical. Method of curing and type of grout used seems to be linked with the performance. Figure 5.34 shows an example of shrinkage cracking in a blockout closure joint.

5.8.3.5. Full-Depth Deck Panel: Connections with reinforced UHPC

Only one bridge was built with this detail and was inspected 3 years after completion, no deficiency was observed. Therefore, for future projects this detail is strongly recommended.

5.8.3.6. Precast concrete Parapets

Joint leakage was not found, and performance of the parapets is good. Misalignment between adjacent parapets sections was noticed. The inspector developed a new tolerance detail to provide good quality control during casting.

5.8.3.7. Connection of Approach Slabs to Bridge Decks

This type of connection had some deterioration due to combination of thermal movements and live loads forces. Therefore, it was concluded that the cast-in-place connection performs better than mechanical connections.

5.8.3.8. Precast Concrete Abutments with Vertical Thread-Bar Connections

No significant leaking between joints was found, and performance is generally good. Issue with misalignment was encountered as there was tight tolerance control. Also, this type is more problematic because of the fit-up tolerance for the grouted joint. The cost increases due to the lower fabrication process.

5.8.3.9. Precast Concrete Pier Elements

No significant problems were found, and piers are performing well.

5.8.3.10. Geosynthetic Reinforced Soil Integrated Bridge System (GRS-IBS)

Only one bridge was inspected and leakage in joints was found due to inadequate drainage. For this case, an improved drainage was recommended.

5.8.3.11. Precast Adjacent Box Beams (side-by-side box beams)

Only one bridge was built with this detail and there were no significant problems to report during the inspections.

5.8.3.12. Other investigations for performance of side-by-side box girders and full-depth deck panel systems; causes and methods to decrease premature deterioration:

Attanayake and Aktan (2015) concluded that regardless of age of construction all side-by-side box beam bridges had longitudinal reflective cracking. Cracks appear along the beam-shear key
interface for this type of bridges, within two to three days after grouting the joints. They noted that reflective cracks appeared in the deck before the deck was subjected to live load and 15 days after deck placement. This was attributed to environmental issues such as shrinkage and temperature variations. These cracking resulted in damages due to leakage of water (Figure 5.35) [158].

![Figure 5.34 Shrinkage crack in the blockout type of ABC closure joint [159]](image)

Other investigations have been done for evaluation of different types of cracks in closure joints. For example, due to shrinkage and/or stress concentration, reflective cracking can be initiated inside the deck from cold joints and sharp corners. Cracking along linear closure joints is another type of damage observed in ABC bridge decks that causes leakage problems for closure joints (Figure 5.35). Corrosion of steel reinforcement within the closure joints can start because of the leakage. It can be concluded that regardless of the type of closure joints used, the ABC superstructure is prone to surface discontinuities and corrosion of the embedded reinforcement [11].

![Figure 5.35 Longitude deck cracking of ABC closure joint [158]](image)

Moreover, Aktan and Attanayake (2013) provided a summary of different research investigations performed along with the causes and methods to abate a premature deterioration of full-depth deck panel systems. Summary of their findings is given below [160]:

Cause 1 - Increased strain values in the top and bottom portions of the beam produced by insufficient stiffness of the bridge superstructure, consequently affecting the integrity of panel-beam connection [160].
Cause 2 - A factor that affects the beam-panel connection integrity is the limited number of shear connectors [160].

Cause 3 - Slippage at the interface resulting from lack of composite action between beams with the deck panels [161]. Shear studs can be used for connecting the supporting system with the precast concrete panels through shear connection pockets.

Cause 4 - Poor condition of overlay [162]. Measures that can be taken towards remediation are rehabilitation of overlay with epoxy concrete overlay, overlay with EP-5 concrete overlay, rehabilitation with Latex Modified Concrete (LMC) as overlay, use of Silica fume in the overlay, and using an overlay with a waterproofing membrane [163], [164], [165].

Cause 5 - Deep shear cracks near the edge of the panels [165]. Treat Crack with High Molecular Weight Methacrylate (HMWM) is a potential measure that can be used both for crack sealing and treatment of concrete surfaces [163], [164].

Cause 6 - In full-depth deck panel systems that are continuous over girders and subjected to significant amount of traffic, punching shear can be a likely mechanism causing failure [166]. Controlling traffic mechanism can be used to keep the deck in good condition [163]. Also, another way to alleviate this problem is using a prestressed deck panel [160].

Cause 7 - Development of cracks in the panels is considered to be due to bending during handling [165]. Transverse prestressing is suggested in order to prevent cracks to develop internally [164], [165].

5.8.4. Defects and anomalies in Steel Bridges

In general, 40% of the bridges in the USA are built of steel. Among ABC bridges, proportion of those using steel elements is not known, but as mentioned earlier, there are several ABC elements that utilize steel. Although most ABC bridges using steel elements are young and there is not enough information on their long-term performance, lessons can be learnt from conventional steel bridges that have similar details and elements. Additionally, some of the steel elements used in ABC bridges, e.g., orthotropic decks, have been in service for a long time and can be reviewed for their susceptibility and potential defects.

One of the most important causes of deterioration of steel bridges is corrosion and corrosion related defects. Exposure to water, especially to marine and salt-water environment is the primary cause of corrosion. Road spray/splash, deck leakage and condensation can be a source of water which can determine the pattern of corrosion on a bridge. Contaminants and ambient temperature can affect the rate of corrosion. Severity of deterioration will depend on how long steel is exposed to salt, oxygen and water [167] as well as on the type of steel. Five main types of corrosion can be recognized for steel bridges:

5.8.4.1. Pitting Corrosion

Pitting corrosion involves loss of material at the surface but in a relatively small area (Figure 5.36). They are considered critical because they can extend into the steel and may be overlooked. In high stress regions this type of corrosion is dangerous as it can cause local stress concentrations [167].
5.8.4.2. Galvanic Corrosion

This type of corrosion occurs in welded or bolted connections as it occurs when two dissimilar metals are electrochemically coupled. The can lead to pit formation [167].

5.8.4.3. Crevice Corrosion

They can be caused by the moisture held within a crevice and can occur in small areas such as between faying surfaces or beneath peeling paint (Figure 5.37). Crevice corrosion can also occur with deep pits [167].
5.8.4.4. Stress Corrosion

Occurs in a corrosive environment when a metal is subjected to tensile stress. In ordinary bridge environment, stress corrosion is usually not a problem for mild carbon steel. In general, higher susceptibility to stress corrosion is related to the lower fracture resistance of a metal [167].

5.8.4.5. Corrosion Fatigue

It is a corrosion phenomenon that involves the combination of crevice, stress corrosion and pitting. This type of corrosion reduces the fatigue life of a metal. Crevice or stress corrosion results in propagation of the cracks, and pits cause stress concentration [167].

With corrosion three basic changes can occur in steel bridges namely reduction of cross-sectional properties, loss of material and buildup of corrosion products. Reduction of section properties decrease the geometric properties and buckling capacity of the members. Smaller net section will occur by loss of material which can increase stress range due to cyclic loading or increase the stress level for a given load. Finally, steel bridges can be affected by the buildup and expansion of corrosion products (pack-rust) pressuring adjacent elements [167]. Corrosion can occur along the top surface of the bottom flange with accumulated water, and/or over the entire web due to deck leakage near the supports (Figure 5.38) [169].

![Figure 5.38 Typical locations of corrosion on a steel girder bridge [169].](image)

5.8.4.6. Performance of corroded bridges

Reduction of capacity of a component can be caused by loss of section and the amount will depend on whether the component is in tension or compression. Corrosion can also affect the capacity in bending, shear and bearing in a steel bridge. Corrosion along the bottom flange and in the web near the supports can reduce flexural and shear/bearing capacity of steel girders, respectively (Figure 5.39) [167]. Stress cycles under traffic loads and aging of steel bridges exacerbate the fatigue cracking in steel bridge structures. Distortion-induced fatigue cracks in connections often result from member interaction of global behavior not considered properly in the original design [170].
Adequate protection against corrosion should be provided for steel elements. Some corrosion mitigation strategies that can be used with steel bridges are the use of corrosion-resistant steel, hot-dip galvanizing, zinc-rich primer paint systems, and thermal spray metalizing [172].

As it was discussed in Chapter 2, one of ABC systems that uses steel elements is the Folded Steel Plate Girder Bridge System (FSPGBS). Corrosion protection for this system is normally provided by hot dip galvanizing of the folded plate before casting of the concrete deck. This can provide for long service life at an economical cost. [24]

5.8.4.7. **Performance of fatigue cracks**

The action of repetitive tensile loads produces growth of cracks which is known as fatigue in steel structures. Existing discontinuities and tensile stresses normal to the discontinuities are the two conditions necessary for fatigue-crack growth [173]. According to de Jong (2004) over the last decades, several details in orthotropic steel bridge deck has shown to be prone to fatigue cracking. Four types of cracks can be categorized as cracks in the deck plate (Figure 5.40), cracks in the longitudinal weld between deck plate and longitudinal trough wall (Figure 5.41), cracks in the trough splice joint (Figure 5.42), and cracks in the connection between the trough profile and the crossbeam (Figure 5.43) [174].
Figure 5. 40 Deck Plate Crack [174].

Figure 5. 41 Cracks in the longitudinal weld trough-deck plate [174].
Figure 5. 42 Crack in the stiffener splice joint [174].

Figure 5. 43 Fatigue crack trough – cross beam connection [174].
5.8.5. **Performance related to Construction Methods**

Self-Propelled Modular Transporter (SPMT)- Using the ABC bridge performance results reported by Utah DOT, Garber and Shahrokhi (2019) stated that cracking was observed in these bridges erected using SPMT. However, it was concluded that it was caused by concrete shrinkage similar to those observed in bridges that had used conventional construction methods. Most of the bridges present a minor leakage and cracking, and cracking has worsened through the years but not enough to produce a major deterioration.

Lateral and Longitudinal Slide-in Bridge Moves- Garber and Shahrokhi (2019) also stated that thermal differential between the deck and end of diaphragms produced isolated diagonal cracking at the corners of the underside of the deck in several bridges due to a lack of expansion joints. Moreover, these bridges were reported to be generally performing well.

5.9. **Further performance research**

There has been limited investigations to monitor the performance of ABC bridges. ABC-UTC, through a collaborative effort among 5 partner universities, has embarked on a coordinated and extensive inspection program to inspect several ABC bridges in various states. The primary objective of this project is to collect much needed information on performance of in-service ABC bridges. This will help the designers and owners to avoid problematic details or seek means to improve the performance. The results will be compiled and published on ABC-UTC website and will become available to outside users and researchers.
CHAPTER 6. DECISION MAKING PROCESS

6.1. Abstract

Decision-making on the use of ABC in general and construction methods, type of elements, and systems in specific is essential for an effective project initiation, design, management and contractual aspects.

After a decision has been made to use ABC in construction of a new bridge or replacement/rehabilitation of an existing bridge, a decision as to what ABC technology is appropriate for a specific site needs to be taken. Several ABC technologies can be found to be technically appropriate at any site. This will mean that the project planners need to decide which technique fits better into a particular project for which multiple methods are identified. Moreover, further investigation for each option and major contributing factors will affect in the final decision. In some cases, however, one method of ABC will stand up as the most appropriate for a project site which will make the decision-making process somehow easier.

This module will introduce available decision-making methods applicable to ABC bridges in general that are particularly applicable also to short-span bridges. This includes decisions on the use of ABC as an alternative to conventional method, selection of construction method most applicable, and determination of type of elements and subsystems.

6.2. Decision making for a new bridge construction

A decision-making framework suitable to specifics of a project is recommended to be used during the project planning process to evaluate whether implementing ABC method or use of conventional methods in a project is beneficial. This report introduces several available decision-making processes among which one with the best applicability can be adopted. Awareness of agency managers about the short-term and long-term positive effects from ABC is important as the benefits far exceed the scope of actual construction [13]. Significant advantages of prefabricated bridge construction can be derived from a careful design, planning and implementation [175]. The main mission of the ABC and the use of prefabricated elements in the bridge construction is reducing the onsite construction time by performing the fabrication and erection the bridge elements offsite as much as possible. This approach can reduce the project cost due to offsite manufacturing, improve safety, and quality that leads to improving the long-term performance of the bridge. One great advantage of ABC method that normally is overlooked is reducing the onsite agency’s oversight and construction management activities and therefore significant saving in agency costs.

Severe traffic control issues at specific sites is one of the main reasons why ABC has often been used. Usually, urban routes follow this case where acute traffic can define the decision of using ABC technologies. For instance, cost impact to the projects, repercussions on travelers and surrounding communities, and loss of revenue due to decreasing traffic impacting businesses located adjacent to the project are only some of the consequences produced by the use of detours. However, avoiding the use of detours is not the only reason to pick ABC technologies. Most of the time, the assumption is that in rural paths traffic control is not going to be problematic. This ignores the fact that there may be no viable detours available to perform any type of work, and actual detours could add dozens of miles to the route [13].
Many parameters can affect the decision on adopting ABC methods over conventional construction. The Federal Highway Administration (FHWA) provides a decision-making process that is general and mostly in qualitative terms, but can help to identify in general terms whether implementing ABC method in a project is beneficial (Figure 6.1) [175]. The manual is divided into three different configurations. Each of the options can be used separately or together and consist of a flowchart, a matrix and a set of considerations [176]. The decision makers including the owners and contractors who are responsible for selecting the construction method should consider the flowchart and factors in utilizing the prefabricated elements in the construction of a bridge. These factors include applicability of design, the capabilities and qualification of contractor and supplier, accessibility to the job site, cost, schedule, and pace of the project. The other factors include responsibility and commitment of the contractor and owner and risk of the project. It should be noted that the owner prefers to complete the job with a minimum price and time with high quality and integrity. However, the contractor prefers to earn a reasonable profit from the project.

![Flowchart for High-Level decision on whether a prefabricated bridge should be used in a project](image)

*Figure 6.1 Flowchart for High-Level decision on whether a prefabricated bridge should be used in a project [175]*
The decision-making matrix developed by FHWA (Figure 6.2) consists of 21 relevant questions where the answers could be “yes”, “maybe”, or “no”. If the majority of answers are “yes” then the decision would be to choose Prefabricated Bridge Elements and Systems (PBES) for the construction. However, depending on the specifics of each project there are also cases where only one or two “yes” can warrant the use of FBES. In this matrix, more factors are examined that those in the flowchart, such as, impact on surrounding environment, impact on local businesses, and the nature of the bridge design. Therefore, this tool is considered to provide more detailed analysis than the flowchart.

![Figure 6.2 FHWA Decision Making Matrix [175]](image)

At the last step, the FHWA process includes a set of considerations in various categories that can be used for a more in-depth evaluation on the use of FBES. These considerations contain questions and detailed answers divided into three categories: rapid constructions, costs, and other factors, each subdivided into several subcategories.
6.3. **Decision Making Tools developed by different State DOTs.**

Some state Departments of Transportation (DOTs) and agencies provide their own decision-making flowchart to investigate the efficiency of implementing ABC in comparison with the conventional bridge construction. Several of these agencies have modified the FHWA flowchart to meet their own goals and concerns. Moreover, some of them also developed their own separate guidelines utilizing own experiences.

### 6.3.1. Utah DOT

Utah DOT has developed a new approach based on evaluating the project with measured responses considering main factors such as delay/detour time, average daily traffic, bridge classification, economy of scale, user costs, safety, use of typical details, and railroad impacts. These factors coincide with UDOT’s projects priority and are weighted against each other. To calculate the ABC rating, the factors are weighted, and the weighted measures are used for analysis. The results provide a direction on the use of ABC for the project. Projects scoring a high rating use ABC, and for the projects scoring a low rating ABC is not used. When results of the scores do not give one or the other method a clear advantage, then options are studied based on costs. For the case of any increase in cost due to ABC implementation then the costs are weighed against road user costs [13].

For the analysis, a worksheet (Figure 6.3) developed by UDOT is used where project’s scores are entered under each criterion and then ABC rating is calculated automatically. Depending on the rating score, the project is categorized in one of the three groups that can be seen in Figure 6.4. For project rating between 0 to 20, the decision on using ABC is at the discretion of the regional director. When the rating is from 20 to 50, then a variety of questions need to be answered. If the answer to one of the questions is “yes” then ABC can be chosen given the site conditions are favorable. Finally, when the ABC rating is above 50, then ABC should be used if site conditions would support using ABC.
ABC Decision Flowchart  June 2010

* Region Director or Project Development Director to evaluate possible indirect benefits.

Figure 6. 3 Utah Department of Transportation ABC Decision spreadsheet available from

Figure 6. 4 Utah Department of Transportation ABC Decision Flowchart available from
6.3.2. Oregon DOT

In collaboration with 7 other states DOTs, the Oregon DOT (ODOT) developed a decision-making tool accounting for characteristics such as complexity, project size, road user characteristics, construction site attributes and environmental requirements. Comparison of conventional construction with ABC is the purpose of this tool by assisting agencies with the decision-making process [13]. The approach of the decision making is based on the Analytical Hierarchy Process (AHP) where various alternative construction strategies can be evaluated by the decision maker when considering qualitative and quantitative criteria [177]. The method compares the relative importance of each factor with other factors by using pair-wise comparisons, both in numerical and verbal scale. The ABC AHP Decision tool was developed using Microsoft Visual Studio .NET as a stand-alone application and it was fully tested on currently-supported Windows versions (i.e. MS Windows XP, Vista, and Seven) [178].

Using this tool, the analysis starts at the highest level with five criteria. These criteria are schedule constraints, indirect cost, direct cost, site constraints, and customer service each of which is then specified by two to nine sub-criteria. Figure 6.5 shows the final criteria hierarchy [176].

6.3.3. Connecticut DOT

Connecticut DOT developed an ABC Design Decision matrix that should be used during the preliminary design phase. This tool can be used for all projects involving bridge deck replacement, entire bridge replacement, or superstructure replacement, and evaluates the suitability and application of ABC methodology. Moreover, at the discretion of Department management, other considerations may be identified in the matrix that can be significant in any individual project for decision making. Figures 6.6, 6.7, 6.8, and 6.9 represent the decision matrix developed by Connecticut DOT. The process is finalized with an ABC rating table after each parameter with relevant information of the construction have been considered [179].

The purpose of the ABC rating table is to compute a comparative rating for the ABC project methodology under evaluation. Project ABC methodology ratings of 60 to 100 are considered good candidates for ABC implementation. Project ABC ratings of 50 to 60 are considered marginal for ABC implementation. Project ABC ratings of less than 50 are not generally considered good candidates for ABC implementation [179]. A presentation by Connecticut DOT on decision making process describes this process in detail [https://abc-utc.fiu.edu/mc-events/connecticut-dots-abc-decision-process-methodology/](https://abc-utc.fiu.edu/mc-events/connecticut-dots-abc-decision-process-methodology/)
Figure 6.5 Final Decision Criteria Hierarchy [178]
CTDOT ABC Decision Making Process

Site Information

Project Description:

Prop. ABC Method:

Conventional Construction Method:

Roadway on Bridge

Average Daily Traffic: __________ vehicles per day

Conventional Construction

Delay Time (Per Delay Time Sheets) __________ minutes
Construction Impact Duration __________ Days
Aggregate Impact Time __________ Person Days

ABC

Delay Time (Per Delay Time Sheets) __________ minutes
Construction Impact Duration __________ Days
Aggregate Impact Time __________ Person Days

Roadway Below Bridge

Average Daily Traffic: __________ vehicles per day

Conventional Construction

Delay Time (Per Delay Time Sheets) __________ minutes
Construction Impact Duration __________ Days
Aggregate Impact Time __________ Person Days

ABC

Delay Time (Per Delay Time Sheets) __________ minutes
Construction Impact Duration __________ Days
Aggregate Impact Time __________ Person Days

Percent Reduction in Aggregate Impact Time

Conventional Construction
Total Aggregate Impact Time __________ Person Days

ABC
Total Aggregate Impact Time __________ Person Days

User Impact Reduction #DIV/0!

Note: Negative value indicated that ABC has more impact
Figure 6.6 Connecticut ABC Decision making table. Page 1 [179].

<table>
<thead>
<tr>
<th>Preliminary Cost Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated conventional construction project cost =</td>
</tr>
<tr>
<td>Required Bridge</td>
</tr>
<tr>
<td>Overbuild</td>
</tr>
<tr>
<td>Total conventional bridge cost</td>
</tr>
<tr>
<td>Estimated CE&amp;I Costs per month</td>
</tr>
<tr>
<td>Field office monthly cost</td>
</tr>
<tr>
<td>CE&amp;I staff monthly cost (field plus main office)</td>
</tr>
<tr>
<td>Total CE&amp;I Monthly Cost =</td>
</tr>
<tr>
<td>Notes: Small field office = $xxx per month</td>
</tr>
<tr>
<td>Medium office = $xxx per month</td>
</tr>
<tr>
<td>Large office = $xxx per month</td>
</tr>
<tr>
<td>Staff = $20,000 per person per month</td>
</tr>
<tr>
<td>Net time savings for ABC =</td>
</tr>
<tr>
<td>Estimated Percent Premium for ABC =</td>
</tr>
<tr>
<td>MPT savings with ABC</td>
</tr>
<tr>
<td>Things that you can eliminate from conventional construction by using ABC</td>
</tr>
<tr>
<td>Overbuild for staging</td>
</tr>
<tr>
<td>Temporary bridge</td>
</tr>
<tr>
<td>Temporary signal</td>
</tr>
<tr>
<td>Other</td>
</tr>
<tr>
<td>Total MPT Savings with ABC</td>
</tr>
</tbody>
</table>

Cost analysis

| Premium for ABC = | $0 |
| CEI Cost Savings = | $0 |
| MPT savings with ABC = | $0 |
| Net cost change for ABC = |
| ABC is less expensive than conventional |
| Net percentage of conventional cost = | #DIV/0! |

Figure 6.7 Connecticut ABC Decision making table. Page 2 [179].
### ABC Rating procedure

Enter values for each aspect of the project. Attach back-up data if applicable.

<table>
<thead>
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<th><strong>Average Daily Traffic</strong></th>
<th>0</th>
<th>No traffic impacts</th>
</tr>
</thead>
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<td>Combined traffic on and under</td>
<td>1</td>
<td>Less than 10000</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>10000 to 40000</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>40000 to 70000</td>
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<td></td>
<td>4</td>
<td>70000 to 100000</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>More than 100000</td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th><strong>User Impact Reduction</strong></th>
<th>#DIV/0!</th>
<th>0</th>
<th>Zero</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated by spreadsheet</td>
<td></td>
<td>1</td>
<td>1% to 20%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>21% to 40%</td>
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<tr>
<td></td>
<td></td>
<td>3</td>
<td>41% to 60%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>61% to 80%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>81% to 100%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Bridge Location</strong></th>
<th></th>
<th>0</th>
<th>Rural Bridge away from town center</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>Rural bridge near town center</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Suburban bridge away from town center</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Suburban bridge near major traffic generators</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>Urban Bridge near major traffic generators</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>Urban Bridge near emergency services</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Use of Typical Details</strong></th>
<th></th>
<th>1</th>
<th>Complex and unfavorable geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Curved and skewed bridges</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Curved bridges</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>Skewed Bridges</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>Simple geometry well suited for typical details</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Work Zone Geometry</strong></th>
<th></th>
<th>1</th>
<th>Short duration project with good geometry &amp; flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detour quality and/or MPT Quality</td>
<td></td>
<td>2</td>
<td>Short duration project with moderate geometry &amp; flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Average project duration with average geometry &amp; flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>Long duration project with moderate geometry &amp; flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>Long duration project with complex geometry &amp; flow</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Site Conditions</strong></th>
<th></th>
<th>0</th>
<th>Significant limitations on work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utilities/ROW/Env. Compliance</td>
<td></td>
<td>1</td>
<td>Moderate construction limitations for portions of the work</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Minor construction limitations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>No Restrictions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Railroad Impacts</strong></th>
<th></th>
<th>0</th>
<th>No Railroad (entry of 0 = not considered in score)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>Freight Siding (Less than 1 train per week)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Light Freight (1 Train per week to 1 Train per day)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Heavy Freight (More than 1 Train per day)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>Commuter rail</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>Electrified Commuter Rail</td>
</tr>
</tbody>
</table>

*Figure 6. 8 Connecticut ABC Decision making table. Page 3 [179].*
Figure 6. 9 Connecticut ABC Decision making table. Page 4 [179].
6.3.4. Wisconsin DOT

Wisconsin DOT (WisDOT) developed a guidance to help determining when to use ABC versus conventional construction, and which ABC methods are most practical for a project. These are summarized in the form of a matrix (Figure 6.10) and a flowchart (Figure 6.11). For a particular project, the decision-making flowchart is used to determine whether to use ABC or conventional method [180]. Disruption to traffic, urgency, user cost and delays, construction time, environment, cost, risk-management, economy of scale, weather, and the use of typical details are the main decision criteria that the matrix is based on [176]. When a score is obtained from the matrix, the project is further categorized into three different categories based on the value of the score. Entering with the score into the flowchart, the first option is if the score is more than 50, ABC should be used if site conditions support it. Then if the score is between 49 and 21, before deciding if ABC is suitable for the project or not, the decision maker has to further examine another set of questions. Finally, if the score is between 0 and 20, only if the project is a program initiative and the site conditions support ABC, the ABC should be used, otherwise conventional construction is used [176]. After the flowchart guides the user to choose an ABC approach for the project, it also helps in choosing the best ABC method by selecting one of two options; minimizing bridge out-of-service time or minimizing the total construction time [176]. If the site conditions support either option, then slide, SPMT, PBES or GRS-IBS are the available options as construction method. If conditions are not met, then the decision maker should consider another ABC alternative [176].

![Figure 6.10 Decision Making Matrix](image-url)[180]
Figure 6. 11 ABC Decision Making Flowchart [180]
6.3.5. Minnesota DOT

In order to implement accelerated bridge construction (ABC) methodologies in Minnesota, State DOT developed a three-stage process to provide a rational, objective, consistent, and defensible method of selecting appropriate method for projects. This helps determining which bridges are best suited for ABC. They stated that the three-stage process should be used as a tool to evaluate the suitability of ABC but should not be viewed as an absolute control in decision making. Other considerations not incorporated in the process may be significant in decision making for any individual project [181]

6.3.5.1. Stage 1

An initial screening and ABC rating is based on a set of quantifiable, and objective measures that includes: Average annual daily traffic (on and under the bridge), User costs (in the form of daily vehicle operating costs), Heavy commercial average annual daily traffic (on and under the bridge), Traffic density measured as (vehicles per day) divided by roadway width on the bridge, and Detour length [181]. Culverts, railroad, and pedestrian bridges are excluded from the evaluation. an overall weighted score is formed from the summary of the criteria and is normalized to a recommendation of “Yes” or “No” regarding further consideration of ABC. “Yes” outcome should be evaluated in Stage 2, “No” should be evaluated in Stage 2 if requested by the District [181]. Figure 6.12 shows an example of Stage 1 form.

6.3.5.2. Stage 2

In this stage the Project Manager can consider issues that are much more subjective and site-specific than those in Stage 1. Similarly, as accelerated construction techniques and methodologies often involve lane or road closures, traffic detours, and extended work hours, there are compromises and trade-offs inherent to specific projects. Therefore, to complete the Stage 2 evaluation (Figure 6.13, 6.14), close coordination with the Construction Resident Engineer, District Traffic Engineer, and District Bridge Engineer is required [181]

For Stage 2, an answer of “Yes”, “No”, “Possibly”, or “Not Applicable (N/A)” is documented. ABC techniques may provide a viable solution when more questions are answered with “Yes” or “Possibly”. Also, identification of which ABC techniques and/or alternative contracting methods may be the most appropriate can be assessed from Stage 2 [181].

6.3.5.3. Stage 3

Identification of a technique or contract administration method, final construction method or a combination of these methods is the goal of Stage 3 process (Figure 6.15). If Stage 2 evaluation indicates that further consideration of ABC is warranted, the Project Manager will select appropriate ABC alternatives and techniques and discuss project specific details with the Bridge Final Design Unit, Bridge Office Preliminary Plans Unit, Regional Bridge Construction Engineer, and other specialty disciplines [181].

205
**Stage 1 - Selection of Accelerated Bridge Construction Projects**
MnDOT Decision Making Tool (DMT) V9 07/22/2013

Score computed using Bridge Management Data (5 Criteria):

### Daily Vehicle Operating Costs - Dependent on Bridge Length

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Score</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.0%</td>
<td>0</td>
<td>No user costs</td>
</tr>
<tr>
<td>16.7%</td>
<td>1</td>
<td>Less than $4,150</td>
</tr>
<tr>
<td>16.9%</td>
<td>2</td>
<td>$4,150 to $9,250</td>
</tr>
<tr>
<td>16.8%</td>
<td>3</td>
<td>$9,251 to $18,100</td>
</tr>
<tr>
<td>16.9%</td>
<td>4</td>
<td>$18,101 to $44,000</td>
</tr>
<tr>
<td>16.7%</td>
<td>5</td>
<td>More than $44,000</td>
</tr>
</tbody>
</table>

**User Cost Formula** = (AADT x $0.31/mile + HCAADT x $0.64/mile) x Detour Length x Br Length Factor

### Average Annual Daily Traffic (AADT)

Combined “On and Under” Bridge

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Score</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.2%</td>
<td>0</td>
<td>Less than 2,400</td>
</tr>
<tr>
<td>16.7%</td>
<td>1</td>
<td>2,401 to 6,650</td>
</tr>
<tr>
<td>16.9%</td>
<td>2</td>
<td>6,651 to 13,500</td>
</tr>
<tr>
<td>16.7%</td>
<td>3</td>
<td>13,501 to 31,000</td>
</tr>
<tr>
<td>16.7%</td>
<td>4</td>
<td>31,001 to 75,000</td>
</tr>
<tr>
<td>16.9%</td>
<td>5</td>
<td>More than 75,000</td>
</tr>
</tbody>
</table>

### Heavy Commercial Average Annual Daily Traffic (HCAADT)

Combined “On and Under” Bridge

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Score</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.0%</td>
<td>0</td>
<td>Less than 165</td>
</tr>
<tr>
<td>16.7%</td>
<td>1</td>
<td>166 to 485</td>
</tr>
<tr>
<td>16.7%</td>
<td>2</td>
<td>486 to 1,085</td>
</tr>
<tr>
<td>16.9%</td>
<td>3</td>
<td>1,086 to 1,950</td>
</tr>
<tr>
<td>16.7%</td>
<td>4</td>
<td>1,951 to 3,750</td>
</tr>
<tr>
<td>16.9%</td>
<td>5</td>
<td>More than 3,750</td>
</tr>
</tbody>
</table>

### Detour Length

Detour Length on Similar Functional Class Rdwy

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Score</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.9%</td>
<td>0</td>
<td>No Detour</td>
</tr>
<tr>
<td>9.8%</td>
<td>1</td>
<td>Less than 1 mile</td>
</tr>
<tr>
<td>24.2%</td>
<td>2</td>
<td>1-2 miles</td>
</tr>
<tr>
<td>17.9%</td>
<td>3</td>
<td>2-7 miles</td>
</tr>
<tr>
<td>16.2%</td>
<td>4</td>
<td>7-14 miles</td>
</tr>
<tr>
<td>15.9%</td>
<td>5</td>
<td>More than 14 miles</td>
</tr>
</tbody>
</table>

### Traffic Density

AADT “On” Bridge

Vehicles per Day/Ft of Bridge Roadway Width

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Score</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.0%</td>
<td>0</td>
<td>Less than 35</td>
</tr>
<tr>
<td>16.7%</td>
<td>1</td>
<td>36-78</td>
</tr>
<tr>
<td>16.9%</td>
<td>2</td>
<td>79-138</td>
</tr>
<tr>
<td>16.9%</td>
<td>3</td>
<td>139-240</td>
</tr>
<tr>
<td>16.7%</td>
<td>4</td>
<td>241-470</td>
</tr>
<tr>
<td>16.7%</td>
<td>5</td>
<td>More than 470</td>
</tr>
</tbody>
</table>

**Scores normalized to 100 point maximum. Bridges with score ≥ 60 selected for Stage 2.**

Figure 6. 12 Example of Stage 1 form [181]
Stage 2 - Selection of Accelerated Bridge Construction Projects

Appropriately selected ABC alternatives can substantially reduce construction time, impacts to users, and improve safety. Alternatives should be considered very early in the scoping process (concurrent with the Bridge Scoping Worksheet) to allow for potential adjustments in letting date, project schedule, funding, design duration, and time needed for pre-fabrication of bridge elements.

This tool should be used during the scoping process to determine whether the following bridge related issues are present or should be considered during project development. The more questions that have “Yes” or “Possibly” as answers, the more likely that accelerated bridge construction (ABC) techniques may provide a viable solution.

This tool should be filled out and recorded by the District Project Manager, with assistance from the District Bridge Engineer, Traffic Engineer, Resident Engineer, and the Bridge Preliminary Plans Unit and Regional Bridge Construction Engineer. Refer to pages 3-6 of this document for additional instructions and guidance.

Prepared By: ______________ Date: __________ District: __________
Additional Assistance Provided By: ___________________

Project Information:

<table>
<thead>
<tr>
<th>Bridge No.</th>
<th>TH:</th>
<th>Let Date:</th>
<th>ADT On:</th>
<th>ADT Under:</th>
</tr>
</thead>
</table>

Project Description (work type, major roadway work also required?, anticipated duration):

<table>
<thead>
<tr>
<th>Question/Issue</th>
<th>Yes</th>
<th>No</th>
<th>Poss</th>
<th>N/A</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Is it likely that this project will include complex traffic control schemes, long detours, or significant user impacts due to bridge construction?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Is it likely that this project will have an extended duration (more than one construction season, or extend into late fall) due to bridge construction?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Is bridge construction on the critical path of this project?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Are there any issues regarding construction timeframes (e.g., fish spawning, bird nesting, high water, permits, major events)?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Are there critical features or services on the route that need to be considered (e.g., hospital, emergency services, transit, school buses)?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Could additional width be needed on culverts, bridges, or shoulders to maintain traffic on the existing route or the detour route?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Does the existing bridge have features that make it difficult to accommodate staging (truss bridge, slab span, beam spacing issues, etc.)?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Is it likely that temporary bridge structures will be needed?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Could there be a need to maintain railroad traffic?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6. 13 Example of stage 2 form, page 1 [181]
<table>
<thead>
<tr>
<th>Question/Issue</th>
<th>Yes</th>
<th>No</th>
<th>Pass</th>
<th>N/A</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>10. Might temporary traffic signals be required?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. Does it appear that maintenance of traffic will require additional right-of-way?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. Will/Can traffic be detoured?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- a. Will the detour route have a detrimental impact on emergency vehicles, school buses, or other sensitive traffic?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- b. Is the local alternate detour route in questionable condition?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- c. Are there load limit restrictions on the detour?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- d. Are there bridge width or height restrictions on the detour?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- e. Are there issues regarding suitability of detour route (length, speed limit, travel time, etc.)?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- f. Are modifications needed at intersections on detour/alternate routes?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13. Are there geotechnical (poor soils, contaminated material, etc.) or utility issues that may affect construction?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14. Could construction impact businesses?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15. Are there significant risks or other factors (site complexity) that could be mitigated by accelerating bridge construction?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Additional Considerations:**
In addition to the issues listed above, consideration should also be given to staging construction ½ at-a-time, “packaging” additional bridges in the vicinity, and acknowledgment of other planned construction work in the area. Also, alternative contracting methods such as design build, CMGC, incentive/disincentive, A+B, etc., or traffic control alternatives such as lane rental should be considered in mitigating traffic impacts.

**Conclusion:**
Based on the findings & conclusions above, further consideration of accelerated bridge construction is warranted:

- YES   NO   Project Manager Name: ___________________________  Date: __________

Comments:

---

**Please send a copy of pages 1 & 2 of this completed form to the Bridge Preliminary Plans Unit at MS 610**

*If further consideration is warranted the Project Manager should contact the Bridge Office Preliminary Plans Unit and the Regional Bridge Construction Engineer for assistance in selecting appropriate ABC alternatives and techniques.*

*Figure 6. 14 Example of stage 2 form, page 2 [181]*
Stage 3 - Selection of Accelerated Bridge Construction Projects

District Project Manager shall coordinate with Bridge Pre-Design, Regional Bridge Construction Engineer to develop alternatives to find the best fit.

- Comparison of alternatives – best fit
- Advantages/Disadvantages of each alternative
- Cost estimates
- Consider use of Oregon DOT AHP ABC decision making tool
- Select final alternative - do the benefits outweigh the costs?

Record the final decision

Contracting Alternatives
A+B
Lane Rental
Incentive/Disincentive
Off Peak Scheduling
Design Build
Construction Manager General Contractor (CMGC)

Structure / Element Alternatives
Full depth deck panels
Inverted Tee beams
Precast superstructure
Precast substructure
Piers / pier caps
Abutments
Wing walls
Lateral slide
Self-propelled modular transporters (SPMT)
Heavy lift
Longitudinal launch
Geosynthetic reinforced soil (GRS) abutments

Figure 6. 15 Example of stage 3 form [181]

6.3.6. Iowa DOT

In order to reach a decision of whether to implement ABC or use conventional method, Iowa DOT developed a two-stage decision-making process. The process starts with an ABC score for the project, then using a decision flowchart and the Oregon DOT AHP ABC decision making tool (described above), the project enters a two-stage filtering phase (Figure 6.16) [176].

First, an ABC rating for the project is developed similar to the UDOT method (described above) based on four decision criteria as out of distance travel, average annual daily traffic, economy of scale, and daily road user cost. Then, based on its rating score, the project can be led into two different criteria. As it is shown in Figure 6.17, if the project’s score is less than 50, the project will be assessed at the request of the district. If the project’s score is between 50 and 100, and site conditions and project delivery support ABC, then the second decision-making phase is used [176].
Finally, further analysis of the projects using ODOT AHP tool which was discussed previously is considered in the second stage. After passing the two-stage filtering process of ABC alternatives as well as the traditional construction method evaluated against ABC, the advisory team will have to determine the required tier of acceleration (directly related to the length of reduction in construction time) based on the project’s impact on traffic, obtaining the bureau director approval, developing the concept, recommending an ABC option, and estimating the project costs [176].

Figure 6. 16 Iowa DOT ABC Decision Making Process
6.3.7. Colorado DOT

Both qualitative and quantitative decision-making tools are used in Colorado DOT (CDOT) for the ABC decision making process in whether to utilize ABC or not, and to determine which ABC method to be used (Far and Chomsrimake, 2013). As seen in Figure 6.18 the CDOT decision-making procedure is a multi-step process. First, an ABC rating for the project is developed similar to the UDOT method based on delay/detour time, average daily traffic, bridge classification, economy of scale, user costs, safety, site conditions, and railroad impacts. Then, based on the score, it is categorized into three options that leads to a flowchart similar to the UDOT (described above) with minor differences (Figure 6.18).

If the score is between 0 and 20, then the decision to use ABC is up to the regional director. If the score is between 20 and 50, the decision maker examines a set of questions before deciding if ABC is suitable for the project. Finally, if the score is above 50, the condition will lead to selecting ABC method if it leads to a lower project cost [176]. When the result points to the use of ABC, two tools
are used to determine which ABC method needs to be used. Figure 6.20 is an example of an ABC Construction matrix that based on complexity of the project can provide suggestions on different methods. After narrowing the options, the AHP from ODOT can be used to select the best ABC construction method [176].

![Diagram](image)

*Figure 6. 18 Colorado CDOT ABC Decision Workflow [182]*

![Diagram](image)

*Figure 6. 19 Colorado CDOT ABC Decision Flowchart [182]*
6.3.8. Washington DOT

Similar to the matrix developed by FHWA a qualitative framework is used by Washington State DOT (WSDOT) to assist in its ABC decision-making process. Figure 6.21 is an example of the Decision-Making matrix used by WSDOT where each item can be answered by “yes”, “no”, or “maybe.” If the majority of answer are “yes,” then the project under consideration will be a good ABC candidate (WSDOT 2009).

<table>
<thead>
<tr>
<th>Substructure</th>
<th>Approach, Embankment &amp;</th>
<th>Superstructure</th>
<th>Super Structure placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-fabricated pier cap</td>
<td>Pre-fabricated pier cap</td>
<td>Pre-fabricated pier cap</td>
<td>Pre-fabricated pier cap</td>
</tr>
<tr>
<td>Pre-fabricated columns</td>
<td>Pre-fabricated columns</td>
<td>Pre-fabricated columns</td>
<td>Pre-fabricated columns</td>
</tr>
<tr>
<td>Pre-fabricated foundations</td>
<td>Pre-fabricated foundations</td>
<td>Pre-fabricated foundations</td>
<td>Pre-fabricated foundations</td>
</tr>
<tr>
<td>Pre-fabricated wingwalls/backwalls</td>
<td>Pre-fabricated wingwalls/backwalls</td>
<td>Pre-fabricated wingwalls/backwalls</td>
<td>Pre-fabricated wingwalls/backwalls</td>
</tr>
<tr>
<td>Continuous Flight Auger Piles (CFA)</td>
<td>Continuous Flight Auger Piles (CFA)</td>
<td>Continuous Flight Auger Piles (CFA)</td>
<td>Continuous Flight Auger Piles (CFA)</td>
</tr>
</tbody>
</table>

**Figure 6.21 Washington DOT ABC Decision Making Matrix [183]**
6.4. **Major Parameters Affecting selection of ABC bridge elements and systems in general**

After decision is made for the use of ABC method instead of conventional construction method employing one of the methods described above, follow-up decisions need to be made on the type of construction method and the types of elements and systems for the bridge.

The case of a new bridge construction affords the designer the freedom to select the most appropriate ABC system for implementation. Based on review of work by others, Mehrabi et al. [184] identified some major parameters that affect not only the decision making for the construction method, but also provide constraints or facilitate selection of details at system and element level. Common factors to be considered in the selection of new ABC Bridge components are shown in Figure 6.22 as described below. This section is adopted directly from work by Mehrabi et al. [184] also available on ABC-UTC website at https://abc-utc.fiu.edu/research-projects/fiu-research-projects/development-of-guide-for-selection-of-substructure-for-abc-projects/

**6.4.1. Time Constraint**

The main reason for using ABC technique in construction of bridges is reducing the on-site time of the construction. However, not all projects have the same level of time constraint, and not all ABC methods can accommodate every time constraint. ABC construction method, and type of prefabricated elements and subsystems can be selected to accommodate the time constraint. It should be noted that the time constrains can be pronounced by other factors such as traffic mobility, weather conditions, bridge site conditions, and environmental conditions [184].

**6.4.2. Risk and Cost of the project**

Transporting the precast bridge components may drive the cost of bridge construction up. Also, transporting the elements and bridge modules into the site may cause damage to the components, pose safety concerns, and may need special shipping method that can increase the risk to the project. There are also risks involved in lifting, moving, and installation of prefabricated elements and systems. Such risks should be evaluated and compared among various ABC methods, and between ABC methods and conventional and cast-in-place construction. The consequences of these risks can increase the cost of the project. As an example, if higher risks exist for long distance hauling and transportation, fabricating the precast components near the bridge location may be preferable. In the same manner, if risks are high for transportation and the site conditions would not allow near-site fabrication, a conventional cast-in-place method may be more advantageous. Another major parameter that can affect the risk and cost involved in ABC projects relates to availability of contractors and their capabilities. It is sometimes the case that local contractors, who have cost advantages for being local, may not have qualification, equipment and skills necessary for implementation of a certain ABC method. Also, availability and proximity to the bridge site for precast plants capable of prefabricating the bridge elements may have significant effect on both costs and risks [184].

**6.4.3. Environmental considerations**

In addition to the other considerations, construction impacts on the environment needs to be considered. Activities in water, as an example, may have a significant impact on the overall project schedule in order to alleviate the negative environmental effects. Because of this, construction may be restricted to a certain time of the year and construction methods could be restricted to those
causing the least harm to the environment. The effect of pile driving on sea fishery and mammals may pose major restrictions and risks to the project [184].

6.4.4. Geometric Considerations

Geometric considerations include the bridge span, width, right of way alignment, elevation, and connections to existing roads on both sides of the bridge. As mentioned, bridge span or girder spacing is normally selected based on the shipping considerations. Once the prefabricated modular systems and bridge elements are fabricated near the site, it is possible to increase the girder spacing over 130 ft. For bridge span up to 130 ft., the pre-tensioning method without the post-tensioning method is used in the site. Once the bridge span is over 130 ft., the post-tensioning technique needs to be used to extend the bridge span length [185]. In the case of substructure elements, when the weight of elements and their shipping is in concern, using element segments and connecting them on the site is the option [184].

6.4.5. Site Condition and Accessibility

In addition to the geometric and structural requirements that come to play in conventional bridge design, additional consideration must be given to the space needed to manufacture large parts of the bridge nearby the site and the space necessary to maneuver such large elements to their final position. Site considerations also include the specifics of the bridge site, such as local space available for erection and assembly of the bridge components, presence of deep water or rapid currents, adjacent property use and setbacks, width and vertical clearance of roads leading to the project site. If water navigation is used to transport bridge elements, the width and depth of water in the area are important site conditions. It also includes human activities, driving habits, and availability of alternative transportation facility in the area. Such factors impact the space available for the project and may favor specific construction types. For instance, the existence of steep slopes may limit the feasibility of transportation of large bridge segments or may require special equipment to allow bridge transportation and erection. When there is a limitation in site accessibility, using the systems with smaller sizes elements are preferable [184].

6.4.6. Design Constraints and Considerations

In the case of new bridge construction, the design considerations include the number of spans, span length, type of support, type of bridge structure, connection type, seismicity of the bridge location, foundation, and layout of bridge roadway connection with other roads. In some instances, for example, implementing a joint less bridge design, full moment connection between bridge members, integral abutments or similar considerations can provide higher integrity and durability for the bridge when compared to other designs [184].

6.4.7. Compatibility between Superstructure and Substructure, and between Substructure and Foundation

In addition to geometric compatibility, the bridge elements and units are expected to be compatible in design and construction with each other. For instance, the performance anticipated for connection between super- and substructure may favor or limit the use of one or another type of substructure [184].
Substructure, superstructure, and foundation must be compatible in design, geometry, material and construction method. Planning and design of bridge segments cannot be performed independently and should take into consideration their compatibility. The substructure in fact seems to have to be strongly dependent on the superstructure that is in direct contact with imposed loading, and also on the foundation that transfers the load to the ground. It is the understanding of the authors that substructure has to be selected such that it accommodates and adapts to the needs and conditions of superstructure and foundation as a link system. In the next sections, it is attempted to describe the selection criteria for type and method of construction for superstructure and foundation, and to see how these will affect the selection of the substructure systems and components [184].

6.5. **Determination of appropriate ABC methods and type of superstructure**

A study conducted by FHWA investigated the consideration of the site accessibility constraints for the applicability of different ABC methods [13]. Viable ABC methods are given by the characteristics of each bridge site as it is in construction of a bridge over roadways or land (Figure 6.23), over railroad or transit (Figure 6.24), and over water or wetland (Figure 6.25) in order to determine the proper construction method. By running through the flowcharts with the available site constraints the most appropriate ABC methods can be determined. Moreover, multiple ABC methods might be acceptable for the same site [13]. As described in previous sections, some State DOT processes for whether ABC is viable alternative to conventional construction method also included follow-up decision-making tool for determining the type of ABC construction method. In any case, the available methods for determining the construction method for ABC follow in general the same criteria and overall decision-making process. This section on selection of construction methods and type of superstructure is adopted directly from work by Mehrabi et al. [184] also available on ABC-UTC website at [https://abc-utc.fiu.edu/research-projects/fiu-research-projects/development-of-guide-for-selection-of-substructure-for-abc-projects/](https://abc-utc.fiu.edu/research-projects/fiu-research-projects/development-of-guide-for-selection-of-substructure-for-abc-projects/)

As shown in Figures 6.23, 6.24, and 6.35, the significant factor in selecting the best ABC method is the accessibility to the project site. In the construction of bridge and superstructure over roadways or land, the availability of a clear travel path is necessary to use the SPMT method. In this method, to reduce the axle’s loads to the allowable load, the SPMT should be adjusted by adding axles. In this case, lane closure, clearance height, and an available detour also should be considered. However, when a space directly adjacent to the bridge is available for the erection of
bridge superstructure, the lateral skidding is a viable construction method. When the adjacent space and clear travel path is not available, the construction-in-site using prefabricated elements and lifting devices is viable. It should be noted that construction using prefabricated elements is a feasible method for all three site conditions [175]. When the bridge is crossing a body of water, it can provide an obstacle or opportunity to use ABC methods [180]. In this situation, the prefabricated elements may be delivered to the site using barges if navigation constraints allow.

In construction over the railroad or transit, the railroad same as water crossing can provide obstacle or opportunity in the bridge construction [175]. It might be possible that heavier bridge components are transferred using the railroad. However, the clearance height and closure period should be considered. Another potential factor is geotechnical constraints relating to the stability, settlement, and capacity of the soil. When a crane is used at the site that normally is accompanied with heavy concentrated load, its effect on the settlement and capacity of soil needs to be considered as well [184].

![Decision Flowchart for Superstructure Construction over Roadway or Land](image)

*Figure 6. 23 Decision Flowchart for Superstructure Construction over Roadway or Land [13]*
Figure 6. 24 Decision Flowchart for Superstructure Construction over Railroad or Transit [13]
Figure 6. 25 Decision Flowchart for Superstructure Construction over Water or Wetlands [13]

6.5.1. Considerations for superstructure system and elements selection

There are different viable systems available to be considered as superstructure for the ABC projects. However, each system has its own advantages and disadvantages. Therefore, a superstructure system should be selected in such a way to meet the project goals, provide higher safety, and be constructed in minimum time. Also, a value analysis is needed to select the best economic system [186], [187]. The factors that should be considered in the selection of each superstructure system is summarized in Table 6.1 provides alternatives for superstructure element types and related considerations [184].
<table>
<thead>
<tr>
<th>Superstructure system</th>
<th>Comments</th>
</tr>
</thead>
</table>
| Precast concrete girder with separate partial-depth precast  | - Lighter sections make the shipping easier or longer spans can be used.  
| deck deck                                                     | - Camber control is difficult.  
|                                                              | - Accommodates more variable geometry.  
|                                                              | - Cast-in-place top part of deck can provide a smooth riding surface.  
|                                                              | - The cast-in-place top part of deck needs additional construction time.  
|                                                              | - Longer time needed to open the bridge to traffic after construction due to curing time for deck.                                                                                                                                                                               |
| Precast (full depth) decked concrete girder                   | - Decked slab girder is normally shallow and suitable for short spans  
|                                                              | - The girder lengths in decked girder could be limited by ultimate strength of the top of slab concrete and live-load deflection  
|                                                              | - The decked U-girder is a shallow and efficient, suitable for short- to medium-length spans of up to 144 feet.  
|                                                              | - The decked BT (bulb-tee) girder was developed to extend the span capability for standard decked sections.  
|                                                              | - The maximum span capability of decked BT girder when using live-load continuity for multi-span bridges is 195-feet.  
|                                                              | - Difficulties in accommodating transverse slope.                                                                                                                                                                                                                           |
| Precast concrete girder with separate full-depth precast     | - Lighter girder sections make the shipping easier or longer spans can be used.  
| deck deck                                                     | - Camber control is difficult.  
|                                                              | - Accommodates more variable geometry.  
|                                                              | - Need additional time to place the deck.  
|                                                              | - Need additional access for deck placement.  
|                                                              | - Require additional depth and material for the girder top flange and haunch.                                                                                                                                                                                             |
| Precast concrete girder with full cast-in-place deck          | - Accommodate more variation in geometry  
|                                                              | - Require additional time to form and case the deck.                                                                                                                                                                                                                       |
| **Steel girder with full-depth precast deck** | -Lighter girder sections make the shipping easier or longer spans can be used.  
-Camber control is difficult.  
-Smaller fabrication tolerances are needed.  
-Require deeper sections.  
-Availability of wide-flange sections may be an issue.  
-Requires close coordination between steel girder and concrete deck suppliers.  
-Horizontal shear design at the interface is critical.  
-Except for box girder, at least two girders are normally needed for each precast deck, affecting the section efficiency.  
-Normally, longer delivery time should be considered.  
-Steel sections are lighter compared to equivalent precast concrete. |
| **Steel girder with partial precast deck** | -Lighter sections make the shipping easier or longer spans can be used.  
-Accommodates complex geometry.  
-Smaller fabrication tolerances are needed. |
| **Pre-decked steel girder including folded plate decked steel girder** | -Lighter sections compared with pre-decked concrete girders make the shipping easier or longer spans can be used.  
-Coordination between deck and girder fabricator is needed.  
- Girders require additional step of painting or galvanizing  
- Additional work needed to accommodate complex geometry.  
- Difficulties in accommodating transverse slope. |
| **Steel girder with full cast-in-place deck** | -Better accommodates different and complex geometries.  
-More diaphragms/cross frames are needed in comparison with the precast deck.  
-Longer construction time is needed for forming and casting the deck. |
| Modular pre-topped concrete girder | -Accelerate the bridge construction  
-Improve durability and easier inspection  
-40 to 90 ft. span range |
|-----------------------------------|--------------------------------------------------|
| Precast I girder                  | -50 to 150 ft. plus span range  
-Six AASHTO PCI standard sections can be used. Other standard sections are also available. |
| Precast bulb tee girder           | -Increased efficiency in comparison to I shaped girder  
-Wide top flange increase stability for handling and shipping  
-Standard AASHTO PCI BT shapes should be used |
| Precast box beam                  | -Good for short to medium span range, 20 to 127 ft.  
-Adjusted box beams are connected using partial or full-depth grouted shear key connection |
| Full-width/Partial-width superstructure systems | -Depends on availability of space near the bridge site, transportation capabilities and construction/installation methods discussed in Section 3-2.  
- Depending on availability of nearby space, the superstructure system can be slid laterally or longitudinally in place or lifted by crane.  
-May range from a narrow transverse strip of bridge to the entire span.  
- Can also include miscellaneous elements such as railing.  
- May contain integral substructure elements. |

### 6.5.2. Suitability of Substructure Types with Respect to Superstructure and Bridge Configuration

Suitability can be defined as having the structural load bearing capacity and at the same being compatible. Compatibility refers to geometric and design consistency. For example, for the substructure to be suitable for receiving the superstructure, it has to have adequate structural load bearing capacity to transfer the loads from superstructure to the foundation. At the same time, the substructure must be able to accommodate the superstructure geometry by width, height and alignment. For example, the width of superstructure, at the minimum by its bearing footprint, shall be enveloped by the substructure. Furthermore, the substructure design and detailing shall accommodate as designed connection to superstructure. For example, if the superstructure design prescribes an integral abutment or pier connection, the substructure shall be able to provide for the establishment of such connection in its detail. If any suitability requirements is not satisfied by the current condition of the substructure, modifications, rehabilitation, and/or retrofitting shall be
performed on the substructure to make it suitable for superstructure. Another way to provide for suitability is to revise the design of the superstructure to be able to make it suitable for the existing substructure (e.g., use lighter deck elements). The decision on which of the two approaches are chosen to provide for suitability should be made with economical (time-cost) and structural considerations [184]. Flowchart in Figure 6.26 shows the process with which the substructure suitability can be checked against the superstructure [184].

![Flowchart of Substructure Suitability](image)

*Figure 6.26 Factors effecting in the selection of existing bridge components [184].*

### 6.6 Available Selection and Design Considerations for Substructure

The FHWA report also provides a general decision flowchart for construction of substructure for ABC projects (Figure 6.27) [13]. The use of this chart is mostly for replacement of existing bridges and less usable for the new bridge construction. This section on selection of substructure is adopted directly from work by Mehrabi et al. [184] also available on ABC-UTC website at [https://abc-utc.fiu.edu/research-projects/](https://abc-utc.fiu.edu/research-projects(fiure-projects/development-of-guide-for-selection-of-substructure-for-abc-projects/)

Some stakeholders have questioned the need for using ABC for constructing substructure for new bridges arguing that the time is not a constraint in this case. However, there are many factors involved in construction that may turn the tide to the benefit of ABC for substructure. Construction of bridge substructure in conventional manner takes most of the bridge construction time. To reduce construction time, the use of prefabricated elements and modular systems are beneficial and very effective. The prefabricated elements and modular systems are normally built in the shop or near the site and assembled at the site. In addition to time saving, this provides for better quality, safety, and control on project schedule and cost. The substructure can be placed over deep or shallow foundation according to the soil and site conditions [185].

The use of modular abutment that can accommodate a joint-free and maintenance-free substructure element is preferable when targeting to reduce the construction time. The modular abutment can be designed and constructed integrally or semi-integrally with the superstructure. In that point, the
use of integral abutment is preferable for providing joint-free riding surface at abutment and full moment connection between substructure elements that can emulate the cast-in-place construction [185]. Another factor should be considered in the construction of substructure over the water is the water activity. Water activity timing and navigation restrictions may affect the design, construction method, and selection of type of the substructure [184].

Figure 6. 27 Decision flowchart for substructure construction [13]
6.6.1. Selection of Substructure Elements and Systems

The type of substructure elements and systems depends on: a) parameters affecting selection of ABC methods and elements in general as described in Figure 6.22, b) compatibility of substructure with superstructure and foundation, and c) parameters specific to the substructure (Figure 6.28).

![Figure 6.28 Bridge substructure element selection parameters [184].](image)

6.6.2. Parameters affecting the selection of bridge elements and construction methods in general

As discussed in the previous section related to selection of construction methods and superstructure element and system type, a set of general parameters discussed influence the selection process with accessibility and availability of space having the major impact. Apparently, these parameters will affect in the same way the selection of substructure as well. For example, if there is no accessibility to transport large systems to the site, individual elements installed by conventional crane have to be used also for the substructure, the same way as for the superstructure. Therefore, for the substructure, the type of elements and methods selected for superstructure should be followed in general. Accordingly, there is no need to repeat the selection process for substructure as far as general parameters are concerned. In the same manner, this also applies to the construction method to be used for substructure, and the size of elements or subsystems. Beyond these preliminary decisions that will follow those of the superstructure, following describes the specifics on substructure in accordance with compatibility with superstructure and foundation, as well as parameters specific to substructure [184].

6.6.2.1. Compatibility of Substructure with Superstructure and Bridge Configuration

In addition to geometric compatibility, the bridge elements and units are expected to be compatible in design and construction with each other. For instance, the performance anticipated for connection between super- and substructure may favor or limit the use of one or another type of substructure. For fully-integral, semi-integral, or siding connection with the superstructure, the abutment or pier cap shall accommodate the transfer of moment and shear as per design and therefore these conditions will become defining parameters for the type of the pier or abutment [184].

6.6.2.2. Compatibility of Substructure with Foundation

Substructure is a component of the bridge that connects the superstructure to foundation. Therefore, the compatibility of substructure with superstructure as well as foundation in design and construction is necessary for integrity and unity of bridge. For instance, the seismic condition
of soil may constrain the use of some types of connections between foundation and substructure, causing limitation in selection of substructure element, design, and construction type [184].

6.6.3. Parameters Specific to Substructure

There are some factors that may only affect the selection of substructure. One of them is exposure of substructure to water, salt, or splash. In this case, special considerations should be considered to select the materials and elements of the bridge substructure that provide for more durability in the related harsh and corrosive environment. Additionally, in some cases the bridge substructure may be impacted by vehicles for the case of bridge over roadway, or in the case of bridge across waterways by debris and vessels. This may result in the use of protective elements around the piers or the use of pier wall in the substructure [184].

6.6.4. Selection of Substructure based on Compatibility with Superstructure and Substructure-specific Parameters

In this section, a flowchart for selection of substructure for ABC projects is developed based on the superstructure system and ABC method considering interrelations and other parameters involved. Similar to the selection of ABC method flowcharts, the substructure selection can be divided into three flowcharts based on the construction of a bridge over roads (Figure 6.23), over railroads (Figure 6.24), and over wetlands (Figure 6.25). By use of these flowcharts, it is possible to define the ABC method and subsequently identify the superstructure systems. It should be noted that the use of prefabricated elements is viable for all types of ABC methods. Nevertheless, prioritization for the use of ABC method should be applied based on all factors involved in selection process including but not limited to cost, safety, quality, and onsite construction time. Consequently, the substructure system can be selected according to the ABC method and the parameters listed in the previous section. A flowchart that can be used to select the substructure types and components is shown in Figure 6.29. As shown in this flowchart, the substructure includes pier and abutment system, buried bridges and modular culverts. The flowchart is divided to its main segments, and for clarity the segments are presented in Figures 6.30 through 6.33. The flowchart in Figure 6.30 will lead to the type of substructure system based on span length and other constraints. As the type of substructure is selected, the substructure elements and systems can be selected using Figures 6.31 to 6.33 for pier and abutment system, buried bridges, and culverts, respectively [184].

When using pier and abutment system, to select the pier elements, it should be considered if piers are affected by the errant vehicle or there is a possibility to collect derbies between piers when the bridge passes over the wetland. In these cases, the wall piers should be used instead of piers. In other cases, the piers and pier columns can be used. In this case, the integration of pier cap or pier wall cap with the superstructure should be considered to determine the connection and accommodation require to join the pier cap and superstructure. Also, this should be considered that cap may be placed directly over the pile or it may be placed over the pier column. Consequently, the pier column should be supported by footing. As shown in Figure 6.31, abutment system includes wing wall and abutment wall. Wing wall can be constructed using precast elements or as a modular unit. In abutment wall, the integrity of abutment with the superstructure is important. When the integration of abutment with superstructure is vital, the use of fully or semi-integral abutment is needed. When the integrity of abutment with superstructure is not important, the cantilever, spill-through, or stub abutment can be used. It should be noted that the use of fully
integral abutment that is constructed with the superstructure is preferable due to its full moment connection with the superstructure as well as increasing the speed of construction [184].

The type of buried bridges can be narrowed down based on availability, environmental effects and span as shown in Figure 6.32. Similar process can be applied for selection of culvert elements from Figure 6.33.

6.6.5. Suitability of Substructure Types with Respect to Foundation

In this section, considering interrelations and other parameters involved, a flowchart for selection of substructure for ABC projects is developed based on the foundation system and the ABC method. As shown in Figure 6.29, the selection of substructure for new bridges can be based on whether the bridge foundation is deep or shallow. The selection of deep or shallow foundation can be based on the site conditions, existence of river, soil conditions, etc., which are discussed in the next sections. However, in this section, a flowchart that can be used to select the substructure types and components based on the foundation is presented (Figure 6.34) [184].

When a deep foundation such as pile foundation is used for the bridge, it may also serve as a bridge pier and connect directly to pier cap (also serve as pile cap). In this case, the bridge does not need a separate pier. When the deep foundation cannot be used as a pier, a pile cap is needed. Pile cap function as it relates to connection to substructure would be like a shallow foundation. Therefore, a pier column or pier wall is required in order to transfer superstructure loads to the foundation. The type of substructure elements will have to satisfy the flowchart presented earlier in Figure 6.29. After selecting the pier wall or pier column, the type of pier cap can be determined by considering the compatibility with the superstructure and connectivity design between substructure and superstructure [184].
Figure 6. 29 Flowchart for selection of substructures [184].
Figure 6. 30 Flowchart for selection of substructure system [184].
Figure 6. 31 Flowchart for selection of substructure elements for pier and abutment system [184].
Figure 6. 32 Flowchart for selection of substructure elements for buried bridges [184].
Figure 6. 33 Flowchart for selection of substructure elements for culverts
Figure 6. 34 Flowchart for selection of substructures with respect to foundation type [184].
### 6.6.6. Considerations for substructure system and elements selection

Bridge substructure includes pier, pier cap, and abutment systems that act as bridge elements that transfer superstructure loads to the foundation [186]. Pier caps are normally connected to the pier that is supported by the footing or pile cap. Piers can sometimes be constructed integrally with superstructure. In certain conditions, pier cap may be connected directly to the extended piles or foundation above the finished grade. Table 6.2 offers some alternatives and related considerations for substructure [184].

**Table 6.2 Substructure system selection considerations**

<table>
<thead>
<tr>
<th>Substructure system</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-pier</td>
<td>Single column with a wide-enough cap that can support superstructure without the need for separate pier cap element</td>
</tr>
<tr>
<td>Open bent with separate pier and pier cap</td>
<td>To support wider superstructure</td>
</tr>
<tr>
<td></td>
<td>Precast individually and connected at the site</td>
</tr>
<tr>
<td>Precast open bent</td>
<td>A combination of pier columns and cap precast together and installed at site. Accelerates bridge construction.</td>
</tr>
<tr>
<td>Column bent with web wall</td>
<td>Similar to above with advantages of wall piers.</td>
</tr>
<tr>
<td>Concrete Filled Tube column/pier</td>
<td>Allows greater design capacity</td>
</tr>
<tr>
<td>Pier cap with integrity details- Integral or semi-integral</td>
<td>Eliminate bearing and reduce maintenance</td>
</tr>
<tr>
<td></td>
<td>Good for seismic area by integrating substructure and superstructure</td>
</tr>
<tr>
<td>Wall pier</td>
<td>Are used when the pier may be affected by the errant vehicles, and in rivers to prevent debris from collecting between columns</td>
</tr>
<tr>
<td>Abutment cap with integrity details- Integral or semi-integral</td>
<td>Better durability and load carrying capacity especially in seismic regions.</td>
</tr>
<tr>
<td>Abutment wall</td>
<td>Cantilever, stub, or spill-through types each with specific characteristics</td>
</tr>
<tr>
<td></td>
<td>Can be designed in segments for easier shipping, and joined together at the site</td>
</tr>
<tr>
<td>Wing wall</td>
<td>Precast cantilever or modular precast</td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------------------------------------</td>
</tr>
<tr>
<td>Beam seat or cap</td>
<td>Built with geosynthetic/reinforced soil or mechanically stabilized earth at the abutments.</td>
</tr>
</tbody>
</table>

### 6.7. Selection and Design Considerations for Foundation

Satisfactory performance of bridge structure is assured by providing adequate support with the selection and design of a proper foundation. To select the most preferred foundation alternatives for a bridge, shallow foundations and deep foundations should be considered. Different deep foundation alternatives should be included in a given condition such as drilled shafts, driven piles, continuous flight auger piles (CFA), micropiles, and other deep foundation systems. Moreover, considerations regarding cost, engineering, and constructability pertinent to a particular site should be included in the selection of a bridge foundation. The items needed to be considered for selecting a bridge foundation according to the bridge design manuals of Oregon DOT [188] and Wisconsin DOT [180], are as follows:

- Capability to meet performance requirements, such as bearing resistance, deformation, lateral resistance/deformation, uplift resistance;
- Consideration of issues like construction access, traffic staging requirements, cofferdams, shoring required, and constructability of the foundation type;
- Foundation cost;
- Capability to meet the requirements of environmental permits, such as confinement requirements, in-water work periods, hazardous materials, vibration or noise effects from pile driving or other operations;
- Related to site constraints, such as access, overhead clearance, utilities, and surface obstructions;
- Post- construction impact and impact of foundation construction on utilities, or adjacent structures;
- Foundation installation impact on right-of-way and traffic.

Based on the above-mentioned factors, an assessment needs to be made whether a deep or a shallow foundation is suitable to satisfy site-specific requirements. Given the right set of conditions, typically spread footings are more cost effective than the deep foundation [180]. Generally, the depth to the bottom of the shallow foundation is equal or less than twice the smallest dimension of the footing. Rafts/mat foundations supporting multiple columns or spread footings supporting single column are typical shallow foundations. For shallow foundations to be applicable, dense or hard soils with adequate bearing resistance are required [188]. Depending on the loads and settlement requirements in less dense soils such as stiff clays or medium density sand, the size of the footings can become very large. The important factors governing the selection of shallow foundation are foundation settlement and lateral loading constraints in addition to bearing capacity. For selection of shallow foundations, other important considerations include requirements for cofferdams, dewatering, bottom seals, over-excavation of unsuitable material, temporary excavation support/shoring, uplift loads, liquefaction, available time to dissipate consolidation settlement prior to final construction, slope stability, environmental impacts and water quality.
impacts, and scour susceptibility. [180]. From the FHWA publication, Selection of Spread Footings on Soils to Support Highway Bridge Structures [189], additional guidance can be obtained for the selection of shallow foundation [190]. Deep foundations should be considered when shallow foundations do not satisfy the project constraints. Transfer of the loads from superstructure to the underlying deposits with higher bearing capacity can be achieved using deep foundations. In any case, it is important to establish the site conditions that would point to the need for a deep foundation [191]. Typical situations in which piles may be needed are proposed by Vesic [192] and can be seen in Figure 6.35. If the lateral, inclined, overturning moments or uplift loads could not be resisted using a shallow footing, a deep foundation should be considered. Also, mitigation of concerns about liquefaction, scour, excessive settlement lateral spreading, and other site constraints can be achieved with the use of deep foundations. The use of deep foundation may be required in areas of collapsible or expansive soils to resist undesirable seasonal movement of the bridge structure [188]. If both deep foundation and shallow alternatives found to be technically feasible, an evaluation of the shallow foundation needs to be conducted. A detailed cost analysis, the magnitude of settlement under anticipated loads, the dimensions and depth of shallow footings depending on the soil bearing capacity may be included in the evaluation. Overall substructure cost, construction time, dewatering and foundation seals, construction risk and claims potential, and the need for cofferdams may be included in the cost analysis. Based on the comparative analysis of feasible alternatives, a final selection of the foundation can be made [191]. Also, stability under vertical and horizontal loading, soil type, long-term settlement, substructure type, required method of foundation installation, cost comparison and estimated length of pile foundation are factors affecting the selection of a deep foundation [180]. Drilled shafts, driven pile, continuous flight auger piles and micropiles are the most common types of deep foundations. According to many state DOTs, the most frequently-used type of deep foundation are driven piles. There are different types of driven piles available such as steel H piles, precast prestressed concrete piles, and steel pipe piles. Where a dense intermediate stratum needs to be penetrated to obtain the required lateral resistance, uplift, or bearing capacity, drilled shaft foundations are advantageous. Moreover, to eliminate the need for a pile casing, pile footing or cofferdams, the drilled shaft foundation can be extended into a column. On the other hand, where foundation retrofitting is required for existing substructures, or headroom is restricted, micropiles can be used as an alternative. Where lateral loads are minimal, Continuous Flight Auger piles are another potential cost-effective foundation alternative of driven or drilled shaft piles [191], [180], [188], [193], [194]]. However, concerns on the quality control of CFA pile construction have been expressed by many DOTs [195]. Based on the above discussion, a flowchart for the selection of foundation for new bridges (Figure 6.36), a table (Table 6.3) based on soil type and soil bearing capacity proposed by Bowels [196], and a scheme shown in Figure 6.37 were developed for the selection of foundation in relation with the type of soil [197].
Figure 6. 35 Situations to select deep foundation [192]
Figure 6. 36 Flowchart for the selection of foundation for new bridges [197].
Figure 6. 37 Flowchart for the selection of foundation based on types of soils [197].
Table 6. 3 Foundation types based on soil conditions (Modified from Bowles [196]) [197].

<table>
<thead>
<tr>
<th>Foundation Type</th>
<th>Applicable Soil Conditions</th>
<th>Non-suitable or Difficult Soil Conditions</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spread footing, wall footings</td>
<td>Any conditions where bearing capacity is adequate for applied load. May use on single stratum; firm layer over soft layer, or weaker layer over firm layer. Check immediate, differential and consolidation settlements</td>
<td>Any conditions where foundations are supported on soils subject to excessive scour or liquefaction</td>
<td>Individual columns, walls, bridge piers</td>
</tr>
<tr>
<td>Mat foundation</td>
<td>Generally, soil bearing value is less than for spread footings. Over one-half area of structure covered by individual footings. Check settlements.</td>
<td>Same as footings</td>
<td>Same as spread and wall footings. Very heavy column loads. Usually reduces differential settlements and total settlements</td>
</tr>
<tr>
<td>Driven pile foundations</td>
<td>Poor surface and near surface soils. Geomaterials suitable for load support 1.5 to 300 feet below ground surface. Check settlement and lateral deformation of pile groups.</td>
<td>Shallow depth to hard stratum. Sites where pile driving vibrations or heave would adversely impact adjacent facilities. Boulder fields</td>
<td>In groups to transfer heavy column and bridge loads to suitable soil and rock layers. Also, to resist uplift and/or lateral loads</td>
</tr>
<tr>
<td>Drilled shafts</td>
<td>Poor surface and near surface soils. Geomaterials suitable for load support located 25 to 300 feet below ground surface</td>
<td>Caving formations difficult to stabilize. Artesian conditions. Boulder fields. Contaminated soil. Areas with concrete delivery or concrete placement logistic problems</td>
<td>In groups to transfer heavy column loads. Mono shafts and small groups sometimes used. Cap sometimes eliminated by using drilled shafts as column extensions</td>
</tr>
<tr>
<td>Micropiles</td>
<td>Any soil, rock, or fill conditions including areas with rubble fill, boulders, and karstic conditions</td>
<td>High slenderness ratio may present buckling problems from loss of lateral support in liquefiaction susceptible soils. Low lateral resistance. Offshore applications</td>
<td>Often used for seismic retrofitting, underpinning, very difficult drilling through overburden materials, in low head room situations, and for projects with noise or vibration restrictions</td>
</tr>
<tr>
<td>CFA Piles</td>
<td>Medium to very stiff clays, cemented sands or weak limestone, residual soils, medium dense to dense sands, rock overlain by stiff or cemented deposits</td>
<td>Very soft soils, loose saturated sands, hard bearing stratum overlain by soft or loose soils, karst conditions, areas with flowing water. Highly variable subsurface conditions. Conditions requiring long piles due to deep scour, liquefiable layers, or penetrating very hard strata or rock, offshore conditions</td>
<td>In groups to transfer heavy loads to suitable geomaterials. Projects with noise and vibration restrictions</td>
</tr>
</tbody>
</table>
6.8. Life Cycle Cost Analysis as a tool for decision making

Maintenance, repair/rehabilitation, and retrofitting/modification costs for bridges or components including the substructure are affected by age and desired remaining service life, the level and suitability of use, and the quality and level of preventive maintenance received as well as the extent of retrofitting and modifications to the existing structure. Other factors such as the ease of maintenance, availability of material and service, and need to limit downtime should also be considered. Accurate analysis requires accurate data. The Life Cycle Cost Analysis (LCCA) of maintenance, repair, and retrofitting applications should be based on the best operating experience and cost data available for the system being evaluated. This section on Life-Cycle-Cost Analysis is adopted directly from work by Mehrabi and Mehrabi et al. ([184], [198], [199]) also available on ABC-UTC website at https://abc-utc.fiu.edu/research-projects/fiu-research-projects/development-of-guide-for-selection-of-substructure-for-abc-projects/.

A common problem faced in structural maintenance is whether an existing system or component should receive major repairs to extend its useful life, retrofitted, modified, or whether it should be replaced with a new one. The problem may apparently contain more than two alternatives of repair or replacement. On the bridge component level, in addition to the repair and replacement options, several strategies comprised of various levels of repair, retrofitting/modifications and replacement can be studied. This may arise from the fact that not all elements of bridge under consideration are at the same condition or need the same repair/maintenance levels.

In any case, the problem can be evaluated using modified form of the TLCC (Total Life Cycle Cost) method of LCCA for inclusion of various alternatives. If the alternatives have unequal useful lives, the comparison should be made on an annual worth (or equivalent annual cost) basis. While the cost of maintenance may run at higher levels for the repair and maintain option, there is no economic advantage to pursuing replacements the annual value or cost is significantly less. Costs included in the analysis should include expenses associated with the acquisition and installation; construction that must be performed to accommodate the new components; maintenance and future upgrades.

If a system or component is performing satisfactorily, routine maintenance should be provided to ensure it continues to perform. On the other hand, the bridge or components may deteriorate unexpectedly due to environmental or other causes to a level that routine maintenance would not be able to assure their service life. In this case, special maintenance or repair activities could become necessary. The additional cost of such special activities may justify consideration of replacement option. When replacement is clearly required, the total life cycle cost method can also be used to select between alternative replacement systems or components. To this, the option of retrofitting or modifications to the structure for conforming to its desired function should be added. The latter may involve a combination of repair/retrofitting and addition and changes to physical and geometric envelop of the structural components. Typically, the choice is between a replacement with a higher initial cost and a lower ongoing maintenance cost or one with a lower initial cost and a higher maintenance cost.

Another maintenance question that might be addressed using LCCA is what level of maintenance should be provided to produce the lowest total life-cycle cost over the service life of the system or component? Different levels of maintenance will increase or decrease the total life cycle cost. The analysis involves determining operating costs and benefits associated with alternative levels of maintenance, calculating the total life cycle cost over the remaining service life, then comparing
results and selecting the optimum level of maintenance. Because there is limited funding available for repair and replacement work, it is vital that agencies provide a level of preventive maintenance which will prevent premature failures and allow the most cost-effective use of maintenance funds.

However, it is realized that cost efficiency may not be the only parameter to be considered in a decision-making process. Position and role of a bridge structure in a highway network is one parameter that may significantly affect the decision making. In other words, interruption in the traffic at local and network level and importance of the road in which the bridge is located plays also a significant role. A life cycle cost analysis of a bridge isolated from the system, though effective and useful, would not be able to quantify all the existing factors. The LCCA results should be evaluated in conjunction with global or system strategic considerations. These may include events related to bridge closure and delays that may have consequences above and beyond monetarily measurable costs [198], [199].

6.8.1. Basic steps in LCCA

In general, steps and procedure for an overall LCCA related to bridge structures can be listed as below [198], [199]:

- Characterize bridge, bridge subsystems, and its elements
- Define planning horizon, analysis scenario, and base case
- Define alternative bridge management strategies
- Specify/select appropriate deterioration models and parameters
- Estimate costs
- Calculate net present values
- Run a sensitivity analysis
- Review results (if not acceptable, modify the strategies and repeat calculations)
- Select preferred strategy

Further information and detailed description of the application of life cycle analysis can be obtained in the following researches [198], [199].

6.9. Decision Making for Replacement, Reuse, Or Retrofitting/ Strengthening of Existing Foundations and Substructures

Decision on whether to reuse with or without modifications and strengthening or replace substructure and/or foundation is eventually an economic consideration let it be with various level of social and political considerations. The owner needs to decide the option that best serves the public and in general the users. This can be facilitated with the help of life-cycle-cost analysis taking into consideration all feasible strategies for addressing the problem in hand. Life-cycle-cost analysis calculated the cost associated with each strategy and tells the user which option provides the least cost over the time period considered in the study. Although it is not always easy to associate cost to every factor affecting the decision, but recent attempts to monetize various items such as user costs have produced valuable information that can be included in the analysis. Furthermore, risk-based analysis methods have been able to account for risk and therefore cost associated with uncertainties and probabilities. An example of such approaches is included in the
next section. There have also been other attempts to develop tools and guidelines to facilitate the decision making. Some are described below [184]. This section on selection of substructure is adopted directly from work by Mehrabi et al. [184] that is based on material in FHWA report for substructure reuse [136] also available on ABC-UTC website at https://abc-utc.fiu.edu/research-projects/fiu-research-projects/development-of-guide-for-selection-of-substructure-for-abc-projects/

SHRP 2 R02 research group at Iowa State University developed “GeoTechTools” to provide the available technology and methodology for reusing and replacing of existing bridges according to the condition evaluated for a bridge and predicted future demand. This web-based tool can be used to select the best option for reusing, replacing, or strengthening of existing bridges [184].

Also, some methods have been developed by European organizations to decide on reuse, retrofit, strengthening, or replacement of existing foundation. A procedure developed for decision making related to deep foundation for buildings is shown in Figure 6.38 [200]. As shown, compatibility of foundation with the substructure/superstructure plays an important role in this decision making. Furthermore, the evaluation, performance and cost analysis of existing foundation help to determine the potential for reuse of substructure [184].

Based on analysis of literature on available means and methods, the current research study has identified a general step-by-step procedure to assist the owners and consultants in their decision for reuse or replacement of substructure and foundation in ABC projects. Figure 6.39 shows a flowchart that can be followed to determine whether retrofitting, strengthening, reuse, modification, or replacement of bridge substructure and foundation is a viable option. According to this flowchart, at first, the durability and integrity of the substructure and foundation is to be assessed followed by structural capacity estimation. Then, based on the capacity analysis, a life cycle cost analysis is to be conducted to evaluate the benefits of reusing the foundation and/or substructure. The life cycle cost analysis should be able to determine the optimum strategy for repair, retrofit, rehabilitation, modifications, or replacement that is economically and structurally justifiable. Durability, integrity and capacity evaluations were described above. The next section explains the basics of life-cycle-cost analysis in general terms for bridge construction [184].
Figure 6. 38 Decision method for reuse of deep foundations [200]
6.10. How to use the decision-making guide provided in this chapter:

This chapter brings together a collection of information in general on decision making for the use of ABC methods for new bridges and type of elements and systems, as well as the use of ABC methods for repair/rehabilitation or replacement of existing short span bridges.

- Decision making on whether to use ABC method versus conventional construction. The users can first review in this chapter the factors influencing the selection process and use the flowcharts that guide them step-by-step to the decision on whether to use ABC or conventional construction.
  - Flowchart in Figure 6.1, and matrix in Figure 6.2 represent FHWA Decision on whether a prefabricated bridge should be used in a project;
  - Figure 6.3 through Figure 6.21 represent 8 different decision-making flowcharts, matrix and software to decide whether a prefabricated bridge should be used in a project.

- Selection of construction methods and type of elements and systems for construction of new bridges. The users can review in this chapter the factors influencing the selection process and use the flowcharts that guide them step-by-step to the selection of the construction methods and the appropriate elements and systems.
  - Figure 6.22 represents a flowchart of parameters affecting selection of ABC components;
  - Figure 6.23 through Figure 6.25 represent the flowcharts for selection of type of construction methods and superstructure;
  - Table 6.1 represents the superstructure system selection considerations;
  - Figure 6.26 shows a flowchart for determining the suitability of substructure to receive the new superstructure;
  - Figure 6.27 represents a flowchart developed by FHWA for overall decision on the type of substructure and foundation in very general terms;
  - Figure 6.28 represents important parameters affecting the selection of bridge substructure and foundation elements;
  - Figure 6.29 through 6.33 represent detailed flowcharts for selection of type of substructure and its elements/systems.
  - Figure 6.34 is a flowchart for selection of substructure and its elements/systems in regards with the type of foundation;
  - Table 6.2 represents the substructure system selection considerations;
  - Figure 6.36 and 6.37 represent flowcharts for selection of foundations systems based on the type of soils.
  - Table 6.3 represents the foundation types selection considerations based on soil conditions.

- Decision on replacement or repair/rehabilitation of existing bridges. Users can review this chapter and sources referenced to learn about evaluation methods for existing substructure and foundations, and condition assessment and capacity estimation. This chapter contains also basics of life-cycle cost analysis for defining and decision making on strategies involving reuse, repair, modification, or strengthening of substructure and foundations.
Flowchart in Figure 6.26 will help the users to check for suitability regarding geometric compatibility, adequacy of capacity, and design and detailing match when considering the reuse of substructure to receive new superstructure;

Figure 6.38 represents flowcharts for decision making method for reuse of deep foundations;

Flowchart in Figure 6.39 contains all steps necessary for evaluation, condition assessment, and capacity calculation of substructure and foundation, and decision making on reuse, modification, retrofitting or replacement of substructure and foundation.
CHAPTER 7. NEW DEVELOPMENTS

7.1. Abstract

Accelerated Bridge Construction (ABC) is an evolving concept in construction. There is significant amount of research in progress to improve ABC and address the knowledge gap in this concept. Accelerated Bridge Construction University Transportation Center (ABC-UTC) led by the Florida international University joined by its partner universities is the only UTC dedicated to performing research, education and workforce development and technology transfer in the area of ABC. Almost all the research and development that have been carried out applies directly to short-span ABC bridges. The objectives of these researches in this center include:

- Improving design, construction, detailing and performance of ABC bridges through innovative research and development,
- Conducting high-impact research with a clear implementation plan for rapid deployment of the new research outcomes,
- Extending principles of ABC to the repair, replacement and preservation of bridges, including multi-hazards and seismic issues,
- Enhancing the service life of bridges constructed using principles of ABC by emphasizing on new materials and technologies and design for service life (at the design stage), preservation, and timely maintenance,
- Assessing the effects of climate change, especially of sea level rise and precipitation patterns on bridges, and develop a general framework for agencies to take timely action,
- Developing traffic safety systems specifically for modular bridge construction for all traffic levels in collaboration with all stakeholders,
- Developing decision-making tools, guidelines, and specifications for adopting principles of ABC for local agencies,
- Developing frameworks for rapid implementation of ABC principles in collaboration with all stakeholders.

Accordingly, the ABC-UTC has embarked on several projects promoting innovative solutions and new concepts for improving ABC. Detailed information about these projects can be found at (https://abc-utc.fiu.edu/). A list and summary of recently completed projects and current ongoing research studies related to substructure and foundation for ABC projects is included below.

7.2. New Systems

Envisioning Connection Detail for Connecting Concrete Filled Tube (CFT) Columns to Cap Beam for High Speed Rail Application: The main objective of this project is to develop sufficient amount of data and proof of concept test, for system(s) that could be used to connect the cap beam and pile cap beam to CFT columns in ABC projects. This is a joint project between FIU and UW.

Eliminating Column Formwork Using Prefabricated UHPC Shells: This research suggests experimental testing and finite element modeling for bridge columns with prefabricate a shell which acts as permanent stay-in-place form for bridge elements. The prefabricated shell is intended to eliminate the conventional formwork and scaffolding while reducing the on-site construction time and acting as a durable protective layer for normal strength concrete inside it.
Extending Maximum Length of the Folded Steel Plate Girder Bridge System (FSPGBS), exceeding 100 ft. with capability to Incorporate Camber: The main objective of this project was to develop a new version of Folded Steel Plate Girder Bridge System (FSPGBS) with maximum span length, exceeding 100 ft. with allowance to incorporate camber.

Extending Application of SDCL to ABC: The objective of this study was to develop necessary details and design provisions for extending the application of the simple for dead and continuous for live load steel bridge system to highly seismic areas.

Development of Prefabricated Bridge Railings: The purpose of this research was to begin the process of developing a new crash-tested prefabricated bridge railing that have durable anchorage details

Field Demonstration- Instrumentation and monitoring of Accelerated Repair Using UHPC Shell: The main objective of this project is to select an existing in-service bridge with damaged column element, retrofit it using UHPC shell, using cast in place technique, instrument it and monitor it to identify deterioration of the repair and substrate material as well as development of corrosion of steel within the column.

Innovative Foundation Alternative for High Speed Rail Application: The objectives of this project includes; development and validation of innovative foundation systems for HSR applications, detailed finite element modeling; and NL FE analysis to investigate the seismic response of HSR bridges with innovative foundations. This is a joint project between FIU and UNR, with FIU focusing on the component modeling and UNR on incorporation into the bridge system.

Eliminating Column Formwork Using Prefabricated UHPC Shells: The research includes experimental testing and finite element modeling for bridge columns with prefabricate a shell which acts as permanent stay-in-place form for bridge elements. The prefabricated shell is intended to eliminate the conventional formwork and scaffolding while reducing the on-site construction time and acting as a durable protective layer for normal strength concrete inside it.

More Choices for Connecting Prefabricated Bridge Elements and Systems (PBES): The objectives of this study are; to collect and select potential alternative materials (e.g. polymer concrete) to replace UHPC in PBES connections; characterize the material and mechanical properties of selected alternatives; and conduct large-scale testing to study the response of the alternative materials as used in structural ABC applications.

Durable UHPC Columns with High-Strength Steel: This study aimed at providing the basic knowledge needed to optimize the design of full prefabricated bridge columns using UHPC and high-strength steel under combined axial and lateral loading. Large-scale tests will be conducted to verify the seismic performance of the novel UHPC columns.

New Seismic-Resisting Connections or Concrete-Filled Tube Components In High-Speed Rail Systems: The overall goals of the proposed research are to investigate CFT and other column-to-pile connections through a literature review, select column-to-pile connections for study in consultation with the CAHSR technical team, investigate the seismic response and resilience of selected connections through FE analysis, and conduct limited structural analysis simulation and parametric study for a HSR bridge system.
Alternative ABC Connections Utilizing UHPC: This project focused on the exploration of UHPC joint details for use in ABC projects through experimental, analytical, and numerical work.

Accelerated Retrofit of Bridge Columns using UHPC Shell – Phase I: Feasibility Study: This research investigated the performance of UHPC as retrofit material for damaged bridge columns. An experimental study was designed to evaluate the mechanical performance of the repaired columns under a combination of static axial and cyclic lateral loads (to simulate operational conditions).

Experimental Investigation of High Performing Protective Shell Used for Retrofitting Bridge Elements: The goal of this project was to provide an alternative method for retrofitting the flexural bridge elements by attaching a layer of UHPC shell to damaged areas.

Integral Abutment Details for ABC Projects: The research aimed at developing ABC compatible integral abutment connections to marry the two technologies together and continue to advance the quality, performance, economics and constructability of bridges to meet the demands of today’s growing infrastructure.

Strength, Durability, and Application of Grouted Couplers for Integral Abutments in ABC Projects: This research focused on the development of integral abutment details utilizing grouted couplers for use in ABC projects and conduct laboratory testing on one or two of the most promising concepts.

Evaluation of Seismic Performance of Bridge Columns with Couplers and Development of Design Guidelines: The overall objective of this study was to compile and interpret data on seismic performance of different types of couplers and establish characteristic column plastic hinge behavior for different coupler types. The study further categorized the couplers with respect to their seismic performance. The results of the study were transformed into draft design guidelines for possible adoption by AASHTO.

Behavior and Design of Precast Bridge Cap Beams with Pocket Connections: The main objective of this study was to compile and interpret data on seismic performance of cap beams with pocket connections and identify behavior, design, detailing, and construction considerations for successful implementation of this category of connections. The results of the study were transformed into design guidelines for possible adoption by AASHTO.

Development and Seismic Evaluation of Pier Systems with Pocket Connections and UHPC Columns: The overall objective of this study was to develop and evaluate resilient bridge piers consisting of prefabricated columns and cap beams subjected to simulated earthquake loading on shake tables. The post-earthquake damage is minimized by using prestressing CFRP tendons to control residual displacements and plastic hinge damage by using ECC and UHPC.

Analytical Investigations and Design Implications of Seismic Response of a Two-Span ABC Bridge System: Extensive computer simulation of the seismic behavior of a 2-span bridge model was conducted to first determine the analytical modeling method that best replicates the shake test results. The model is then utilized to determine important parameters and develop ABC seismic design guidelines based on the findings.

Shake Table Studies of a Bridge System with ABC Connections: ABC connections for prefabricated members are particularly critical in moderate and high seismic zones because earthquake forces place high demand on inelastic deformation of adjoining columns. Structural integrity of the bridge has to be maintained by capacity-protected connections that experience little
or no damage. The overall objective of this study was to investigate the seismic performance of a large-scale bridge system that integrates some of the more promising ABC connections that have been proof tested as individual components.

7.3. **New Technologies**

**Robotics and Automation in ABC Projects: Exploratory Phase:** The use of automation and robotics in ABC projects has numerous advantages including increased quality of prefabricated elements, and reducing the accident rate at construction sites. In order to facilitate the implementation of automation and robotics, a comprehensive literature review and feasibility studies will be carried out to identify suitable mobile robots, construction material, prefabricated elements, and in-situ connections.

**Rapid Retrofitting Techniques for Induced Earthquakes:** The objective of this project is to develop analysis techniques to study the effect of large number of small earthquakes on bridges and identify appropriate ABC methods for repair of bridges damaged by induced earthquakes. Expected outcomes will be new analysis tools and guidelines to assess for damage from induced earthquakes and specifications for application of ABC repair methods.

**A Predictive Computer Program for Proactive Demolition Planning:** The project objective was to enhance the predictive capability of bridge demolition process by developing a computational framework that can efficiently simulate feasible demolition scenarios and take the guesswork out of equation.

7.4. **Inspection, Evaluation and Performance**

**Corrosion Durability of Reinforced Concrete Utilizing UHPC for ABC Applications:** The overall objective of this project was to investigate the corrosion durability performance of UHPC joints between precast reinforced concrete sections.

**Performance Comparison of In-Service, Full-Depth Precast Concrete Deck Panels to Cast-in-Place Decks:** The primary objective of this project was to determine the actual in-service performance of full-depth, precast deck panels compared to conventional cast-in-place (CIP) decks.

**NDT Methods Applicable to Health Monitoring of ABC Closure Joints:** This project involved search, identification, and adaptation or development of practical and economical methods for field inspection and damage detection of ABC closure joints, immediately after completion and periodically thereafter during its service life.

**Performance of Existing ABC Projects – Inspection Case Studies:** As the initial deployments of ABC projects age, it becomes necessary to inspect the structures for both maintenance decision making and for assurance of adequate service life performance. Current inspection methods used for traditional bridge structures can be modified to establish inspection protocols for ABC projects. Once inspection protocols have been developed, existing ABC projects can be inspected. After which, any apparent performance trends can be documented, and best practices identified. This is a joint project with participation of ISU, FIU, OU, UNR and UW.

**Tsunami Design Forces for ABC Retrofit:** The catastrophic damage that tsunamis cause to coastal communities is often exacerbated by the destruction of much of the transportation infrastructure.
To reduce the impacts of tsunamis, it is essential that transportation agencies retrofit bridges using methods that minimize disruption to the current transportation system. This project is expected to provide initial estimates of forces that a tsunami would impose on a bridge as the result of debris-laden flows.

**Principal and Considerations for Design of Small Unmanned Aerial Vehicles for Inspection and Survey:** The ABC Drone (ABCD) project was designed to investigate the applications within the ABC methods where drone technology can be utilized for improving or facilitating the process for accuracy, economy, timeliness and safety. It will provide guidelines to overcome the many challenges of using drones for inspection and construction programs.

**Inspection and QA/QC for ABC Projects:** The objective of this research was to explore available nondestructive testing technology to determine applicability for the inspection and quality control of accelerated bridge construction components.

**Performance Evaluation of Structural Systems for High Speed Rail In Seismic Regions:** The overall goals of the proposed research are to evaluate the structural systems presently under consideration by CAHSR, develop alternative concepts and obtain feedback from CAHSR to guide their further development, and develop preliminary calculations and drawings for selected Conceptual Designs for CASHR evaluation.

### 7.5. Planning, Contracting, and Implementation

**Complex Network Perspectives Towards Accelerated Bridge Construction (ABC):** The objective of this study is to present a method for assessing the vulnerability of a bridge network system and a strategy for improving its resiliency. With growing attention to risk-based inspection and maintenance of infrastructure, accurate knowledge of the vulnerabilities and importance, as well as consideration of interrelation among bridges in a network becomes crucial. The bridge network system in the state of Florida, USA will be used as a case study in this project.

**Demolition Requirements for Bridge Construction Projects – Best Practices Guideline (Phase I):** The goal of this project was to determine the current state of practice and state of the art in bridge demolition (both conventional and ABC) and develop a best practices guideline for bridge demolition. Phase I of this project involved a survey of State DOTs on their bridge demolition practices.

**Understanding Critical Impacting Factors and Trends on Bridge Design, Construction, and Maintenance for Future Planning:** The main objective of this project is to understand the trends of critical impacting factors and examine how these factors may impact the way that bridges are designed, constructed, and maintained.

**Estimating Total Cost of Bridge Construction using ABC and Conventional Methods of Construction:** The objective of this project was to create a framework for evaluating and utilizing public costs as part of the decision-making processes associated with bridge construction and the development of a public cost analysis and estimation tool. This is Phase II of the project.

**Synthesis of Available Contracting Methods:** While the traditional contracting method for state DOTs is primarily unit price contracting, there are alternatives, including cost plus, lump sum, lump sum with guaranteed maximum price, and progressive lump sum with a guaranteed maximum price. To date there has been little investigation into the use of these alternatives on ABC projects, this project will explore the use of these options to understand the state of practice and provide insights and lessons learned for DOTs.
Identify the Risk Factors That Contribute To Fatalities and Serious Injuries and Implement Evidence-Based Risk Elimination and Mitigation Strategies: In this project, available data on bridge construction site safety will be compiled and interpreted to provide quantitative data supporting that ABC improves safety through avoidance/reduction of number of accidents/crashes and associated costs. This project will be carried out through collaborative efforts between UNR, FIU, and ISU.

Contracting Methods for Accelerated Bridge Construction Projects: Case Studies and Consensus Building: This research project consists of a thorough exploration of current contracting methods for ABC projects via surveys, case studies, content analysis, interviews, documentation and observations.

Bidding of Accelerated Bridge Construction Projects: Case Studies and Consensus Building: This research project consists of a thorough exploration of current bidding methods for ABC projects via surveys, case studies, content analysis, interviews, documentation and observations.

Development of Guidelines to Establish Effective and Efficient Timelines and Incentives for ABC: The main objective of the proposed project was two folds: 1) Provide guidelines to evaluate the direct and indirect costs (traffic delays and opportunity losses) under following conditions: conventional construction, only ABC techniques, only incentivizing strategies, and combination of ABC and incentivizing strategies; and 2) Develop a decision-making framework to compare the total costs and durations of each of the candidate techniques to optimize for the lowest cost and construction duration techniques accordingly.

An Integrated Project to Enterprise-Level Decision Making Framework for Prioritization of Accelerated Bridge Construction: This project aimed to develop a decision-making algorithm that brings together the project-level decision process that involves the choice of optimized construction techniques together with the enterprise-level process that implements regional prioritization schemes considering indirect costs (such as drivers’ delay, economic impact, opportunity losses, economic growth, and social investments) in addition to the direct costs associated with implementation of the ABC techniques.

7.6. Materials

Development of Non-Proprietary UHPC Mix: The proposed study by FIU is part of a larger overall project including all five of the ABC-UTC partner universities. The main objective of this proposed study is to develop a non-proprietary UHPC mix design, labeled “ABC-UTC Non-Proprietary UHPC Mix,” made with local materials that can achieve the necessary mechanical properties and durability for use in bridge components, repair, and connections. This is a joint project with participation of OU, FIU, ISU, UNR and UW.

Development of Non-Proprietary UHPC Mix – Application to Deck Panel Joints: The goal of this project is to test the effectiveness and validity of non-proprietary UHPC mixes for ABC deck panel connections. Full-scale experimental testing will be conducted for two types of the connections and using different material sources for the UHPC.

Development of Non-Proprietary UHPC Mix – Evaluation of the Shear Strength of UHPC: Ultra-high-performance concrete is a relatively recent advancement in cementitious composite materials with mechanical and durability properties far exceeding those of conventional concrete, which makes it an ideal material for bridge deck joints and other connections. While considerable
Information has been developed about many characteristics of UHPC, information about shear behavior is sparse. This project investigates experimentally the behavior of UHPC mixes subject to a variety of stress states, focusing on shear and including variables such as mix design and fiber content. The experimental data collected in this project will be used to develop a constitutive model for the shear behavior in UHPC, and in particular the non-proprietary UHPC materials being developed by the partner universities.

Optimization of Advanced Cementitious Material for Bridge Deck Overlays and Upgrade, Including Shotcrete: This research project addresses the design considerations required for successful application of UHPC as an alternative material for deck overlay. The research project conducts a comprehensive literature review on bridge deck overlay, material level testing, large scale level testing for UHPC bridge deck overlays, and numerical modelling to optimize design parameters.

Material Design and Structural Configuration of Link Slabs for ABC Applications: The objective of this research was to develop details and recommendations to properly implement a link slab in jointless bridges constructed with ABC techniques. This will be accomplished through a comprehensive set of experimental tests and numerical simulations.

Investigation of Macro-Defect Free Concrete for ABC including Robotic Construction: The goal of this project was to assess important characteristics and to develop conceptual uses for this new material with a specific focus on accelerated/robotic bridge construction.

7.7. Guidelines, Synthesis, and Course Modules

Compilation of ABC Solutions: The objective of the project was to compile information on existing accelerated bridge technologies and present the information in a manner useful to designers.

International Database of ABC Research: This project involved the development of a comprehensive database that is both user friendly and easily navigable.

Development of Guide for Selection of Substructure For ABC Projects: The primary objective of this project is to provide guidelines for decision making by the designers and bridge owners for the selection of substructure and foundation for new bridges and replacement of existing bridges using ABC methods. This is a joint project between FIU and OU, with OU focusing on foundation and FIU on remaining.

Development of Manual for Enhanced Service Life of ABC Projects: The main objective of this project was to develop a manual devoted to service life performance of ABC projects.

Development of ABC Course Module: Design of Link Slabs: This project builds on the findings from a former ABC UTC-sponsored research project on link slabs and develops a short course module to provide the design guidelines and practical recommendations necessary to properly implement a link slab in jointless bridges.

Development of ABC Course Module – The Risk Due to Induced Earthquakes and Accelerated Solutions: The objective of this continuing education course is to provide the bridge community with the opportunity to learn how to estimate the cumulative seismic demand on bridges, both accelerated and conventional, due to a large number of small-to-moderate earthquakes and to educate engineers on the potential use of ABC repair/retrofit technologies. The 1-hour web-based
course will provide training on the ABC-UTC Guidelines for Assessing Effect of Frequent, Low-Level Seismic Events. Also, a brief survey of available ABC repair techniques appropriate for cumulatively damaged bridges will be provided.

Development of ABC Course Module – Seismic Connection: The goal of the proposed research is to provide a summary of the different types of seismic connection that can be achieved using ABC methods, for the benefit of future users who may not be familiar with the extensive literature on the subject. Many different connection types have been developed, so the primary effort will go into the process of categorizing them in a rational way.

Accelerated Repair and Replacement of Expansion Joints: The objectives of this research are to conduct a literature review on replacement and elimination of bridge deck expansion joints; to develop methods for accelerated bridge expansion joint replacement and elimination; and to promote ABC for bridge deck expansion joint repair.

Synthesis of Rapid Bridge Rehabilitation: Provides information on techniques and technologies for rapid bridge rehabilitation were gathered and organized in a synthesis report.

Synthesis of Available Methods for repair of Prestressed Girder Ends: The goal of this project is to synthesize the available literature on bridge girders repair methods with focus on prestressed girders and end zones damage. The synthesis will summarize and compare the design and application procedure of different methods to provide a guide or catalog for bridge engineers working on girders end repair.

Design of CFST Components and Connections for Transportation Structures: Course Module: The course module will provide an overview of the research conducted, design expressions for the CFST components and connections, nonlinear modeling techniques, system-level response to vertical and lateral demands including earthquake and tsunami loading, and design examples.
References


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[189] N. C. Samtani, E. Nowatzki and D. Mertz, "Selection of Spread Footings on Soils to


Schedule
Progress of tasks in this project is shown in the table below.

<table>
<thead>
<tr>
<th>Item</th>
<th>% Completed</th>
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<tr>
<td>Percentage of Completion of this project to Date</td>
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<table>
<thead>
<tr>
<th>Research Task</th>
<th>2019</th>
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<tr>
<td>Task 1 - Literature Review</td>
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<td>Task 2 - Develop the outline of the course</td>
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<td>Task 3 - Develop course modules</td>
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<tr>
<td>Task 4 - Conducting a trial course for FDOT</td>
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Work Performed
Work To be Performed