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16. Abstract
The bridge structures nationwide and in the United States are aging, and in need of repair or in some cases replacement. Depending on the state of the damage to the bridge and other project specific requirements, the decision makers will choose either repair or replacement. Given the higher cost of replacement of the bridge or even the damaged girders in the bridge compared to most of the available repair techniques, the repair option has gained popularity among the decision makers. This is because using a proper repair approach, as a long-term or even a short-term solution, can lead to benefits that could not be achieved otherwise. The main benefits are considerable savings in both time and cost. Additionally, an appropriate repair approach can also help to avoid adverse environmental impacts, interruptions to service, overburdening of nearby infrastructure, and local opposition to construction. The objective of this report is to provide a synthesis of the available methods on the repair of reinforced concrete bridge girders used in practice and/or in research studies. Commonly utilized repair materials are briefly described. Different applications of the repair methods (i.e. repair for shear, flexure, or fire) are then described in detail, while providing information on the causes of damage for each case in addition to typical solutions and case studies. Step by step procedure of the typical solutions mentioned earlier is then described in detail. Finally, recommendations on the proper material and appropriate repair procedures for specific applications are provided by the authors. This is intended to enable researchers, engineers, and decision makers to compare the available repair methods more conveniently to find the optimal repair approach for specific projects based on the economic, environmental requirements as well as structural and construction conditions.

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Synthesis of Available Methods for Repair of Reinforced Concrete and Prestressed Concrete Bridge Girders

Final Report

August 2020

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The bridge structures nationwide and in the United States are aging, and in need of repair or in some cases replacement. Depending on the state of the damage to the bridge and other project specific requirements, the decision makers will choose either repair or replacement. Given the higher cost of replacement of the bridge or even the damaged girders in the bridge compared to most of the available repair techniques, the repair option has gained popularity among the decision makers. This is because using a proper repair approach, as a long-term or even a short-term solution, can lead to benefits that could not be achieved otherwise. The main benefits are considerable savings in both time and cost. Additionally, an appropriate repair approach can also help to avoid adverse environmental impacts, interruptions to service, overburdening of nearby infrastructure, and local opposition to construction. The objective of this report is to provide a synthesis of the available methods on the repair of reinforced concrete bridge girders used in practice and/or in research studies. Commonly utilized repair materials are briefly described. Different applications of the repair methods (i.e. repair for shear, flexure, or fire) are then described in detail, while providing information on the causes of damage for each case in addition to typical solutions and case studies. Step by step procedure of the typical solutions mentioned earlier is then described in detail. Finally, recommendations on the proper material and appropriate repair procedures for specific applications are provided by the authors. This is intended to enable researchers, engineers, and decision makers to compare the available repair methods more conveniently to find the optimal repair approach for specific projects based on the economic, environmental requirements as well as structural and construction conditions.

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Chapter 1. INTRODUCTION

Bridge girders worldwide are in need of maintenance, repair, or even replacement due to any of the following reasons or combination of them [1-14]:

- upgraded loading requirements such as a combination of age and severe environmental loading such as carbonation
- seismic retrofit to satisfy code requirements
- chloride attack, corrosion, and deterioration
- damage caused by accidents or increased loads due to heavier vehicles and traffic volume,
- failure to design for future loading
- fatigue damage accumulation
- accidental damage such as overheight vehicle impact
- initial design flaws, construction defects, lack of maintenance
- more stringent assessment codes
- changes in temperature and moisture
- changes in understanding and change of use

Approximately 30% of more than 607,000 bridges and 23% of 163,000 single span concrete bridges in the United States are currently classified as either structurally deficient or functionally obsolete. The former is described as a bridge with deficiencies such as corroded elements that need to be repaired. The later, however, can be referred to a bridge that has inconsistencies with the current code requirements, such as narrow shoulders or lane widths, or inadequate clearance for oversize vehicles [15, 16].

Replacing bridges can cause economical loss and inconvenient vehicle traffic [17], and is usually a more expensive option compared to repair [18]. For bridge girders in particular, repair costs of the prestressed I girders range from 35% to 69% of the cost of the superstructure replacement [19]. Additionally, it can cause environmental impacts, interruptions to service, overburdening of nearby infrastructure, and local opposition to construction [6]. Studies indicate that average girder replacement costs $8000 per ft of girder and takes one to two months to complete which means that it is expensive and time consuming [20]. Accordingly, in certain projects retrofitting is the only option because of budgetary restrictions that bridge owners are facing [21]. Harries et al., [22] classified bridge girder damage intensities into minor, moderate, and severe levels. Each intensity and the corresponding effects on the member's capacity as well as the required repairs are reported in Table 1-1.

A majority of the United States' transportation infrastructure is over 50 years old [5]. This makes the repair and strengthening of bridge structures a crucial topic ahead of all nations, which should be done efficiently and in an economic way. Some of the important factors in evaluating a proper repair method are safety, repair time, and economy [3]. Otherwise, in the absence of an economical and efficient repair technique, the bridge should be considered deficient. This is the case for one in nine of the nation's bridges [5], and in order to eliminate the bridge deficient backlog by 2028 in the US, $20.5 billion would need to be invested annually.

Table 1-1. Damage classification

Damage classification [22]				
Minor	Moderate	Severe		
		Severe I	Sever II	Severe III
Damage does not affect member capacity	Damage does not affect member capacity	Requires structural repair	Requires structural repair	Damage is too expensive
Repairs are for aesthetic or preventative purposes	Repair is done to prevent further deterioration	Repair is done to restore ultimate limit state	Repair is done to restore both the ultimate limit state and the service limit state	The member must be replaced

Assessment and strengthening of deficient bridges in the United States has been estimated as being in excess of $140 billion [6], which is still a huge amount of money. The purpose of this study is to gather the information about different materials and methods of bridge girder repair implementation that have been used so far in practice or even merely as research projects. The focus is on the repair of reinforced concrete bridge girders as more than 60% of the bridge inventory in the US are made of reinforced concrete [23]. The outcome of the study is meant to enable researchers, engineers, and decision makers to compare the available repair methods more conveniently to find the optimal repair approach for specific projects based on the economic, environmental requirements as well as structural and construction conditions.

Table 1-2 shows examples of real-life bridge girder repair projects, inside the US or internationally, with girder deficiency and repair approach explained briefly. US sates that were found to have real-life bridge repair projects in the literature are highlighted in the US map in Figure 1-1.

Table 1-2. Examples of real-life bridge girder repair projects

1- Interstate 244 (I-244) bridge over the Arkansas River, Tulsa, Oklahoma
Initial construction date-repair date:1960-2013
Deficiency: AASHTO Type II girder end corrosion, tests proved no shear deficiency
Repair approach: Demolished
[24]

2- I-10 Littlewoods Bridge, New Orleans, Louisiana **Initial construction date-repair date:** 1967-2015 **Deficiency:** Corrosion, service life **Repair approach:** Repair program before bridge replacement (5 to 10 years): external reinforcement: post-tensioning using both highstrength steel rods and Carbon Fiber Composite Cables (CFCC) as the secondary support /scheduled to be replaced in 2020 [25]
3- Bridge 27568, Hennepin County, Minnesota **Initial construction date-repair date:** 1975-2013 **Deficiency:** Corrosion, shear strengthening **Repair approach:** A reinforced shotcrete based repair: encasing supplementary steel reinforcement in shotcrete over a 4 ft. length of the girder /bridge was replaced in 2017 [26]
4- bridge in Gyeonggi-do, South Korea **Initial construction date-repair date:** 1960-2017 **Deficiency:** Flexural deficiency **Repair approach:** NSM CFRP bar [17]
5- KY 218 over Blue Springs Creek Bridge, Hart County, Kentucky **Initial construction date-repair date:** -2011 **Deficiency:** Vertical cracks near girder ends in end spans over the pier **Repair approach:** CRP applied on vertical and horizontal faces of uncracked beam ends at abutment [27]
6- Caldwell Road over Blue Grass Parkway Bridge, Anderson County, Kentucky **Initial construction date-repair date:** -2011 **Deficiency:** Over-height truck impact of edge beam-severed rebar and concrete spalling **Repair approach:** CRP applied on bottom and vertical faces to span damaged area and then confined with triaxial carbon fabric [27]

7- KY 81 Bridge, McLean County, Kentucky **Initial construction date-repair date:** -2012 **Deficiency:** Concrete spalling and corroded rebar from deterioration in edge beam **Repair approach:** CRP applied on entire length of span on bottom and vertical faces, with triaxial carbon fabric U-wraps for shear strength [27]
8- Sunnyside-Gotts Road over I-65 Bridge, Warren County, Kentucky **Initial construction date-repair date:** -2012 **Deficiency:** Over-height truck impact of edge beam-severed prestressing tendons and concrete spalling **Repair approach:** CRP with large-diameter rods applied on bottom surface to span beyond damaged area and then confined with triaxial carbon fabric [27]
9- KY 55 Bridge, Carroll County, Kentucky **Initial construction date-repair date:** -2013 **Deficiency:** Concrete spalling and corroded rebar in multiple beams due to deterioration **Repair approach:** CRP applied entire length of span on bottom and vertical surfaces of Deteriorated beams, with triaxial carbon fabric U-wraps for shear strength [27]
10- KY 80 over I-69 Bridge, Graves County, Kentucky **Initial construction date-repair date:** -2013 **Deficiency:** Over-height truck impact on multiple beams-damaged prestressing tendons and concrete spalling **Repair approach:** CRP panels applied beyond damage length on bottom and vertical faces in all impacted spans and then confined with triaxial carbon fabric [27]
11- KY 11 over Cat Creek Bridge, Powell County, Kentucky **Initial construction date-repair date:** -2013 **Deficiency:** Concrete spalling and corroded rebar from deterioration in edge beam **Repair approach:** CRP panels applied entire length of span on bottom and vertical surfaces of deteriorated beam, with triaxial carbon fabric U-wraps for shear strength [27]

12- I-64 over River Road elevated expressway, Louisville, Kentucky **Initial construction date-repair date:** -2014 **Deficiency:** Concrete spalling and corroded rebar from deicing agent penetration **Repair approach:** CRP panels applied entire length of pier cap span on bottom and vertical surfaces to span beyond deteriorated areas and then confined with triaxial carbon fabric [27]
13- W.H. Natcher Parkway over US 68 Bridge, Warren County, Kentucky **Initial construction date-repair date:** -2015 **Deficiency:** Over-height truck impact on multiple beams-severed prestressing tendons and concrete spalling **Repair approach:** CRP panels applied beyond damage length on bottom face in all impacted spans and then confined with triaxial carbon fabric [27]
14- US 150 bridge over Beech Fork River in Nelson County, Kentucky **Initial construction date-repair date:** 1955-2007 **Deficiency:** diagonal cracks **Repair approach:** SFRP sheets applied to the bottom and the vertical faces of the girders [28]
15- Cartwright Creek Bridge on the border of Washington-Nelson County, Kentucky **Initial construction date-repair date:** 1955-2007 **Deficiency:** diagonal cracks **Repair approach:** SFRP sheets applied to the bottom and the vertical faces of the girders [28]
16- Five locations along the I-65 Expressway in Jefferson County, Kentucky **Initial construction date-repair date:** 1960s-2013 **Deficiency:** cracking **Repair approach:** CFRP horizontal fabric and vertical wrapping [29]
17- Eddy Road project over I-90, Ohio **Initial construction date-repair date:** -2015 **Deficiency:** Corrosion: strands exposed, loose concrete and spalls were identified

Repair approach: The hired structural engineer by PSI suggested removing the unsound concrete and Seal with a micaceous iron oxide, and refined tar resin coating. ODOT did not accept the Tar sealer proposal. They requested removal of the loose material followed by mortar repair and cover with a fiber wrap (CFRP) which was never used in this type of application before. [30]
18- I-17 bridge over 19th Avenue and the Jefferson Street bridge of I-17, Arizona **Initial construction date-repair date:** -2017 **Deficiency:** vehicle impact damage **Repair approach:** EB CFRP sheets [31]
19- Lyndon B. Johnson (LBJ) Express construction project, located on I-635 and I-35 freeways, Dallas, Texas **Initial construction date-repair date:** Not found **Deficiency:** impact damage: concrete loss and strand exposure (The overpass had been completed while the old route was open below, causing a temporary vertical lower clearance than the final design, leading to the impact) **Repair approach:** fiber glass (GFRP) rebars, bonding epoxy and repair mortar [3]
20- Indian River Bridge, Melbourne, Florida **Initial construction date-repair date:** 1948 (constructed) – 1969 (widened) –1 995 (repair1) –1999 (repair2) **Deficiency:** Corrosion **Repair approach:** repair1: CFRP wraps, both wet layup and procured laminate, repair2: bidirectional CFRP wrap, wet layup
21- Bridge on Highway 401 in Ontario, Canada **Initial construction date-repair date:** Not found **Deficiency:** overheight vehicle impact, extensive torsion-shear cracks, shear strengthening, flexural strengthening not necessary **Repair approach:** CFRP U-wraps. Three girders were rehabilated and one girder was replaced [12, 32]

22- A cast-in-place concrete bridge in Texas

Initial construction date-repair date: Not found

Deficiency: fire damage

Repair approach: shotcrete layer on welded wire mesh followed by CFRP longitudinal sheets on the girder soffit and discontinuous CFRP U-wraps around the girder web

[33]

23- P/S girder in a bridge in Texas

Initial construction date-repair date: Not found

Deficiency: impact damage resulting in concrete fracture and one severed prestressing strand

Repair approach: continuous CFRP U-wraps

[33]

24- concrete bridge in Texas

Initial construction date-repair date: Not found

Deficiency: impact damage resulting in concrete cover spalling and loss of prestressing strands

Repair approach: splicing some of the severed strands and offsetting the remaining of the damaged strands using CFRP sheets, in conjunction with additional CFRP U-wraps

[33]

25- concrete bridge in Texas

Initial construction date-repair date: Not found

Deficiency: impact damage resulting in concrete fracture and severed prestressing strand

Repair approach: strand splicing and continuous CFRP U-wraps

[33]

26- concrete bridge in Texas

Initial construction date-repair date: Not found

Deficiency: impact damaged repeatedly

Repair approach: CFRP continuous and discontinuous U-wraps

[33]

27- Scheifele Bridge, in the Regional Municipality of Waterloo, Ontario

Initial construction date-repair date: 1960-2005

Deficiency: corrosion damage

Repair approach: continuous and discontinuous CFRP U-wraps [34]
28- Bridge 49-4012-0250-1032 near Sunbury, Northumberland County, Pennsylvania **Initial construction date-repair date: -** **Deficiency:** extensive overall damage (had been considered for replacement) **Repair approach:** continuous CFRP sheet on the soffit and discontinuous CFRP U-wraps [35]
29- I-565 bridge of Interstate Highway 565 in Huntsville, Alabama **Initial construction date-repair date:** 1994-2007 **Deficiency:** wide cracks compromising the strength of the girder end region **Repair approach:** 4-ply FRP system applied at the bottom flange of girders [36]
30- Route 378 Bridge Over Wynantskill Creek, New York **Initial construction date-repair date:** 1932-1999 **Deficiency:** freeze-thaw cracking as well as flexural and shear strengthening **Repair approach:** EB longitudinal FRP laminates in conjunction with FRP U-wraps [37, 38]
31- Willamette River Bridge located near Newberg, Oregon **Initial construction date-repair date:** 1954-2001 **Deficiency:** significant diagonal cracking in the high-shear regions near the supports **Repair approach:** EB CFRP U-wraps [39]
32- Ebey Slough Viaduct, Washington **Initial construction date-repair date:** 1968-(1999, 2007, and finally 2010) **Deficiency:** corrosion and concrete spalling **Repair approach:** longitudinal and transverse CFRP plies [40]
33- The Main Street Bridge (No. 4 Overpass), Winnipeg, Man., Canada **Initial construction date-repair date:** 1963-2003 **Deficiency:** Impact damage, flexural deficiency

Repair approach: EB prestressed CFRP sheet on the girder soffit [41]
34- KY3297 Bridge over Little Sandy River in Carter County, Kentucky **Initial construction date-repair date:** unknown-2001 **Deficiency:** shear deficiency **Repair approach:** side bonded diagonally oriented CFRP strips [42]
35- War Memorial (Uphapee Creek) Bridge, Alabama **Initial construction date-repair date:** Not found **Deficiency:** Flexural deficiency **Repair approach:** EB CFRP strips on the girder soffit [43]
36- Bridge P-53-702, City of Edgerton, Rock County, Wisconsin **Initial construction date-repair date:** 1930-2002 **Deficiency:** Flexural deficiency **Repair approach:** CFRP strips on the girder soffit attached using mechanical fasteners [44]
37- Wood River Bridge, Nebraska **Initial construction date-repair date:** unknown-2009 **Deficiency:** impact damage **Repair approach:** strand splicing [45]
38- Bridge G270, Iron County, Missouri **Initial construction date-repair date:** 1922-unknown **Deficiency:** load carrying capacity **Repair approach:** CFRP sheets on the girder soffit [46]
39- Brown School Road Bridge, Creasy Springs Bridge, and Coats Lane Bridge, Missouri **Initial construction date-repair date:** 1970s-unknown **Deficiency:** shear and flexural deficiency (upgrading needed)

Repair approach: Discontinuous CFRP U-wraps [46]
40- A bridge in Rome, Italy **Initial construction date-repair date:** 1969-1999 **Deficiency:** flexural deficiency **Repair approach:** continuous CFRP U-wraps [47]
41- Bridge in South Troy, Rensselaer County, New York **Initial construction date-repair date:** 1932-1999 **Deficiency:** shear and flexural deficiency **Repair approach:** EB CFRP sheets on the girder soffit + discontinuous CFRP U-wraps + discontinuous CFRP strips under the deck in between the girders [48]
42- Bridge A10062, Louis County, Missouri **Initial construction date-repair date:** Not found **Deficiency:** impact damage, flexural deficiency **Repair approach:** EB CFRP sheet on the girder soffit + discontinuous CFRP U-wraps [49, 50]
43- Bridge A-4845, Missouri **Initial construction date-repair date:** Not found **Deficiency:** impact damage, flexural deficiency **Repair approach:** EB CFRP sheets on the girder soffit + CFRP U-wraps around the girder bottom bulb [51]
44- Bridge in Alabama **Initial construction date-repair date:** 1952-1995 **Deficiency:** Flexural deficiency **Repair approach:** EB CFRP plates on the girder soffit with or without continuous CFRP or GFRP side plates [52]

It should be noted that although most repair techniques are expected to enhance the capacity of the element being repaired, but a member must have adequate residual capacity in case the external repair either fails or is damaged [53].

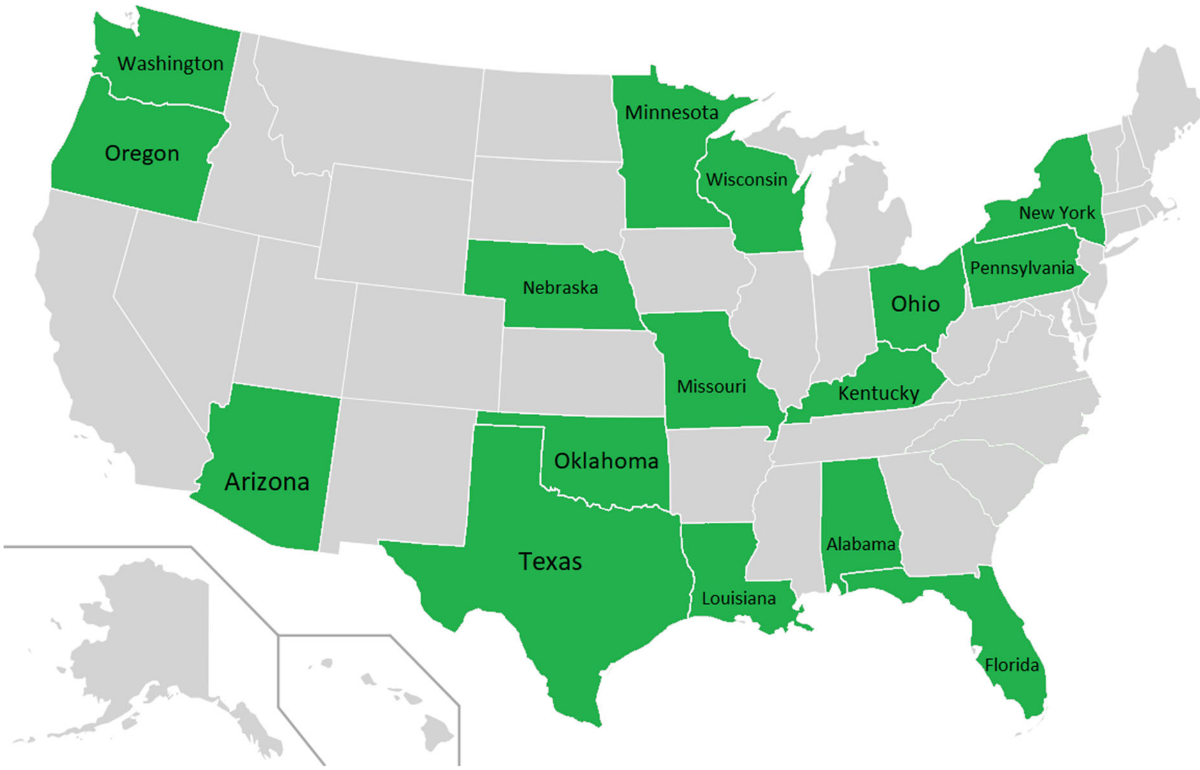


Figure 1-1. US states found in the literature, as of March 2020, with real-life bridge repair projects.

Chapter 2. REPAIR MATERIALS

In this section, materials commonly used in the bridge girder repair projects are briefly introduced. These materials include: (1) Fiber reinforced composites (polymeric composites, cement based composites, and hybrid composites) (2) steel (3) Ultra High Performance Concrete (UHPC) (4) Ferrocement (5) Shotcrete (6) Coatings and sealers. Table 2-1 lists different variations of these common repair materials as well as their advantages and disadvantages.

Table 2-1. Advantages and disadvantages of different repair materials [3-5, 7, 9, 17, 20, 25, 27, 28, 53-76]

Carbon Fiber Reinforced Polymer (CFRP) **Advantages:** High temperature resistance (Smaller thermal effects), chemical attack resistance, damping resistance, high strength and modulus of elasticity (the highest in FRP materials), light weight, high Strength to weight ratio corrosion resistance, high durability, high creep and fatigue resistance (highest in FRP materials), low construction costs, good Fire resistance/not flammable, high thermal conductivity in some forms, Low coefficient of thermal expansion, Nonpoisonous, Excellent EMI (Electromagnetic Interference) shielding property, convenient and rapid implementation, minimal interruption to service, reduced labor for installation and maintenance, negligible relaxation under load, and favorable life-cycle costs, magnetic transparency, ease and speed of repair, superior mechanical properties, high tensile strength, minimal impact on the dimensions and service conditions of existing structures, speed and simplicity of application, versatility in conforming to various cross-sectional shapes, uniform quality, availability **Disadvantages:** Brittle fracture, High cost (but, application/labor costs are so greatly reduced that they compensate for the high material cost), difficult to splice, high skill set and special equipment needed for the installation, Anchorages have to be factory installed, Supplier has no current US manufacturing plant and a long lead time is needed to order the material, i.e. rapid crack propagation without appreciable deformation due to mismatch of tensile strength and stiffness with that of concrete, Low tensile modulus compared with its strength
Glass Fiber Reinforced Polymer (GFRP) **Advantages:** high resistance to corrosion, Modulus of elasticity close to concrete, Highest percentage of strength recovery **Disadvantages:** Lower elasticity and ductility compared to steel, AFRP, and CFRP. Lower elastic modulus and tensile strength than CFRP, so any given field repair would likely require more GFRP material than CFRP. For example, seven layers of glass fiber textile are equivalent to one layer of carbon-fiber textile in terms of axial stiffness. The repaired substrate should be dry for installation, thus weather conditions can delay the project.
Basalt Fiber Reinforced Polymer (BFRP) **Advantages:** light-weight, cost effectiveness, high temperature resistance, high tensile strength, good freeze–thaw performance, good bond behavior, and easy application. better performance in acidic environments than GFRP and higher failure strain than CFRP, strength and stiffness of BFRP is between that of GFRP and CFRP, good performance on bond behavior,

Disadvantages: N/A
Aramid Fiber Reinforced Polymer (AFRP) **Advantages:** speed and simplicity of application, versatility in conforming to various cross-sectional shapes **Disadvantages: N/A**
Steel Fiber Reinforced Polymer (SFRP) **Advantages:** high strength and stiffness, comfortability and flexibility, high tensile strain, bond-ability **Disadvantages: N/A**
Fabric Reinforced Cementitious Matrix (FRCM) **Advantages:** Inherent heat resistance and compatibility with the concrete substrate (i.e., can be applied on a wet surface and allow vapor permeability). Light weight, high tensile strength, and ease of application. Can be applied on wet surfaces. Does not require special safety equipment. **Disadvantages:** Further research is needed to address long-term fatigue performance, At this time, FRCM should not be used as a repair alternative to bridges with a considerable level of damage and/or high traffic volume
Ultra High Performance Fiber Reinforced Concrete (UHPFRC) **Advantages:** high mechanical and durability properties **Disadvantages:** higher cost
Textile-Reinforced Mortar (TRM) **Advantages:** low cost, friendly for manual workers, fire resistant, and compatible to concrete and masonry substrates material which can be applied on wet surfaces or at low temperatures, high tensile strength and pseudo-ductile Behavior **Disadvantages: N/A**
Steel **Advantages:** well-known properties, vast experience for the intended purposes, flexible (in case of rods and tendons) – amenable to field changes for splicing and cutting, contractor's familiarity with the material, UV resistance, Similar thermal property as the existing concrete girders, availability, short installation time, does not disrupt operations **Disadvantages:** High corrosion potential when exposed and without special treatment, Heavy i.e. difficult to handle in tight spaces, need for welded or bolted splices which can create weak regions in the plate or lead to stress concentrations at the plate-member interface, the need of formwork for an extended amount of time when attaching steel plates, impracticality of increasing the member's cross-sectional area due to limited clearance and increased dead load,

the need for coating and painting that result in high maintenance cost, expensive, temporary weakening
Aluminum alloy **Advantages:** economical, effective and easy to install, high strength to weight ratio, high ductility, high corrosion resistance, high thermal resistance, and reasonable cost, easy to form and easy to bond to RC surface using epoxy with or without mechanical anchorages **Disadvantages: N/A**
Ferrocement **Advantages:** higher tensile strength to weight ratio, toughness, ductility, durability and cracking resistance that is considerably greater than conventional cement based materials. **Disadvantages:** Limited to be used in harsh environments, increase in the weight of the beam

2.1. Fiber-Reinforced composites

Fiber-reinforced composites, as shown in Figure 2-1, are a combination of two different materials (i.e. the reinforcing fibers and the matrix) with significantly different mechanical and/or chemical properties. When the fibers and the matrix are combined together, they create a material with properties unique from the components that comprise it. The type of matrix and fiber, orientation of the fibers, as well as the ratio of matrix to fiber content will affect the properties of the resulting composite [5].

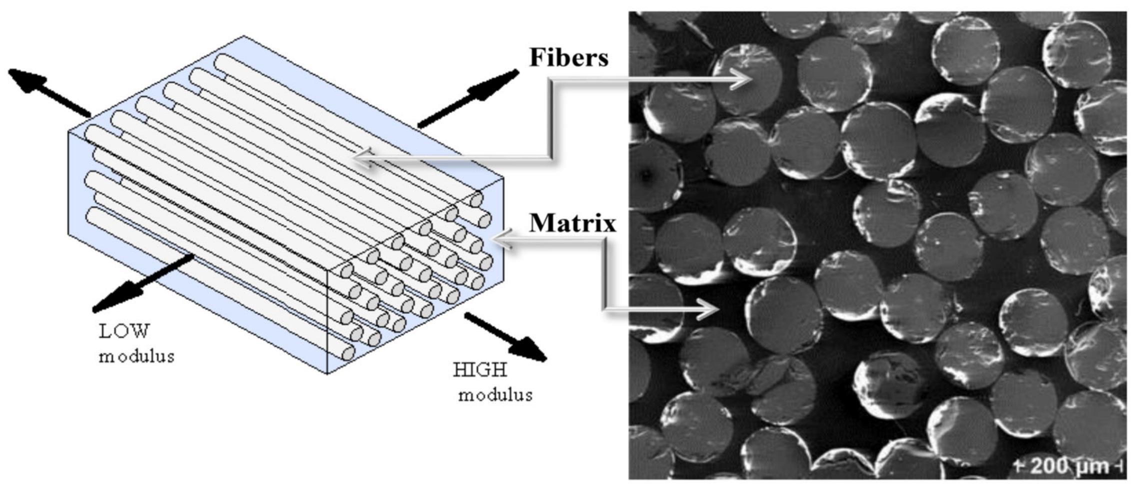


Figure 2-1. Schematic of fiber-reinforced composites [5]

Fibers can be orientated unidirectional (0º) or bidirectional (0º, 90º or 45º, -45º). Unidirectional fabrics are usually used in applications where tensile forces are only present in one direction, such as flexure of a beam [5]. Although it is also possible to have one or multiple layers of FRP fabric in which the weave is effectively unidirectional with only a small number of fibers perpendicular to the primary direction, to maintain the integrity of the loose fabric [6].

Strengthening of concrete members using Fiber-Reinforced composites, initially used for aerospace applications, started in mid-1980s, and it has gained popularity in the recent years, especially for bridge repair applications, due to their superior characteristics such as: high strength-to-weight ratio, anti-corrosive properties, high tensile strength, insect and fungal resistance, low thermal conductivity, ease of installation, and flexibility in application. Fiber-Reinforced composites are about 85% to 73% lighter than the steel. This means ease of handling and less equipment and workforce requirements on site [20, 55, 58, 77-81].

Despite the higher cost of the Fiber-Reinforced composite materials compared to steel, they are usually the preferred strengthening approach for long-term repair projects due to their superior characteristics listed above. This is while steel materials with proper corrosion treatment might be a better choice for short-term retrofit projects [25].

Fiber materials can be formed into numerous different configurations such as bars, laminates, plates, strips, wraps, unidirectional or multidirectional sheets, ropes, and cables (see Figure 2-2). Each of these have their own advantages and disadvantages for a given specific repair application (see Table 2-2).

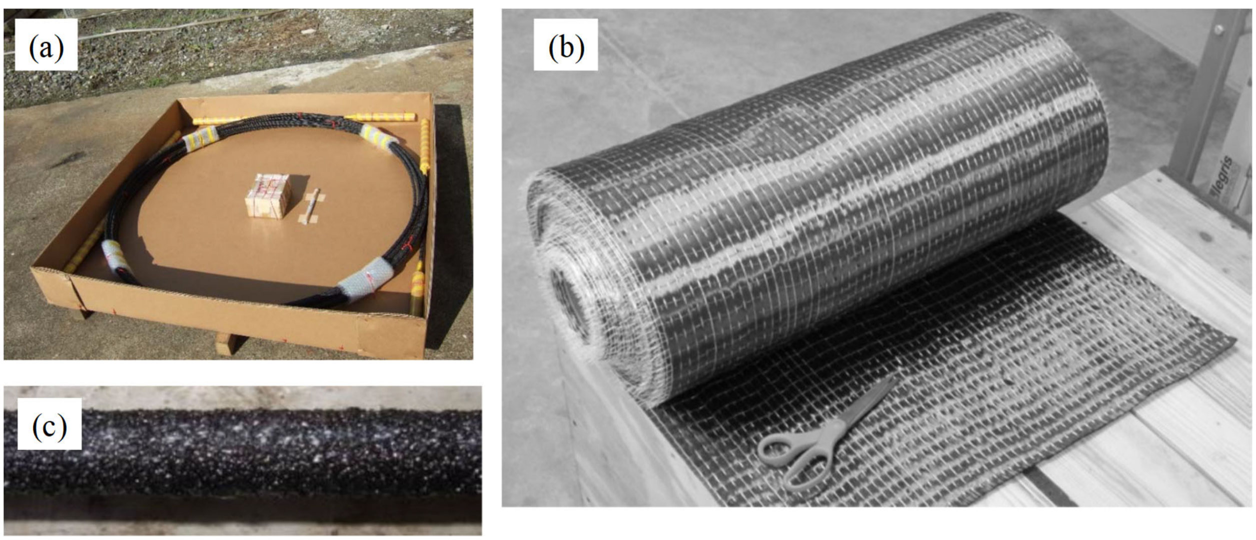


Figure 2-2. Different configurations of fiber-based materials (a) Carbon fiber composite cable [25] (b) CFRP bar [17] (c) CFRP fabric [72]

Table 2-2. Advantages and disadvantages of different repairing formats [3, 5]

1. bars: as near surface mounted or internal reinforcement **Advantages:** does not affect bridge aesthetics, thus appropriate for the repair or strengthening of new bridges. **Disadvantages: N/A**
2. sheets **Advantages:** Ability to shape any surface

Disadvantages: adversely affects bridge aesthetics, thus not the best choice for new bridges
3. wraps **Advantages:** Ability to shape any surface, better anchorage compared to U-jackets **Disadvantages:** expensive, impractical because they require access to the top of the beam which is most likely covered by the deck
4. U-jackets **Advantages:** do not require access to the top of the girder **Disadvantages:** expensive
5. NSM rods **Advantages:** less expensive **Disadvantages:** might require access to the top of the beam in case of shear strengthening

Different types of fibers have been utilized so far in structural engineering. Examples are Aramid, Steel, Basalt, Carbon, and Glass (see Figure 2-3), while carbon is the most commonly used due to its stiffness [20, 33, 65, 82]. See Table 2-1 for a list of advantages and disadvantages for each material. Figure 2-3 shows the examples of different fiber materials.

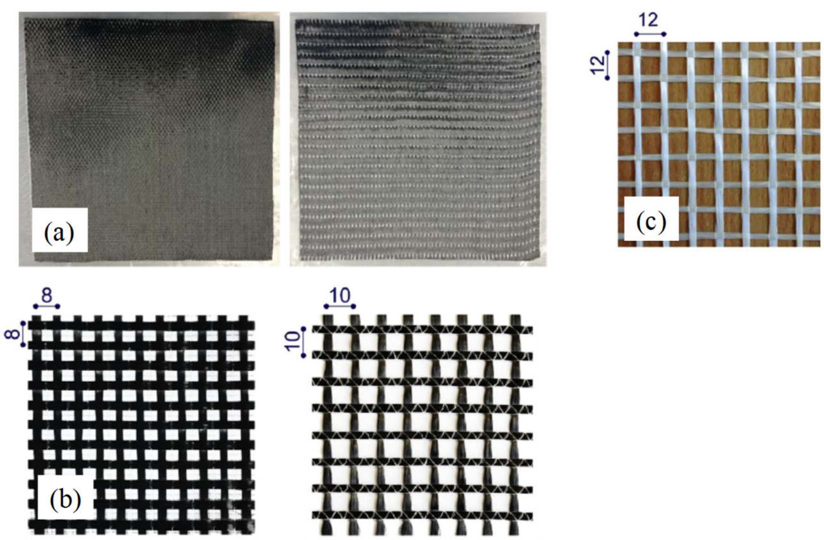


Figure 2-3. Different types of fiber materials: (a,b) Carbon fibers with different fiber densities [4, 60] (c) Glass fibers [4]

For repair and strengthening purposes, fibers can be used either in a polymer matrix such as epoxy resins or in cementitious mortars, leading to different characteristics for the resulting composite. The former is the most common approach, referred to as fiber-reinforced polymers (FRP), while the latter is a newer approach which is intended to compensate for the shortcomings of the polymer matrix used in the FRP materials. Polymeric composites and cement-based composites are described in more details in the following sections.

2.1.1. Polymeric composites

A common way of using FRP systems for concrete repair is through the use of fibers embedded in a polymeric resin such as unsaturated polyester, epoxy, vinylester, phenolic, and polyurethane resins. Epoxy resins are the most common matrix in structural repair applications due to their characteristics such as good adhesive properties, low shrinkage during curing, and resistance to environmental degradation [5, 64]. The fibers and the resin work as a system together, where the fibers provide load carrying capacity, high tensile strength, and rigidity in the longitudinal direction, while the resin protects and transfers the load to the fibers, working like a binder to the thems [55, 64, 66]. Figure 2-4 shows the individual component and composite behavior of a typical FRP material in tension. Choosing a proper matrix is important since it can affect the failure mode of the strengthening material. If the ultimate strain of the matrix is less than that of the reinforcing fibers, the brittle matrix might fail before the fibers reach their maximum strength [5].

However, the long-term durability and economy of FRP materials is a major concern [78, 83]. This becomes specifically important where complex environmental and mechanical loading situations are combined together. For example, in Michigan, in winters, sub-zero temperatures may cause changes in mechanical properties of FRP material and create additional damage, and the presence of deicing salts could accelerate such deterioration. In summers, on the other hand, high temperature, especially coupled with high humidity, has a different but additional possible detrimental effect on the FRP material [66]. More importantly, one of the major limitations in using FRP materials as the repair or strengthening approach is the ductility of the element. The ductility of the concrete members strengthened with FRP materials decreases with the amount of FRP used. Therefore, a strengthening limit approach is often suggested in guidelines and codes in order to restrict the use of high amounts of FRP [70].

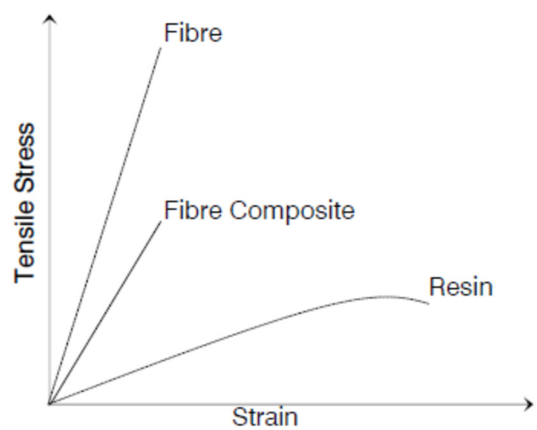


Figure 2-4. Tensile stress-strain relationship for a typical FRP and its fiber and matrix components [5]

2.1.2. Cement based composites

This material consists of fibers embedded in a cementitious matrix. Similar to fiber reinforced epoxy composites, in the fiber reinforced cement-based composites, the fibers are the tensile load carrying elements, while the cementitious matrix with high compressive strength and low tensile strength is responsible for transferring the loads [60]. Use of fibers with cementitious matrix instead of epoxy resin was proposed in early 1980s, but did not gain that much attention until late 1990s. Cementitious matrix has several advantages over conventional epoxy resins in terms of fire resistance, performance under ultraviolet (UV) radiation, permeability, thermal reversibility, time dependant behavior and long term response, and cost. Additionally, having similar mechanical, chemical, and physical properties as the concrete substrate is another advantage. Unlike the FRP installation safety requirement because of the characteristics of the used resins, installation of cementitious matrix can be done merely by simple troweling techniques and protective equipment for typical concrete applications. Also, unlike FRPS, cementitious matrix can be applied to wet surfaces, and thus the project will not be affected by weather conditions as much. The different types of cement-based composites include Sprayed Concrete, Textile Reinforced Mortar (TRM), Textile Reinforced Concrete (TRC), Fiber Reinforced Concrete (FRC), Fiber Reinforced Cementitious Mortar (FRCM), and Mineral Based Composites (MBC) [20, 78, 84].

One of the most popular cement-based composites is Fabric Reinforced Cementitious Matrix (FRCM) with different applications in practice and for research [18, 60, 64]. It has gained popularity due to its inherent heat resistance and compatibility with the concrete substrate. It consists of one or more layers of dry fabrics mentioned before (Carbon, Glass, Aramid, or Polyparaphenylene benzobisoxazole (PBO) fabrics, etc) that are sandwiched between layers of compendious mortars (see Figure 2-5). Dry fabrics imply that the fibers are not fully impregnated by the matrix, contrary to FRP systems [60, 64].

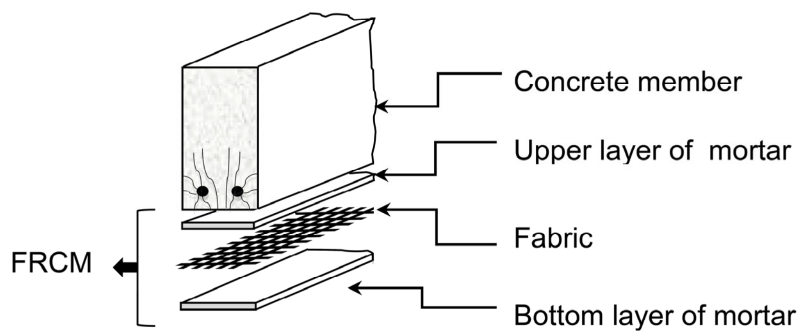


Figure 2-5. Schematic representation of FRCM [55]

Figure 2-6 also shows an illustration of FRCM mesh rolls.

Figure 2-6. Ruredil FRCM mesh rolls [20]

Figure 2-7 shows the individual components of an FRCM material including the polyparaphenylene benzobisoxazole (PBO) fiber fabric and the stabilized inorganic cementitious matrix.

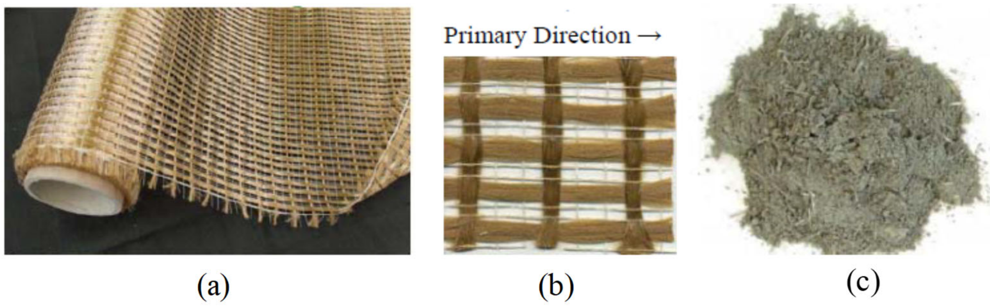


Figure 2-7. FRCM Material Constituents: a) Mesh Fabric Roll, b) Mesh Fabric Grid, c) Mortar [60]

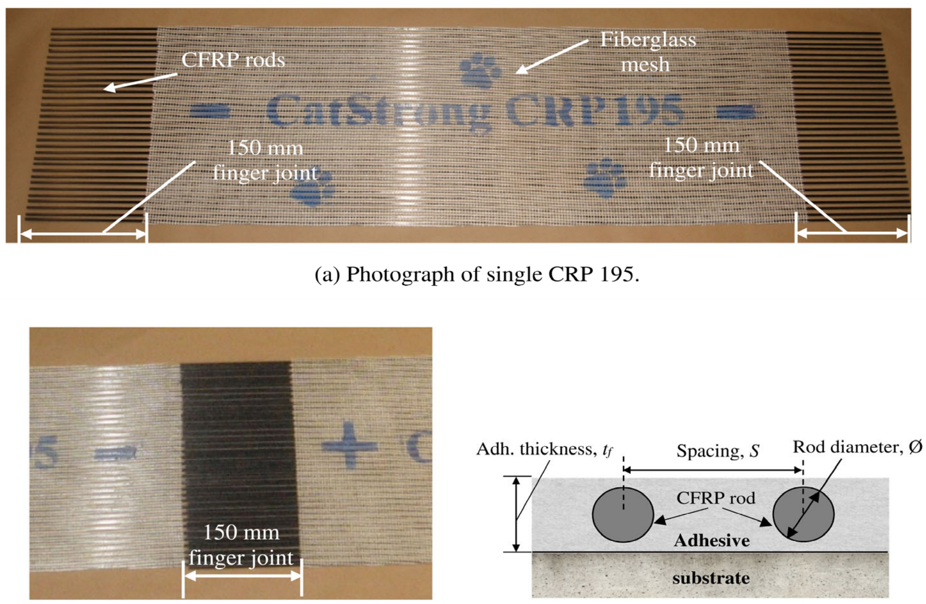
Another popular cement-based composite is Textile-Reinforced Mortar/Concrete (TRM/TRC) material (see Figure 2-8). This material has been proposed for the structural repair of concrete members to address the cost effectiveness issue of the FRP materials. It combines advanced fibers in form of textiles (with open mesh configuration) with inorganic matrices, such as cement-based mortars and it is expected to gain more popularity for repair projects due to its advantages (see Table 2-1) over commonly used FRP materials [4]. The major advantages of TRC are its high tensile strength and pseudo-ductile Behavior. The latter is characterized by large deformations due to its tolerance of multiple cracking [68].

Figure 2-8. Textile-Reinforced Mortar (TRM) [4]

2.1.3. Hybrid fiber reinforced composites

Different fiber-based composites can be combined together as a hybrid to enhance the strengthening efficiency. For example, they can provide a progressive failure pattern to compensate for the loss of ductility that is observed in traditional fiber-reinforced materials [78]. Additionally, fiber reinforced materials remain elastic up to failure. This is while hybrid materials can experience yielding as in steel. The modulus of elasticity of the fiber reinforced material can be low or high depending on the fiber and the matrix utilized [60, 78]. Another issue with the FRP strengthening methods is the costly equipment and considerable labor needed for continuous application of the material. Examples of such applications are the retrofit of the bridges over waterways, freeways and multilane roadways, and deep ravines, as well as for retrofitting other long-span members or members with limited access. In case of a bridge located over a roadway with multiple traffic lanes, lane closure under the entire span might be necessary, causing prolonged and costly traffic congestion. An economical solution to this problem can be splicing of the FRP plates. However, there is lack of sufficient research in this regard. Also, previous laboratory and field applications has found FRP splicing to be susceptible to debonding failure at the splice primary plate interface (Jawdhari, Harik et al. 2018, Peiris and Harik 2018). To overcome this issue, CFRP rod panels (CRPs), which can be categorized as hybrid composites might be used. CRPs are produced using small-diameter CFRP rods, typically ≤5 mm, mounted on a fiberglass backing to keep them together can be used. The CFRP rods are externally bonded to the concrete member with an epoxy or cementitious mortar which covers them entirely. Owing to the finger joint technique (see Figure 2-9.), which will further be defined in section 3.5., short panels of the CRP material can be used in a modular fashion to cover long strengthening lengths. This reduces the number of personnel and equipment needed during the retrofit. The CRP strengthening method has been used in nine bridge retrofit projects in Kentucky/USA (see Table 1.2) (Jawdhari, Harik et al. 2018, Peiris and Harik 2018).

Another new, non-conventional hybrid material are CFRP-honeycomb (H-Lam-C) and GFRP-honeycomb (H-Lam-G) composites. Figure 2-10 shows an illustration of such materials. As it can be seen, the system is composed of low density honeycomb core that is made of aramid fiber paper coated with heat-resistant resin, and then sandwiched between two layers of CFRP or GFRP panels [85].



(a) Photograph of single CRP 195.

(b) Photograph of two spliced CRPs at the finger joint.

(c) CRP placement

Figure 2-9. CFRP rod panel (CRP) retrofitting technique [61]

2.2. Steel

Steel material in different forms (i.e. rods, bars, tendon, plates, strand splice systems, and steel jackets) has been traditionally used for the strengthening of structural concrete members. Post tensioned rods, strands, and bars should be anchored to the girder through corbels or brackets (typically referred to as ‘bolsters’). The anchoring devices will be mounted onto the girder’s side, or sometimes the soffit. They are then tensioned by jacketing against the bolster. PT-steel may also be anchored to existing or purpose-cast diaphragms between girders as shown in Figure 2-11 [82].

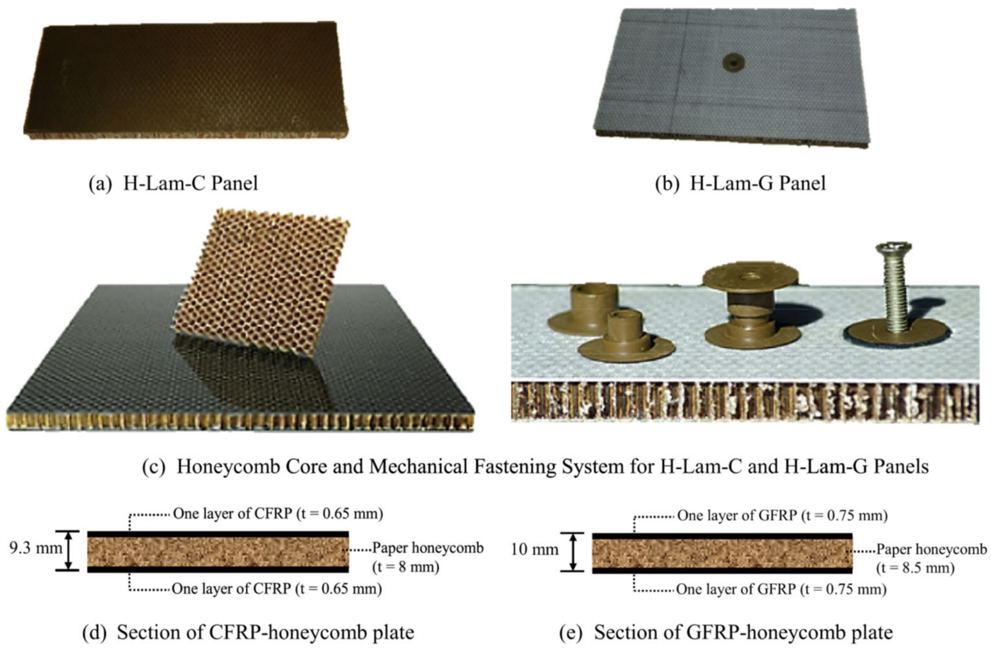


Figure 2-10. Illustration of H-Lam-C and H-Lam-G composites [85]

Figure 2-11. PT-steel anchored to girder using steel bolster bolted through girder web (second PT bolster on back of web) [82]

Using steel plates for strengthening of concrete elements started in 1960s as fast and economical solution compared to the demolition of the structure. Externally bonded steel plates are relatively quick, cause minimal site disruption, and produce only minimal change in section size. The drawbacks of this method are poor corrosion resistance at the steel/epoxy interface which might result in a decrease in strength and local debonding, as well as its heavy weight which can cause difficulty in handling the steel plates on site. Also, occurrence of undesirable shear failures, and the need for butt joint systems as a result of limited workable lengths. Furthermore, based on the number of lifting machines that can be placed on site, there might be a limitation on the length of the steel plates which can be of concern for elements of higher length. Overall, due to weak corrosion resistance and difficulty in handling on site, steel material is not the best option for bridge applications where elements are subjected to harsh environmental conditions and the cost of in situ work is considerable [58, 78]. Steel plates used for strengthening beams in shear or flexure can be bolted or bonded to the surface of the beam. Bolt arrangement, thickness and depth of the steel plate, attachment methods etc. are factors that can affect the performance of the strengthening approach [69].

Steel jackets are another method of repairing concrete elements. It includes the use of steel plates to encase the girder section. Accordingly, the girder strength is restored. It also might require shear heads, studs or through bars to affect shear transfer between the steel jacket and substrate girder. Steel jacketing is a cumbersome technique. In most applications, field welds are necessary to 'close' the jacket. Additionally, the jacket will need to be grouted in order to make up for dimensional discrepancies along the girder length. Therefore, due to the complexity of the system and the fact that it has not been sufficiently tested, the authors in [82] indicate the use of steel jackets is not recommended. It is generally believed that the CFRP repairs address all advantages of steel jackets while overcoming some of their drawbacks.

2.3. Ultra-high performance fiber reinforced concrete (UHPFRC)

Application of this material for structural rehabilitation of concrete elements started more than a decade ago given the drawbacks associated with the two most popular retrofit materials mentioned earlier (FRP and steel). This material has low permeability, high strength, high tensile strength and high toughness. Compared to other common rehabilitation materials. It has more homogeneity due to the elimination of coarse aggregates in its matrix. It also contains lower amount of free water which result in superior characteristics. In addition, it is ductile and it can have excellent bond with normal concrete [58, 86, 258, 259]. Figure 2-12 shows an example application of the UHPC material to RC beams.

Figure 2-12. Application of UHPFRC strips to the damaged RC beam [58]

2.4. Ferrocement

Ferrocement is a special type of reinforced concrete consisting of galvanized steel wire mesh reinforcement embedded in a cement matrix. Use of this material for concrete strengthening dates back to mid-1980s. One drawback to the use of this material and other materials that involve reinforcement embedded in a relatively thick matrix applied in situ to the strengthened element is that they are more labor intensive compared to materials that are in laminate or sheet forms.

Strengthening elements with forrocement is considered a type of section enlargement which can be used to enhance flexural and shear capacity of the beams [69, 78].

2.5. Shotcrete material

Shotcrete is dry cement, sand and aggregate wetted at a nozzle and sprayed at high velocity. This technique involves the pouring of sprayed concrete (shotcrete) on the supplemental reinforcement to the element to be repaired or strengthened [78]. Similar to Ferrocement, this material also requires more labor compared to prefabricated materials in laminates or sheets. Also, it increases the section size of the strengthened element, thus, changing the member capacity. Figures 2.13 to 2.15 illustrate the procedure for the implementation of this technique.

Figure 2-13. Supplemental reinforcement before application of the shotcrete [26]

Figure 2-14. Application of the shotcrete material to the girder [26]

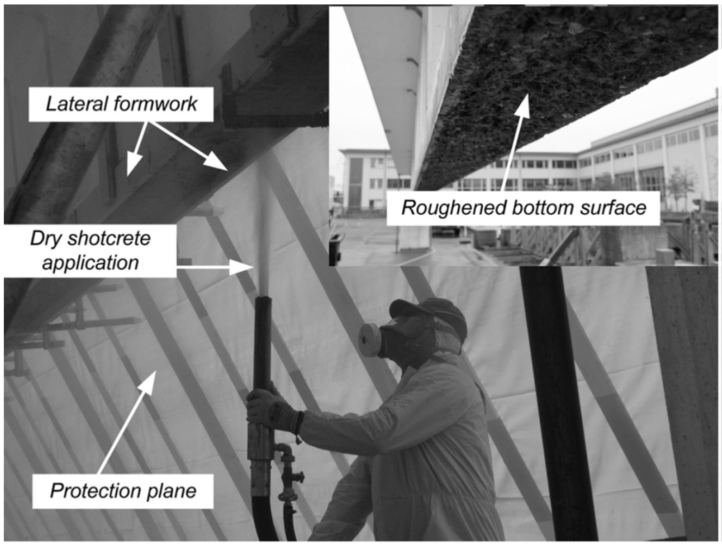


Figure 2-15. Application of shotcrete for leveling the initial camber in the girder [87]

2.6. Coatings and sealers

Coatings and sealers are used for improving the service life of the bridge. They reduce corrosion of concrete reinforcement and improve the characteristics of concrete matrix in order to avoid various types of deterioration. This is done by sealing the surface of the concrete to prevent ingress of chrorides, modifying the concrete to reduce its permeability so that the time it takes for the chlorides to reach the reinforcement is increased, and also protecting the reinforcement from chlorides when it reaches the steel. Coatings are one or two component organic liquids that are applied to a prepared concrete surface in one or more layers in order to prevent the ingress of water into the concrete and the diffusion of chloride ions. The service life of coatings depends on the type of coating material applied and the field exposure conditions. Sealers are solvent-based liquids that are also applied to a prepared concrete surface to prevent the entry of liquid water and harmful ions. They are classified into two groups of penetrating and surface sealers [19, 88].

Chapter 3. REPAIR APPLICATIONS

Favorable failure mode is the flexural failure due to either concrete crushing or rupture of tensile reinforcement. Adequate precautions should be taken to postpone the undesirable modes of failure: shear failure and FRP debonding [59]. Shear failure of RC structures occurs in a brittle manner and without prior warning, and thus, brings up undesirable consequences. Collapse of the de la Concorde overpass in Laval, Canada, which killed and seriously injured eleven people is an example of such mode of failure [89]. In case of using FRP for strengthening, three additional possible failure modes are introduced: FRP rupture, delamination of the concrete cover, and debonding of FRP from the concrete substrate. The last two are usually lumped together and referred to as FRP debonding. In case FRCM is used as the repair material, even more failure modes might be introduced including shear/tension debonding of the concrete cover of the FRCM, debonding at the interface between the FRCM and the concrete substrate, interlaminar debonding, and slippage of the fiber mesh within cementitious matrix [20]. At a local level, failure can occur one of four ways: (1) the cement matrix, (2) the adhesive, (4) the FRP/adhesive interface, or (4) the adhesive/concrete interface [55].

Depending on the design and specific conditions of a bridge structure, predominate issue for the girders of the bridge might be shear or flexural deficiencies. After the implementation of the repair, the efficiency of the results depend on the bonding performance of the repair material and the girder as well. In the absence of appropriate bonding performance, predominate mode of failure might be debonding of the repair material. Additionally, corrosion and fatigue are two parameters that can intensify the deficiencies of the bridge and cause shear, flexural, or debonding failures, hence adversely affecting the service life of the bridge. In the following sections, bridge girder repair methods for shear and flexure deficiencies are explained in detail. Due to the importance of the effects of corrosion and fatigue, these two parameters are also discussed in detail as parameters affecting the serviceability of the bridge. Repair methods associated with fire hazards are also explained since it is a fairy new topic and entails special repair techniques. For each of the shear and flexural deficiencies, serviceability performance, and for fire hazards, first, the causes of the damage are explained. Then, available common solutions for the repair of each specific deficiency are identified, and finally, different case studies seen in the literature are pointed out.

3.1. REPAIR for SHEAR

In this section, case study of 19 shear repair projects conducted in the past 10 years are demonstrated, followed by a brief description of 26 older shear repair studies.

3.1.1. Causes of damage

One of the requirements of the current codes in the assessment of old RC bridges is evaluating their shear capacity. Shear deficiency of RC concrete girders can be caused by insufficient amount of shear reinforcement, corrosion of existing shear reinforcement, and low concrete strength and/or increased design load [4, 6]. Corrosion at girder ends is also one of the reasons for possible shear deficiency of the bridge girders which as a result might expose the shear reinforcement and cause corrosion of the reinforcement as well. It should be noted that the end regions of the girders are more susceptible to corrosion due to proximity to the deck joints which exposes them to the seepage and chlorides from deicing salts. Keeping that in mind, it should also be noted that the shear demand of the girder in the end regions is the highest. This becomes even more critical for prestressed girders since the load is transferred to the beam through bond between the prestressing strands and the concrete in the end zones of such girders, causing even more shear demands. High potential for corrosion together with high shear demands, makes the girder end regions in need of special care in terms of shear capacity requirements [15]. One of the causes for corrosion is the deterioration of girder ends due to deicing salt exposure in cold climates [55]. Over the past 40 years, since the 1960s when officials started applying deicing salts in the winters to the bridge structures, the deterioration rate of the concrete girders has increased significantly. This has caused both economic and technical issues for bridge structures. Deterioration of the bridge girder ends is a particularly critical issue because of the proximity to the expansion joints. This becomes more crucial if the expansion joint fails and all of the deicing salts drain over the girder end. Furthermore, partially fixed girder end, such as one created by a frozen bearing, may impose additional stress at the girder end. When the build-up stress is relieved, the girder might crack in tension or in shear [23]. Figure 3-1 shows an example of a typical damage at the end of AASHTO bridge girders.

Figure 3-1. Damage in the end region of an AASHTO bridge girder [23]

One of the situations where the shear strength of prestressed bridge girders becomes important is when the beams are transversely post-tensioned in the horizontal plane and made contiguous within a deck. This is a common typology of bridge girders used for railway under bridges, with simply supported spans ranging from 6 to 20 m [90].

3.1.2. Common solutions

The most common material for shear strengthening of concrete beams is FRP [91]. If the Externally Bonded (EB) technique is used for FRP shear strengthening, it might be used in the three following common forms: complete wrapping, 3-sided U-wraps, and 2-sided face plies (see Figure 3-2). The full wrapping approach is the most efficient shear strengthening scheme. This is because it is capable of achieving FRP rupture failure mode, utilizing the FRP's full strength. However, debonding most likely occurs first. ACI, AASHTO, and ISIS (Intelligent Sensing for Innovative Structures) recommend the use of closed wrapping in beams whenever possible. However, most RC beams are cast monolithically with slabs, and therefore the technique is rarely adopted in the field. U-wrap is popular in practice because of its wide applicability and ease of installation. However, most U-wraps and almost all the two sided retrofits result in a FRP debonding failure mode with very little ductility. In these cases, anchoring the fibers, preferably in the compression zone, can be used to increase the effectiveness of the FRP system. Properly design anchors can result in the fibers reaching their tensile capacity prior to debonding like in a full-wrap system. The U-wrap configuration is most practical, and its effectiveness is significantly improved with proper anchorage systems [55, 66, 90, 92, 93].

The complete wrapping method, however, cannot be applied to T-beams because of the presence of the flange. Therefore, the next most efficient method for T-beams which are common in bridge engineering practice would be partial U-wrapping of the accessible downstand portion of the beam. Additionally, it should be noted that in most T-beams, the neutral axis of occurs within the depth of the flange. The U-wrap, however, terminates below the flange. Therefore, the anchorage region of the U-wrap is located below the neutral axis, i.e. in the tension region of the beam. Also, this means that the tension and compression regions of the beam will not be connected by the wrap [6, 55].

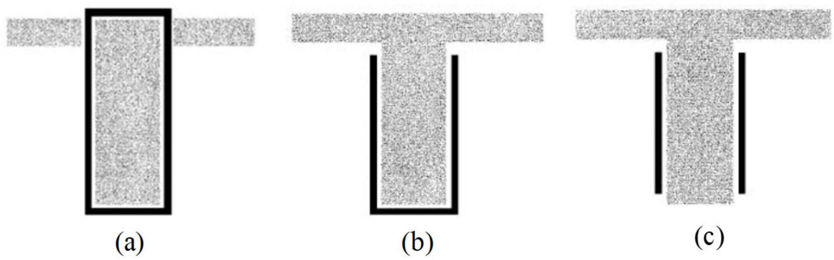


Figure 3-2. wrapping schemes for EB FRP shear laminates: (a) complete closed wrapping (b) 3-sided U-wraps (c) 2-sided face plies [55]

The deep embedment (DE) method is another technique that is mainly used for shear strengthening of girders, especially where access to the girder web is not possible [90]. In this method, vertical or inclined holes are drilled into the concrete section, in the shear zone, upwards from the soffit (see Figure 3-3). The bond between the strengthening bars and concrete is created using epoxy resin.

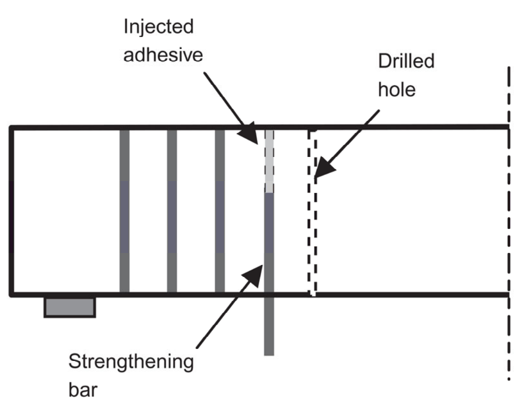


Figure 3-3. Shear strengthening using the DE technique [90]

In addition to the application of the repair material to the surface of the concrete as shown in Figure 3-2, other repair approaches such as placing the repair material inside the cover of the concrete girder (Near Surface Mounted (NSM) method) can be used as well. Section 3.1.3 provides different case studies using different repair schemes in this regard.

3.1.3. *Case studies*

Case study 1: Dirar et al., [94] studied the behavior of T-shaped beams strengthened in shear using CFRP sheets. The T-shaped section was used because it adequately simulates the slab-on-beam construction method. The CFRP sheets were applied around the web of the beams using epoxy resin. The shear strengthening approach, according to their experimental study, lead to 9.7% to 26.2% increase in the capacity of the beams, proving the effectiveness of the CFRP sheets for shear strengthening of the beams.

Case study 2: Belarbi et al., [95] investigated the performance of CFRP U-wraps in shear strengthening of RC beams (see Figure 3-4). The beams used for the experimental studies were designed to mimic the geometry of beams used in a bridge located in Troy, New York. The bridge was built in 1932 and since then has suffered from severe corrosion damage and had been strengthened with FRP sheets. The experimental results showed that the FRP strengthening technique used was able to increase the beams' shear strength by 23% to 26%. Different anchorage system for enhancing the bond behavior between the concrete surface and the CFRP sheets were used. Detailed description of these systems and their effect on the performance of the beam is explained in section 3.1.5.

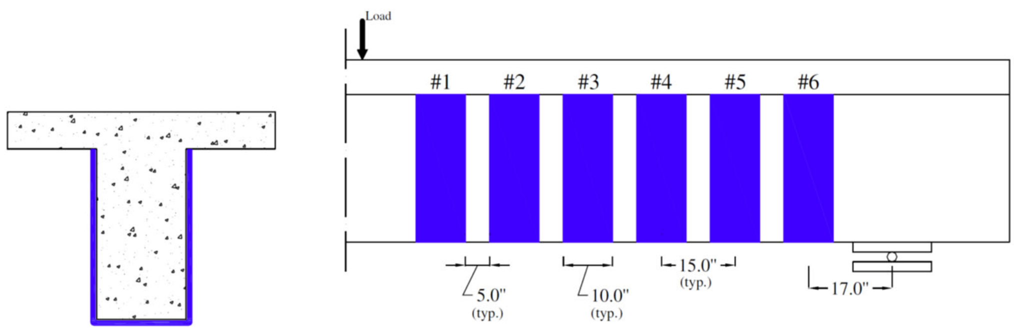


Figure 3-4. Externally bonded CFRP U-wraps for shear strengthening of RC beams [95]

Case study 3: Dias and Barros [96] studied the effectiveness of the NSM shear strengthening technique using precured CFRP laminates placed in grooves in the web of RC beams. Different CFRP arrangements were used, and their performance was compared in terms of load carrying capacity, stiffness, and failure mode. The CFRP laminates were placed either vertically or obliquely on the web of the T-shaped beams. Two different orientations (45º, 60º) were used for the oblique CFRP laminates. Experimental results showed that the inclined laminates were more effective than vertical laminates, providing a significant increase in terms of ultimate load and ultimate deflection. Also, the shear resistance of the beams has increased with the percentage of laminates. Finally, predominate failure mode was shown to be debonding through the laminate-adhesive interface (laminate sliding).

Case study 4: Goebel et al., [97] studied the behavior of aging conventionally reinforced concrete deck girder bridges. The girders of these bridges usually exhibit diagonal cracking, and are considered inadequate in shear. The aforementioned authors investigated the effect of NSM CFRP shear strengthening of the girders. This method includes placing CFRP strips inside vertical grooves in the web of the girders, filled with epoxy. They concluded that the NSM CFRP strengthening approach significantly increased the shear strength of the girders compared to the controlled unstrengthened girders. The global stiffness of the girders, however, was not significantly changed. The primary mode of failure of the girders was debonding of the NSM-

CFRP and peeling of the concrete cover for the tightly spaced strips. For some specimens, the diagonal deformations were reduced. This proposed that the repair approach was able to constrain diagonal crack opening. Finally, NSM CFRP shear strengthening seemed to be more effective for regions with positive moment than the regions with negative moment, due to anchorage past the level of the flexural tension steel.

Case study 5: Baggio et al., [16] studied the performance of different shear strengthening methods using CFRP, GFRP, and FRCM. They showed that full depth u-wrapped FRP sheets performed better than partial depth U-wraps. Additionally, use of FRP anchors further improved the shear capacity and ductility of failure and delayed debonding of the FRP material. It was also shown that FRP strengthening could change the mode of failure from a shear to flexural failure. Figure 3-5 shows an illustration and schematic of the strengthening approaches used, including full CFRP and FRCM U-wraps and partial GFRP U wraps.

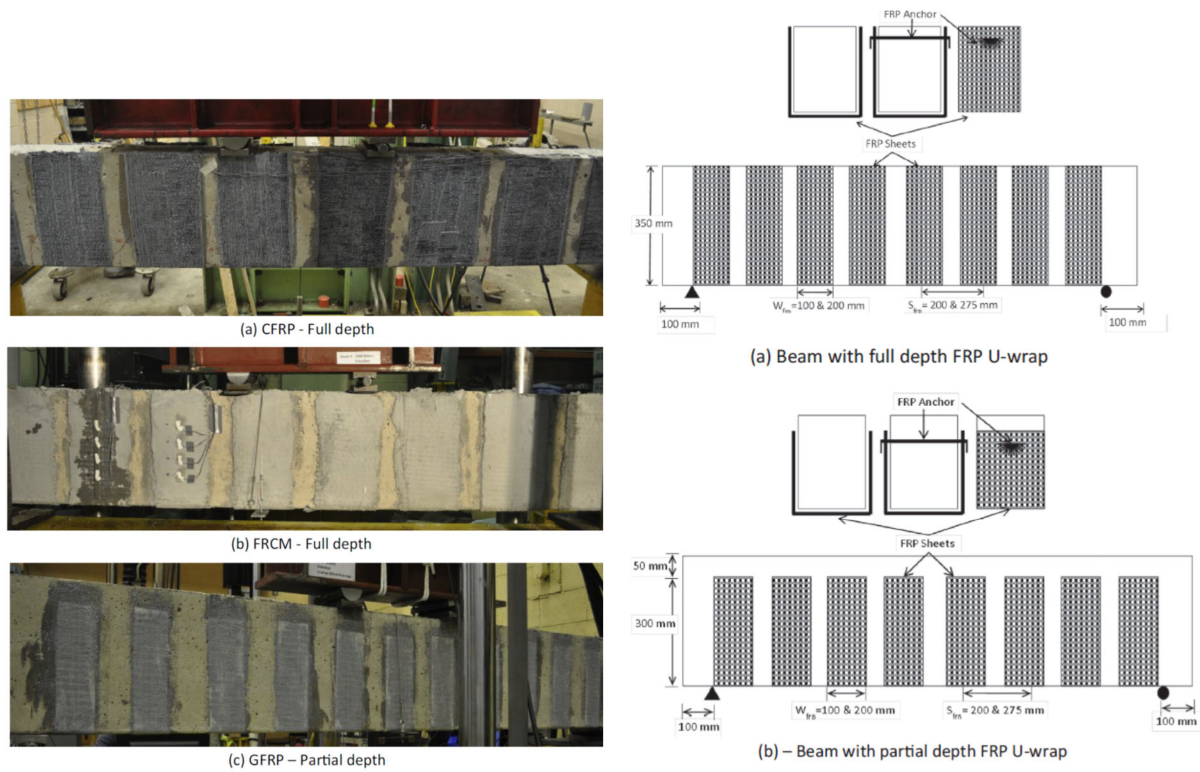


Figure 3-5. Illustration and schematic view of the shear strengthening techniques used by Baggio et al. [16]

Case study 6: L-shaped laminates (See Figure 3-6) have been proposed as a new technique for shear strengthening of the girders. El-Saikaly and Chaallal [98] showed that the L-shaped laminates are able to extend the service life of RC T-beams subjected to fatigue loading, while being technically feasible and efficient. Moreover, they demonstrated that the addition of L-shaped laminates enhanced the shear capacity of the beams and changed the failure mode from brittle to ductile under static loading.

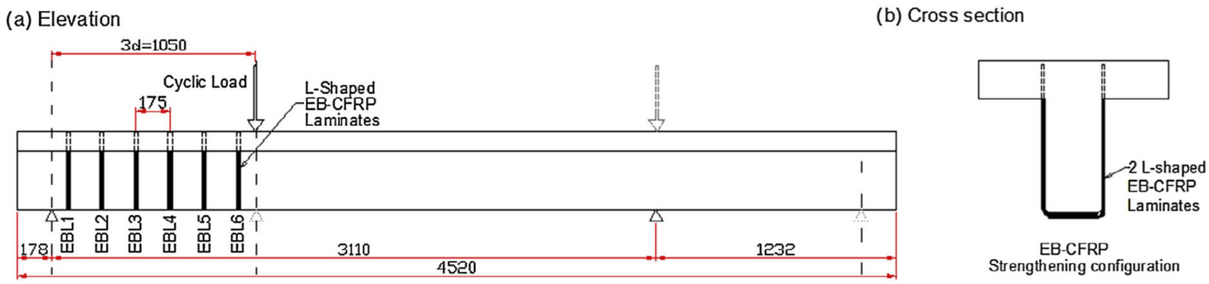


Figure 3-6. Two L-shaped laminates for shear strengthening of T-shaped girders [98]

Case study 7: Figure 3-7 shows schematic of the repair of AASHTO girders in shear using CFRP U-wraps. In the same study, Ramseyer and Kang [23] also implemented the same repair approach using GFRP U-wraps. They also did the shear strengthening of another AASHTO beam using NSM steel rods. This repair approach is shown in Figure 3-8. As can be seen, holes were drilled into the beam flange at both sides of the web, where the steel rods were placed in. The ends of the rods were then connected and hand-tightened to the steel angles.

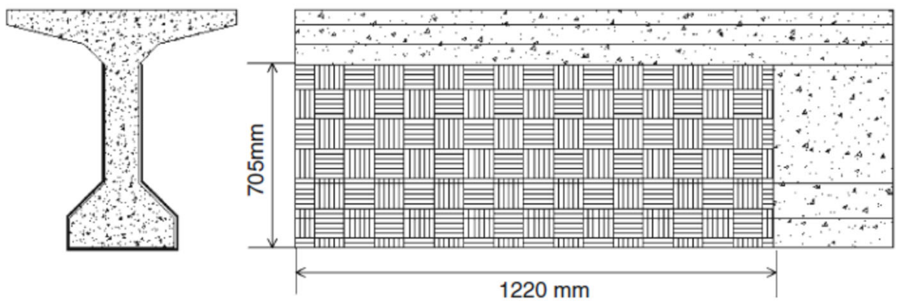


Figure 3-7. Schematic of the shear strengthening of AASHTO beams using CFRP U-wraps [23].

Figure 3-8. Shear strengthening of AASHTO girders using NSM rods [23]

They concluded that: (1) epoxy injection can provide stiffness and stability to the repair. (2) CFRP can provide the greatest amount of stiffness recovery, while GFRP results in the most strength recovery. (3) The NSM rod repair has the potential to provide the most strength recovery if a distribution plate is used on the beams.

Case study 8: Figure 3-9 shows shear strengthening of a PC girder by CFRP wrapping around the total cross section to include the compression zone. A wet layup procedure was used for this purpose [87].

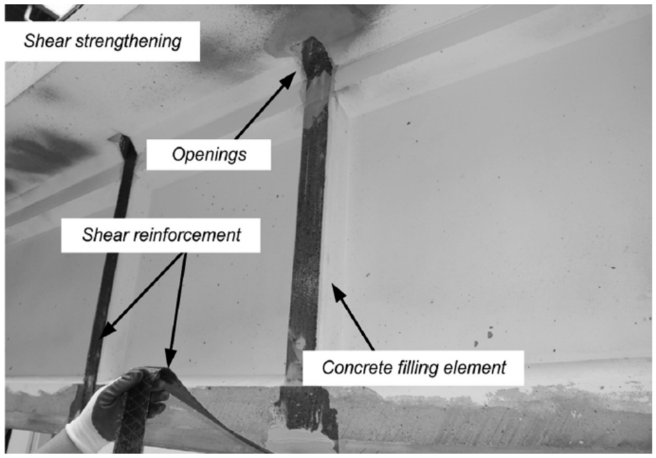


Figure 3-9. Shear strengthening of PC girders using CFRP wraps [87]

Case study 9: Abdalla et al., [7] used aluminum alloy (AA) plates externally bonded to the sides of rectangular beams using Sikadur-30LP epoxy resin. Figure 3-10 shows different configurations of such strengthening technique. In their study, capacity of the strengthened beams was increased by 24%–89% compared to the un-strengthened beam.

Case study 10: Panda et al., [99] investigated the performance of RC T-beams strengthened in shear with continuous side-bonded GFRP sheets. The test results indicated that the efficiency of the strengthened girders in shear increased by 12.5% to 50%. It was also observed that one layer of GFRP is a more effective repair approach compared to two three layers. The reason for this might be that with increasing the number of layers, the possibility of delamination increases. Additionally, for one layer repair approaches, the failure mode is due to GFRP rupture. Whereas for two or three layer repair approaches, the mode of failure is GFRP debonding. It should also be noted that as the number of GFRP layers was increased, the ductility of the beams was also increased.

Case study 11: Mofidi and Chaallal [100] used CFRP U-wraps for shear strengthening of RC T-beams in both continuous and discontinuous configurations. The experimental results showed that the increase in strength using discontinuous CFRP strips is significantly greater than continuous sheets. However, the maximum deflection is greater in case of CFRP strips. It was also shown that wider CFRP strips in the discontinuous configurations were able to contribute more to the shear capacity of the strengthened beam. The aforementioned authors also investigated the effect of FRP strip location with respect to transverse-steel location. They concluded that installing CFRP strips midway between steel stirrups results in an increase in the maximum failure load as well as in the Stiffness of the beam compared to installing FRP strips in the same location along the longitudinal axis as steel stirrups. However, the latter configuration results in more flexible behavior than the former.

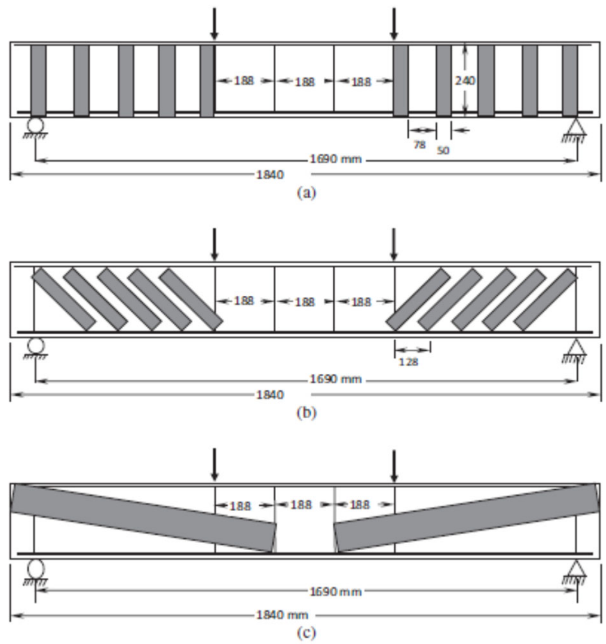


Figure 3-10. Shear strengthening using externally bonded Aluminum Alloy plates [7]

Case study 12: Qapo et al., [8] studied the effect of the spacing between CFRP strips using FE analysis. The CFRP strips were used for shear strengthening of the beam as 3-sided U-wraps. Figure 3-11 shows an illustration of the utilized repair approach. The effect of CFRP thickness was also investigated. They concluded that the increase in the CFRP thickness enhanced the predicted CFRP contribution and consequently the predicted shear force capacity. Also, the predicted CFRP contribution increased by increasing the CFRP width-to-spacing ratio.

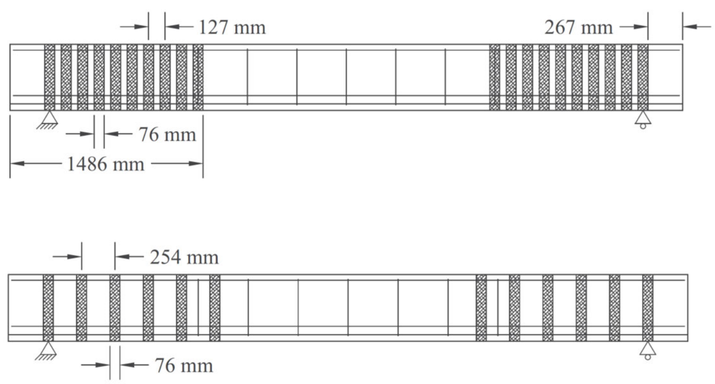


Figure 3-11. three-sided CFRP U-wraps with different spacing for shear strengthening [8]

Case study 13: Qin et al., [101] used two methods for shear strengthening of rectangular RC sections with corroded shear links (See Figure 3-12): (1) one layer of continuous U-shaped EB CFRP sheets or (2) 10-mm sand coated embedded CFRP rods spaced at 275 mm center-to-center. The tests results showed that when the corrosion level in the shear links increased from 7% to 12%, the CFRP rods' ability in strengthening the section decreased from 19% to 15%, while for the EB CFRP sheets, the shear enhancing ability dropped from 12% to 11%. It should be noted that the embedded method was implemented at the beam construction level, so it is not considered a repair method for existing girders, but rather a strengthening method for new girders.

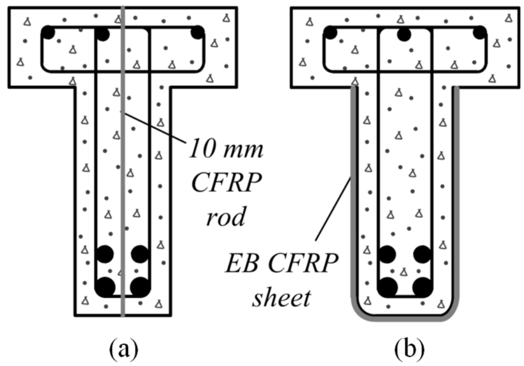


Figure 3-12. schematic of two methods of shear strengthening used by Qin et al. [101]

Case study 14: Farghal [10] used CFRP U-wraps and CFRP two-sided sheets for shear strengthening of T-beams (see Figure 3-13), which were found effective in extending the fatigue life of the girders. Although the failure mode of the girders was brittle, but the U-wraps did an acceptable improvement in increasing the ductility.

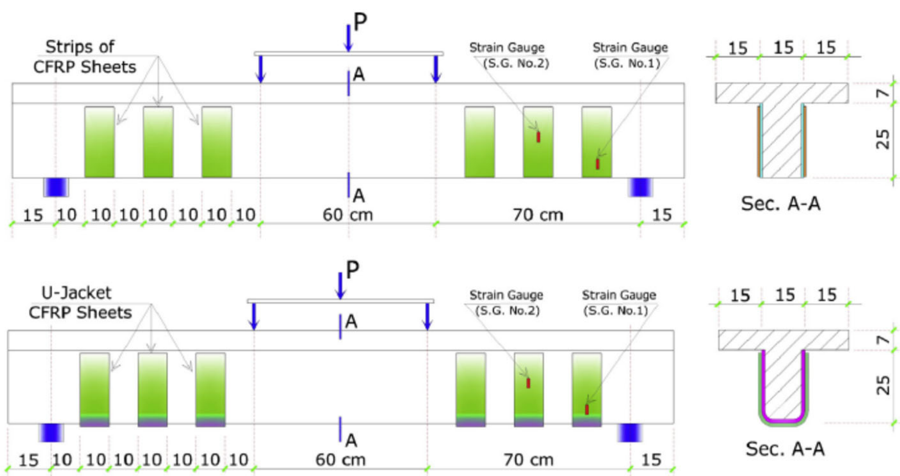


Figure 3-13. shear strengthening of RC beams using CFRP sheets [10]

Case study 15: A PC bridge in Ontario, Canada was damaged by the impact of an overheight vehicle which caused concrete spalling on the bridge girder. The spalling exposed the bottom layer of steel strands in the flange, but no damage was observed in the strands themselves. The collision caused bottom part of the girder to rotate, thus creating torsion-shear diagonal cracks. Figure 3-14 shows the crack pattern along the girder. The flexural capacity of the girder was not significantly decreased, thus no flexural strengthening was required. However, the girder was shown to be deficient in shear, thus shear strengthening was required [12].

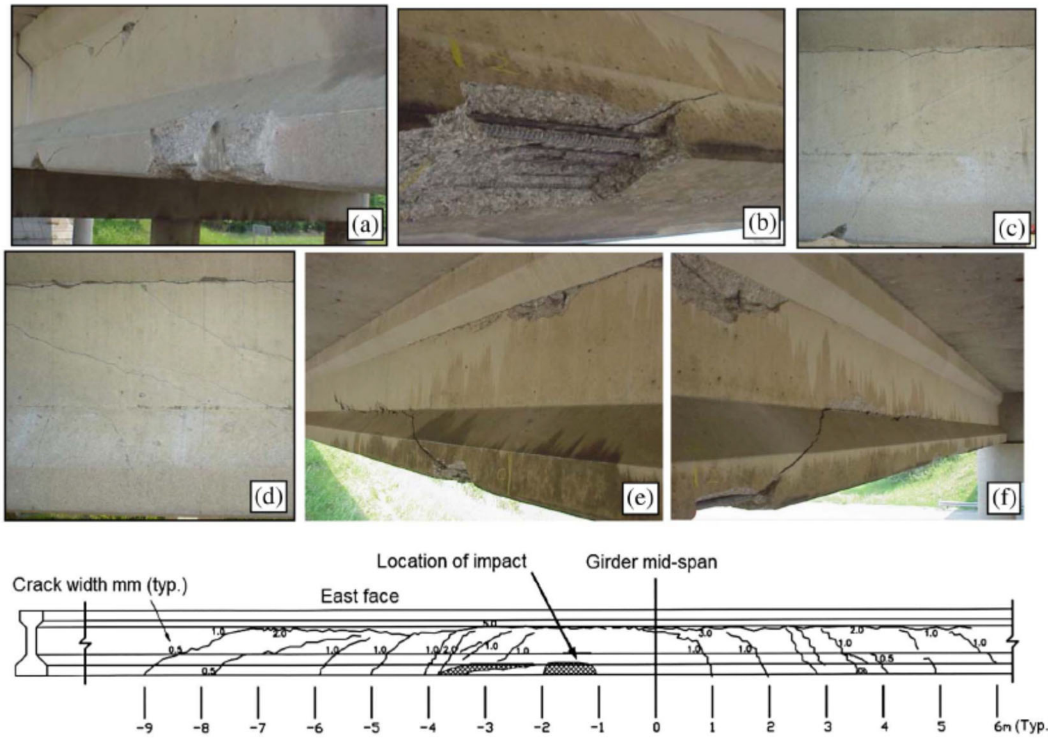


Figure 3-14. Cracking pattern of the PC girder damaged by overheight vehicle impact: (a) impact face at the bottom flange (b) back side of the bottom flange at the impact point (c) and (d) diagonal cracks on the left and right sides of the impact point, respectively (e) and (f) visible cracks on the left and right sides of the impact point at the back face of the girder, respectively [12]

For the purpose of shear strengthening of the girder, repair approach illustrated in Figure 3-15 has been used. As can be seen, this approach consists of the application of CFRP U-wraps in conjunction with longitudinal CFRP strips to provide anchorage and support for the wrap at the web-haunch junctions. They might also contribute to the flexural capacity of the girders, but their major effect is on girder shear capacity [12].

Case study 16: Murphy et al., [71] conducted a series of experiments for better understanding the behavior of RC beams strengthened in shear using CFRP sheets. For this purpose, they used CFRP U-wraps oriented at 90 and 45 degrees relative to the longitudinal axis of the girders. They showed that the failure modes of the beams are complex and highly dependent on the repair parameters such as different CFRP configurations and anchorage system. They also showed that the application of CFRP sheets to the surface of the concrete girders externally, might not increase the load carrying capacity of the girder.

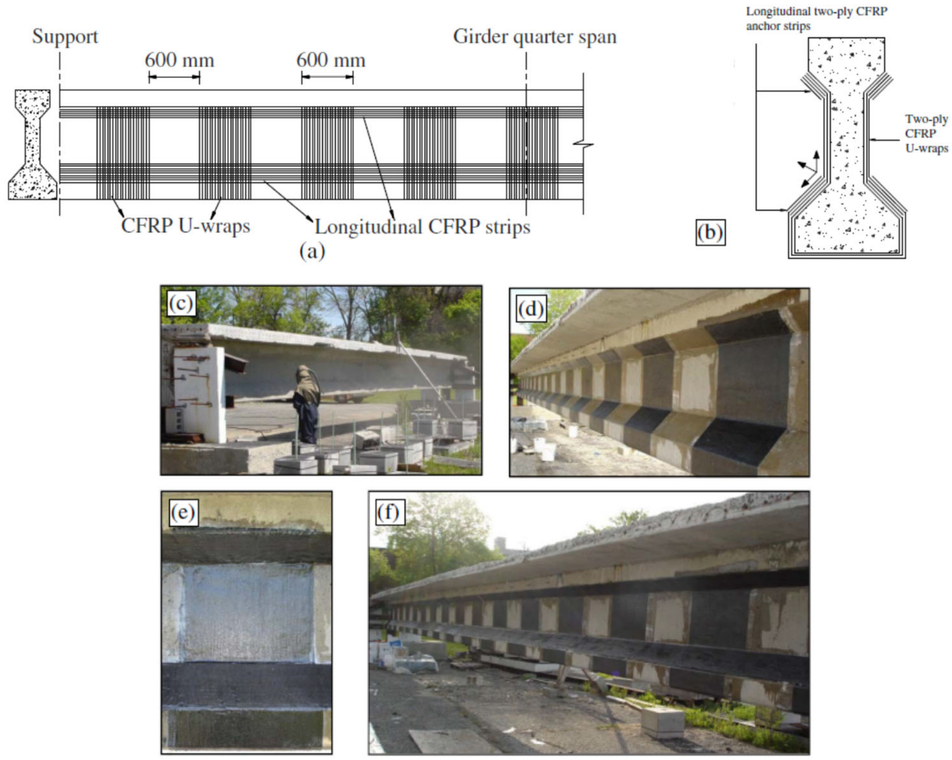


Figure 3-15. Repair scheme used for shear strengthening of the damaged girder: (a) along girder elevation (b) on the cross-section (c) sand blasting (d) application of the first CFRP layer (e) application of the longitudinal CFRP strips (f) final rehabilitated girder [12]

Case study 17: Kang and Ary [102] studied the behavior of PC beams strengthened in shear using U-shaped CFRP wraps if various amount and different spacing (see Figure 3-16) through experimental testing. The strengthened specimens responded with an increase in ductility and in shear capacity, when the spacing of the CFRP strips was less than half the effective depth of the PC beams. The ductility was increased by 28% and the shear capacity was increased by 38% compared to the control beam. CFRP spacing larger than the half of the effective depth hardly improved the shear behavior of the beam. Therefore, spacing of the strips should be specified with care.

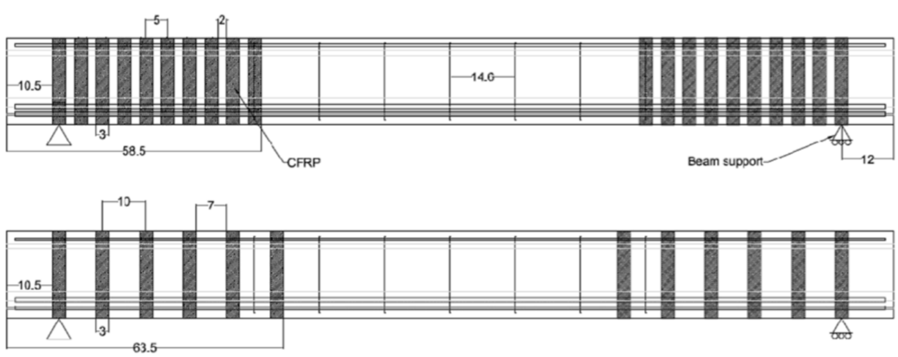


Figure 3-16. CFRP U-wraps in two different configurations for shear strengthening of the beam [102]

Case study 18: The Willamette River Bridge located near Newberg, Oregon was repaired for shear in year 2001. The reason for the repair was significant diagonal cracking in the high-shear regions near the supports. CFRP laminates were used as U-wraps, covering the web and the soffit of the girders. Additionally, although not common in shear strengthening projects, CFRP strips were placed along the web soffit and along the top of the web to provide supplemental flexural reinforcing. Inspection of the bridge in year 2004 and further experimental studies indicated that the mode of failure, for both fatigue and non-fatigue situations, is debonding of the CFRP strips in the flexural tension zone near the deck-stem interface. Therefore, field inspections for debonded regions should focus on these regions. Also, diagonal cracks increased under fatigue loading conditions. The shear capacity, however, was not significantly affected by fatigue [39].

Case study 19: Foster et al., [6] found that the thickness of the CFRP U-wraps used for strengthening of RC T-beams did not have an effect on the shear capacity of the strengthened beam.

Table 3-1 lists the shear repair approaches used in the literature from year 1997 to year 2018.

Table 3-1. List of different shear repair approaches used in the literature

No.	Author	Repair approach
1	Shield and Bergson [26], Pilarski [103]	Shotcreting
2	Andrawes, et al. [55]	CFRP and GFRP U-wraps + longitudinal strips as anchorage or NSM FRP bars on the girder web
3	Shaw and Andrawes [104]	CFRP and GFRP U-wraps + longitudinal strips as anchorage
4	Tetta, et al. [4]	Textile reinforced mortar (TRM) jackets with textile-base fan shaped anchors
5	Raicic, et al. [105]	Deep embedment with FRP/steel bars
6	Qapo, et al. [80]	Embedded FRP bars
7	Michels, et al. [87]	Discontinuous complete wraps with CFRP strips
8	Foster, et al. [6]	Continuous CFRP U-wraps with and without anchorage
9	Abdalla, et al. [7]	Side bonded Aluminum alloys (vertical and oblique)
10	Qapo, et al. [8]	EB CFRP discontinuous vertical U-wraps on the girder end regions
11	El-Saikaly and Chaallal [98]	Two EB CFRP L-shaped laminates embedded into the girder flange

12	El-Saikaly and Chaallal [106]	Continuous CFRP U-wraps
13	Qin, et al. [101]	Continuous CFRP U-wraps, embedded CFRP rods
14	Farghal [10]	Discontinuous vertical CFRP U-wraps/side bonded sheets
15	El-Saikaly, et al. [92]	Discontinuous CFRP L-strips + CFRP ropes embedded into the top of the girder web as anchorage
16	Baggio, et al. [16]	CFRP and GFRP and FRCM vertical discontinuous full depth and partial depth U-wraps
17	Choo, et al. [29]	CFRP longitudinal fabric EB on the I-girder's soffit, web, and sides + discontinuous vertical CFRP U-wraps
18	Cerullo, et al. [12]	Discontinuous vertical CFRP U-wraps + longitudinal CFRP strips
19	Bae, et al. [107]	Discontinuous vertical CFRP U-wraps
20	Azimi and Sennah [32]	Discontinuous vertical CFRP U-wraps + longitudinal CFRP strips
21	Ramseyer and Kang [23]	CFRP and GFRP continuous U-wraps
22	Murphy, et al. [71]	CFRP discontinuous vertical and inclined U-wraps + horizontal CFRP straps as anchors or continuous anchor bolts or discontinuous anchor bolts
23	Kang and Ary [102]	Discontinuous vertical CFRP U-wraps
24	Goebel, et al. [97]	NSM CFRP bars on the girder web
25	Dong, et al. [108]	EB discontinuous vertical and inclined CFRP or GFRP sheets on the girder web + horizontal CFRP or GFRP sheets
26	Dirar, et al. [89]	Continuous CFRP U-wraps
27	Dirar, et al. [94]	Continuous CFRP U-wraps
28	Dias and Barros [96]	NSM vertical or inclined CFRP laminates on the girder web
29	Belarbi, et al. [95]	Discontinuous vertical CFRP U-wraps + horizontal CFRP strips or discontinuous mechanical anchorage

30	Bae and Belarbi [93]	Discontinuous vertical CFRP U-wraps + horizontal CFRP strips or discontinuous mechanical anchorage
31	You, et al. [109]	Discontinuous vertical CFRP U-wraps + horizontal CFRP strips or discontinuous or continuous mechanical anchorage
32	Rteil and Soudki [34]	Continuous and discontinuous vertical CFRP U-wraps + longitudinal CFRP strips
33	Petty, et al. [110]	Discontinuous vertical or inclined CFRP U-wraps + horizontal CFRP strips as anchorage or embedment of the vertical CFRP laminates along the bottom and top web-to-flange connection as anchorage
34	Panda, et al. [99]	Externally side bonded GFRP sheets
35	Mofidi and Chaallal [100]	Discontinuous vertical CFRP U-wraps
37	Pantelides et al. [111]	side bonded external post-tensioned carbon fiber rods
38	Chaallal et al. [112]	CFRP continuous U-wrap wo anchorage
39	Islam [113]	NSM CFRP bars, vertical
40	Higgins et al. [114]	discontinuous EB CFRP U-wraps, vertical, w/o anchorage - discontinuous NSM vertical FRP strips
41	Higgins et al. [115]	discontinuous CFRP U-wraps w/o anchorage, vertical
42	Galal and Mofidi [116]	continuous CFRP U-wraps with mechanical anchorage
43	Durham et al. [117]	Side bonded vertical and diagonal discontinuous EB CFRP strips, no anchorage
44	Wang et al. [118]	EB CFRP plates at the soffit + discontinuous EB GFRP U-wraps
45	Simpson et al. [42]	side bonded CFRP strips diagonally oriented
46	Higgins et al. [119]	discontinuous CFRP U-wraps, Four strips of EB longitudinal CFRP on the two sides of the girder web + two strips of longitudinal EB CFRP at the center of the top flange
47	Bousselham and Chaallal [120]	continuous CFRP U-wraps w/o anchorage

48	Tabatabai [121]	FRP wrap
49	Masoud et al. [122]	For rectangular girders: discontinuous GFRP U-wraps + longitudinal GFRP strips as anchorage - discontinuous GFRP U-wraps + longitudinal GFRP strips as anchorage + longitudinal CFRP straps for flexural strengthening
50	Czaderski and Motavalli [123]	EB prefabricated CFRP L-shaped plates
51	Phillips [124]	**For T-girders:** 45º oriented NSM bars with or without anchorage.
52	Nanni et al. [125]	**For T-girders:** precured CFRP laminate on the girder soffit + CFRP U-wraps at both ends at the longitudinal CFRP termination points + discontinuous inclined NSM CFRP bars on both sides of the girder web
53	Manos et al. [126]	**For rectangular beams:** continuous CFRP full wraps for shear repair – for flexural repair: EB CFRP sheets on the girder soffit + continuous CFRP full wraps
54	Chaallal et al. [127]	**T-girders:** continuous CFRP U wraps around the girder stem
55	Barnes et al. [128]	**Rectangular girders:** steel plate on girder sides, bolted or using adhesive
56	Hag-Elsafi et al. [48]	**T-girder:** EB CFRP sheets on the girder soffit + discontinuous CFRP U-wraps + discontinuous CFRP strips under the deck in between the girders
57	Deniaud and Cheng [129]	**T-girder:** discontinuous CFRP U-wraps, vertical
58	Hutchinson [130]	**I girders:** CFRP U-wraps, vertical or diagonal, with or without anchorage. The anchorage is longitudinal CFRP strips on the girder web.
59	Kachlakev and McCurry [131]	EB CFRP on the girder soffit slightly wrapped up to the sides for flexural repair – continuous GFRP U-wraps for shear repair – combination of the two for both shear and flexural repair
60	Naaman [132]	**rectangular girders:** continuous CFRP U-wraps with or without EB CFRP sheets on the girder soffit – discontinuous side bonded CFRP strips with or without EB CFRP sheets on the girder soffit

61	Hutchinson and Rizkalla [133]	**I girders:** CFRP laminate strips on the girder soffit + CFRP U-wraps (vertical or diagonally oriented) with or without anchorage. Anchorage used here is a wide longitudinal sheet on top of the U-wraps
62	Norris et al. [134]	**Rectangular beams:** continuous CFRP U-wraps – EB CFRP sheet on the girder soffit +CFRP continuous U-wrap at a distance at both ends of the girder

3.2. REPAIR for FLEXURE

In this section, case study of 15 flexural repair projects conducted in the past 10 years are demonstrated, followed by a brief description of 99 older flexural repair studies.

3.2.1. Causes of damage

One of the major causes of flexural deficiency in bridge girders is overheight vehicle collisions (see Figure 3-17). This happens when a vehicle's height is greater than the vertical clearance between the roadway and overpass and the vehicle strikes the overpass [135].

a) Lake View Drive collapse onto I-70. Impact damage led to significant strand loss, subsequent corrosion and eventual collapse under girder self-weight. [Pittsburgh Post-Gazette]

b) Impact damage to facia beam of Crawford Lane over I-70. [Kasan]

c) Bridge over I-26 north of Columbia SC showing evidence of significant vehicle impact. [Harries]

Figure 3-17. Examples of bridge girder damage due to overheight vehicle impact [135].

The overheight vehicle impact can even happen during the construction of the bridge as stated in [3]. The project described in the aforementioned reference was a bridge overpass construction project. In this project, the overpass had been completed while the old route was open below, causing a temporary vertical lower clearance than the final design, leading to the impact (see Figure 3-18).

Figure 3-18. Vehicle impact damage on bridge girder [3]

Although an accurate record of the number of overheight vehicle impacts is not available in the literature, but it is estimated that 1100 of such collisions happen yearly in the United States [20] which proves the necessity for more investigations on the repair of collision damaged bridge girders.

According to ElSafty et al., [136] and Gangi [137], vehicle collision happens in the US 25 to 35 times per year and per state.

In the year 2008, it was reported that just in the state of New York, 32 bridges had been impacted a total of 595 times since the mid 1990's [72].

Fu et al., [138] indicated that the frequency of overheight accidents reported in Maryland have increased by 81% between 1995 and 2000. Also, an analysis of the statewide accident database by the aforementioned authors showed that of the 1,496 bridges susceptible to impact by overheight vehicles statewide, 309 (20%) have been struck, with 58 (4%) having required repairs.

The Texas Department of Transportation (TxDOT) maintains over 33,000 on-system bridges, 85% of which are concrete bridges. As of year 2011, TxDOT had repaired more than 30 impact-damaged concrete bridges using CFRP materials. Some of these bridges were severely damaged where replacement had previously been the only option for them [33].

The vehicle impact can cause damage to the girder concrete cover or cut through the steel reinforcement and/or prestressing cables [72]. Figure 3-19 shows an example of impact damage to both the concrete cover, while Figure 3-20 shows an example of severe damage to the steel reinforcement.

Figure 3-19. Severe concrete spalling due to over-height truck impact damage [27].

Figure 3-20. Example of lateral impact damage on the steel reinforcement [72].

Impact damage ranges in severity. Kasan et al., [53] defined a damage spectra for impact damage of the bridge structures by categorizing them into three groups of minor damage, repairable damage, and severe damage. Schematic of this spectra is shown in Figure 3-21. As can be seen, in case of minor and severe damages, repairing the element is not practical. A repairable damage, defined as a case in which repair is practical, is a state between minor and severe damages. In general, impact damage does not cause immediate collapse of the structure. However, when untreated, it can result in further or accelerated deterioration often resulting in significant prestressing steel corrosion [135].

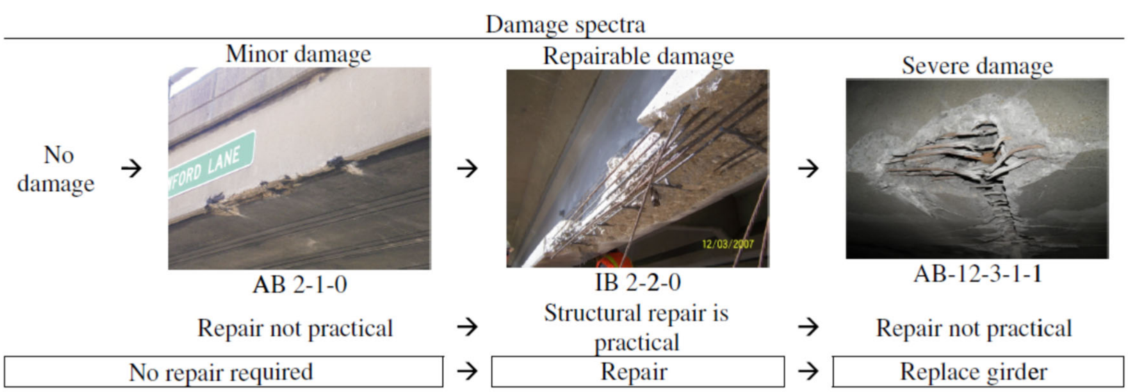


Figure 3-21. Schematic of the design spectra defined by [53].

Harries et al., [82] also provided a damage spectra for prestressed concrete girders with damage intensities defined as: MINOR, MODERATE, SEVER I, SEVER II, SEVER III, SEVER IV. The classification is based on strand lost and camber of the girder. The threshold between SEVERE III and SEVERE IV essentially represents the 'repair or replace' criterion. This is while the threshold between SEVERE I and SEVERE II represents 'Repair or No action' based on the judgment of the design professional. Choosing a proper repair approach for a specific damage state depends on the specifics of the element being repaired and the project requirements. Harries et al., [82] provided a flow chart for the repair selection of prestressed concrete box girders as well as prestressed concrete single-web girders (see Figure 3-22 and Figure 3-23).

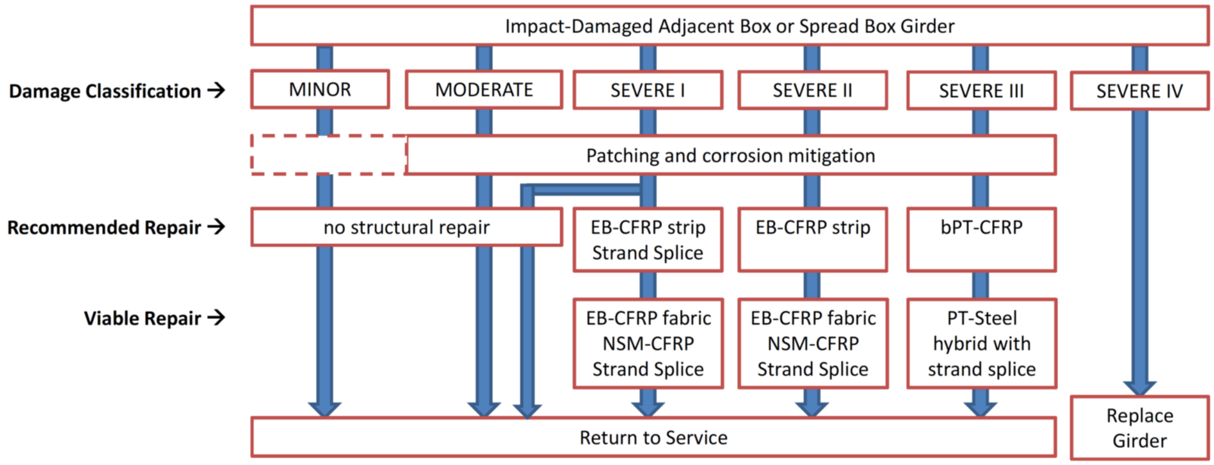


Figure 3-22. Flowchart for the repair selection of prestressed concrete box girders [82].

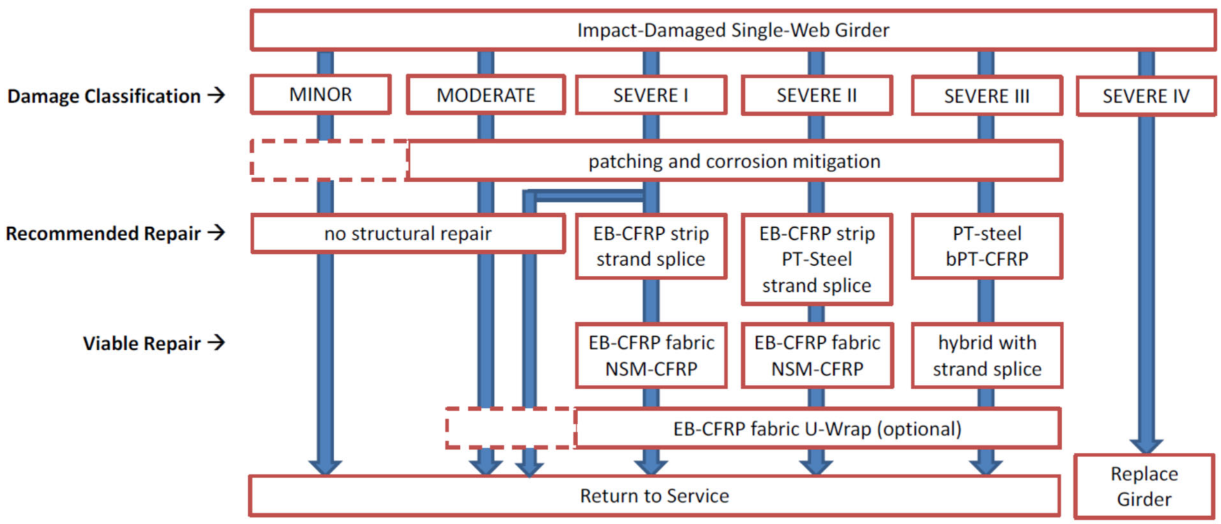


Figure 3-23. Flowchart for the repair selection of prestressed concrete single-web girders [82].

Although it would be best to prevent any collision damages to occur, but it is important to have practical, quick, and cost-effective repair schemes in case overheight vehicle impacts occur [20]. The following section identifies common methods for the repair of bridge girders in that have flexural deficiencies due to vehicle impact damage or other causes.

3.2.2. Common solutions

For flexural repair, it is often recommended that the repair material is applied to the soffit of the girder since the material near the neutral axis is less efficient in strengthening the element [139]. Also, when selecting a repair approach, it is important to consider the area available on the girder for the application of the repair material. In order to make use of the material efficiently, as mentioned before, it is best for it to be applied completely on the girder soffit (tension side of the girder). Extending vertically up the web has reduced efficiency and does not affect the ultimate debonding limit state [53]. This is considered as the earliest and most basic method for upgrading and retrofitting the beams in flexure [78]. This might be done using the EB or the NSM technique. Figure 3-24 shows the application of procured FRP laminates with different widths to the bottom of the girders through epoxy adhesives (EB technique).

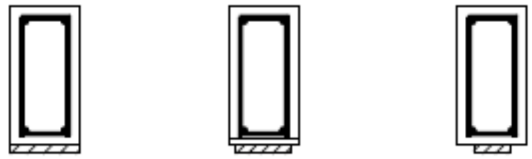


Figure 3-24. CFRP laminates for flexural strengthening of girders [140]

EB CFRP strips can restore or increase the flexural capacity, control cracking, reduce deflections under subsequent load [82]. Cai and Xia [9] demonstrated that for a cast-in-place concrete T-beam, the ultimate capability can be improved by 39 percent.

Specifically for the repair of impact damaged bridge girders, traditionally, strand splicing and external post tensioning have been used. These methods, however, have only been partially satisfactory as they are unable to restore complete ultimate capacity of the damaged member [18]. Therefore, application of the repair material to the soffit of the girder has become the most common method of flexural repair.

3.2.3. Case studies

Case study 1: An example of severe impact damaged bridge girder is shown in Figure 3-25. The entire web and bottom flange between two interior diaphragms were fractured. The girder had 44 prestressing strands which only one of them was severed by impact. The remaining strands all retained their original tension. Normally, a girder with this level of damage would have been replaced. TxDOT engineers conducted a cost and time comparison between repair and replacement. The conclusion was that the repair option can be done in one forth the time and for half the cost of replacement. Therefore, repair using one ply of continuous CFRP U-wraps, covering the entire bottom flange and web between the two diaphragms (see Figure 3-25), was chosen. The bridge was repaired in 5 days with a total direct cost of $47,000. The installed CFRP was inspected 5 years later with no sign of delamination or other deterioration of the CFRP composite (see Figure 3-25c) [33].

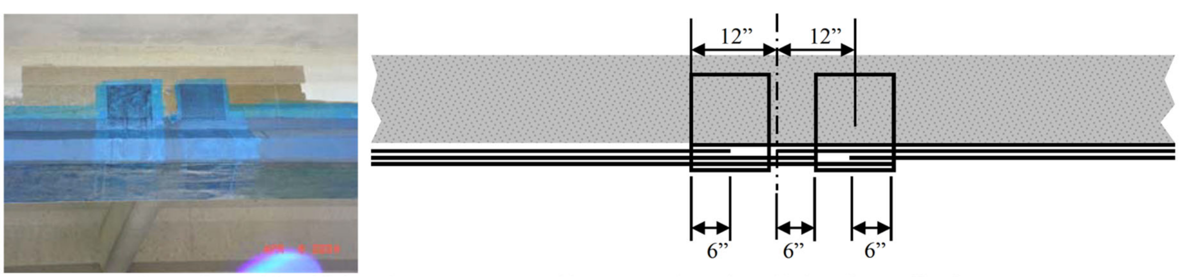
Case study 2: Figure 3-26 shows an impact damaged bridge girder with severed prestressing strands, located in Texas. Eight prestressing stands out of a total of thirty two strands were severely damaged. The spalling and eight severed strands are clearly seen in Figure 3-26. TxDOT engineers decided to use strand splicing in conjunction with CFRP U-wraps for the repair of the girder. Details of the repair procedure is shown in Figure 3-27. The repair procedure included splicing of five of the damaged strands and using CFRP as supplemental tensile reinforcement to offset the three un-spliced strands. All eight severed strands were not spliced because the splicing devices had to be staggered to facilitate concrete placement, which requires removal of more sound concrete. The bridge was repaired in 8 days at a cost of $25,800 [33].

a) The impact damaged beam. b) A continuous CFRP “U” wrap was used. c) The repaired beam after 5 years later.

Figure 3-25. Impact damaged P/S bridge girder in Texas and its repair using continuous CFRP U-wraps [33].

Figure 3-26. Impact damaged bridge girder with severed prestressing strands in Texas, 2004 [33]

Five strands were spliced. Steel pins installed in repair areas. Spliced strands were tensioned.



Overlap splice with additional “U” wraps at mid-span to phase installation for traffic flow

Figure 3-27. Strand splicing and CFRP application for the repair of an impact damage bridge girder in Texas [33]

Case study 3: Another concrete bridge affected by impact damage is shown in Figure 3-28. As it can be seen, the bottom flanges and most of the web of two girders were fractured. One beam had four broken strands, while the other girder had three damaged strands. This means that 85% to 90% of the strands of the two beams were undamaged. Again, TxDOT decided to use strand splicing and CFRP wraps as the repair approach. Longitudinal CFRP sheets with the carbon fibers parallel to the beam were wrapped around the bottom flange and up the side of the beams. Wrapping the CFRP up the sides of the flanges reinforces the bottom flange laterally so as to armor the flange to withstand future impacts (see Figure 3-28). Such impact was probable because of the low vertical clearance of the bridge. The repair was done in one week after the impact at a cost of $70,470. Almost one year after the first impact event, the bridge was damaged again by another impact (see Figure 3-29). The CFRP did appear to laterally strengthen the bottom flange to resist re-impact and reduce the extent of damage. The concrete at the impact point was pulverized and one strand facing the impact was cut. TxDOT decided to use the CFRP repair approach again. The damaged portion of CFRP was removed by saw cutting. The damaged concrete was also removed. The severed strand was spliced. The concrete was repaired and new CFRP plies were lap-spliced over the existing CFRP layers. The repaired girder is shown in Figure 3-29. The repair was completed in 7 days at a cost of $35,000 [33].

Two beams were severely damaged.

About 1/3 of beam length was damaged.

Strands was spliced and tensioned.

Installing the CFRP strengthening.

Figure 3-28. Impact damage to a concrete bridge girder in Texas [33]

Figure 3-29. The re-impacted bridge girder a year after the original CFRP repair [33]

Case study 4: Multiple impact damage is a critical issue for bridges with low vertical clearance. A good example is a concrete bridge in Texas, shown in Figure 3-30. This bridge was subjected to impact damage a couple of times which resulted in large cracks and were repaired by epoxy injection. Later on, the bridge was subjected to three other major successive impacts in 2006, 2007 and 2008. CFRP repair approach was used for the three last impacts.in order to resolve the issue of repetitive impact damages, one solution is to increase the bridge clearance. However, this solution is costly and it might be faced by some restrictions. Another solution, considered by TxDOT engineers is the use of CFRP as “sacrificial” reinforcement to protect the primary reinforcement and the prestressed strands [33].

Major impact damage (2006).

Repaired with CFRP in 2006.

Impacted again in 2007.

Repaired again with CFRP.

Impacted the 3rd time in 2008.

Repaired the 3rd time with CFRP.

Figure 3-30. Multiple impact damaged bridge girder and its repair using CFRP [33]

Case study 5: Graeff [72] conducted an experimental study on the flexural strengthening of impact damaged RC and PSC girders, repaired with CFRP fabrics attached to the soffit of the girders. On order to enhance the flexural repair and to prevent debonding, the effect of CFRP U-wraps with different spacing and configurations (see Figure 3-31) was also investigated. In general, it was concluded that CFRP laminates are able to increase the load carrying capacity of the beams, while reducing deflections. The extent of the capacity increase depends on the reinforcement ratio and the level of damage. For the RC girders: In case the CFRP shear enhancement was not needed, the configuration of transverse U-wraps with spacing between them has shown to provide the same flexural benefits when compared to a fully wrapped beam, with evenly spaced transverse U-wraps being the most efficient. It was also noted important that the damaged section of the girders with loss of reinforcement should be covered with transverse and longitudinal strips to reduce the crack propagation in this region, the critical region. Otherwise, it can initiate early debonding. For the PSC girders, they concluded that again, if shear enhancement is not needed, spacing close to that of the depth of the composite girder can be applied for the U-wrap configuration design to constitute a safe CFRP repair. They also indicated that caution should be taken into the design of such girders as more brittle failures were observed for the CFRP strengthened girders compared to the control undamaged girders [72, 141].

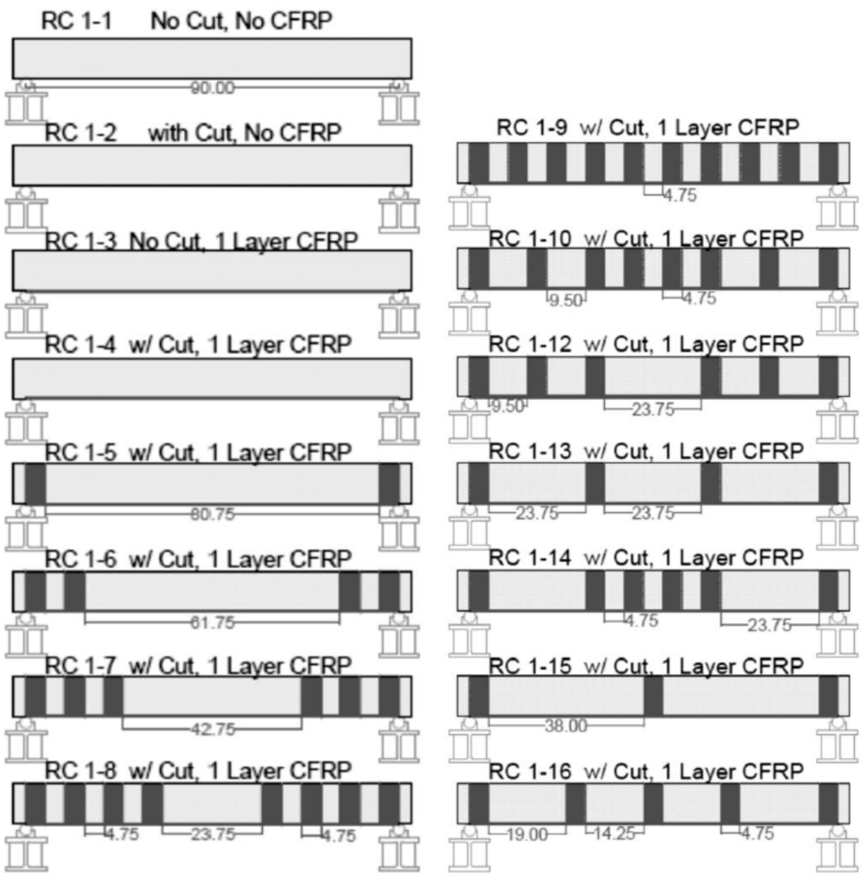


Figure 3-31. Different configuration layouts for transverse CFRP U-wraps in combination with the longitudinal CFRP strengthening of the girder's soffit [72]

Case study 6: Figure 3-32 shows the procedure for the repair of a PC bridge girder that has experienced impact damage. Strand splicing, patching, and FRP U-wraps are used respectively for the repair. The externally applied FRP affords some protection to the patch and, significantly, provides some continuity or 'bridging' between the patch and surrounding concrete. To protect the

GFRP and epoxy resin from UV light exposure, a final protective top coat was applied. This also serves for aesthetic reasons as well [82].

Figure 3-32. Procedure for repair of an impact damaged girder using strand splicing, patching, and FRP U-wraps [82]

Case study 7: Yazdani and Montero [3] utilized GFRP bars for the repair of an overpass bridge which was damaged by vehicle collision in Dallas, Texas. While being under construction. Figure Figure 3-33. shows the schematic of the damaged area as well as the details of the repair. Both longitudinal and transverse GFRP bars were utilized. Two longitudinal bars were located on the top and bottom of the damaged section area and were continued for a length equal to 4.3 m. Transverse reinforcement spaced at 152 mm was also provided between the two longitudinal bars (see Figure 3-33).

Case study 8: Michels et al., [87] used two prestressed CFRP strips on the entire soffit of the girder in the longitudinal direction for flexural strengthening. This system is shown in Figure 3-34.

Case study 9: Charalambidi et al., [142] studied the behavior of rectangular and T-shaped beams strengthened in flexure using both EB and NSM CFRP laminates. As can be seen in Figure 3-35, in the former technique, CFRP laminates with 100 mm width and 1.2 mm thickness are attached to the soffit of the beams. In the later technique, two CFRP laminates were placed into the slits inside the concrete cover surface. Additionally, to avoid fragile shear failure, transverse CFRP sheets were placed on the shear spans of the beams. According to the results of the tests with fatigue loading, in all cases, failure was due to tensile fracture of the steel reinforcement. Moreover, for the beams strengthened with EB laminates, the steel fracture was followed by FRP laminate debonding. The NSM strengthened beams, however, maintained a full bond with the concrete substrate even after the fatigue fracture of steel bars. Therefore, they might be able to provide residual capacity to the retrofitted beams for collapse prevention.

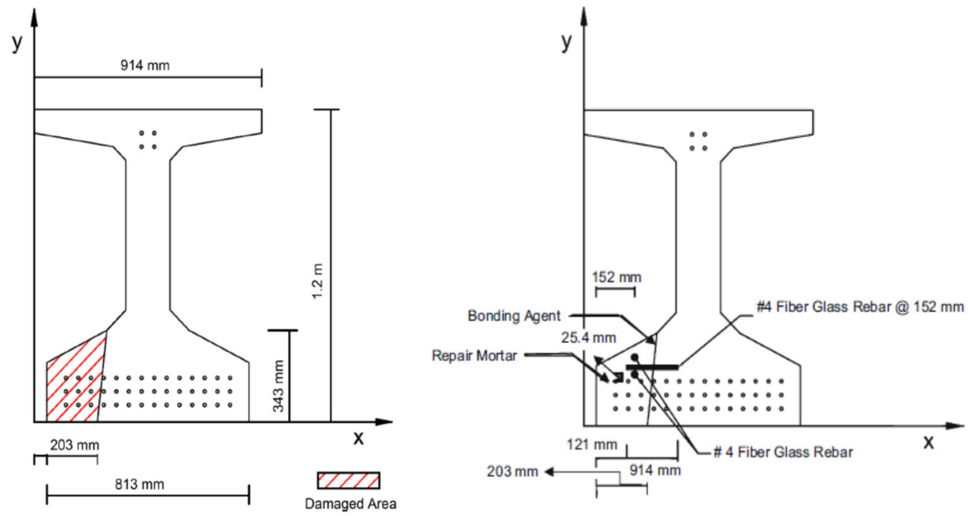


Figure 3-33. Repair approach for an impact damaged girder in Dallas, Texas [3]

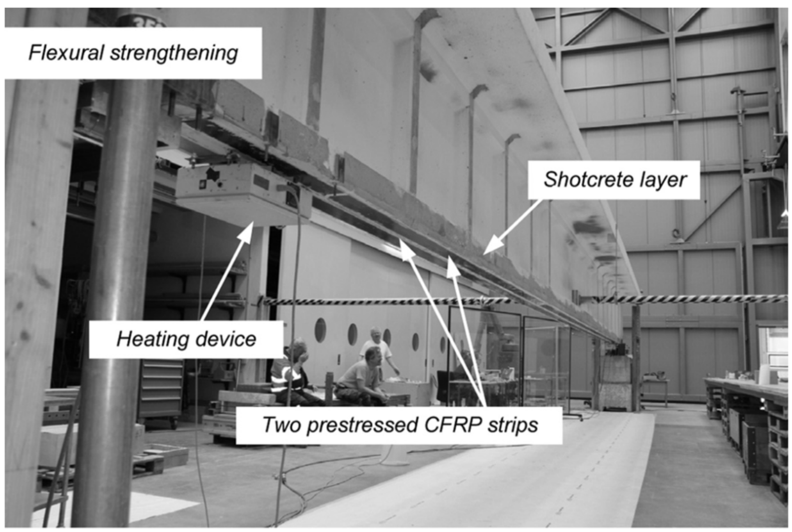


Figure 3-34. Flexural strengthening using two prestressed CFRP strips on the girder soffit [87]

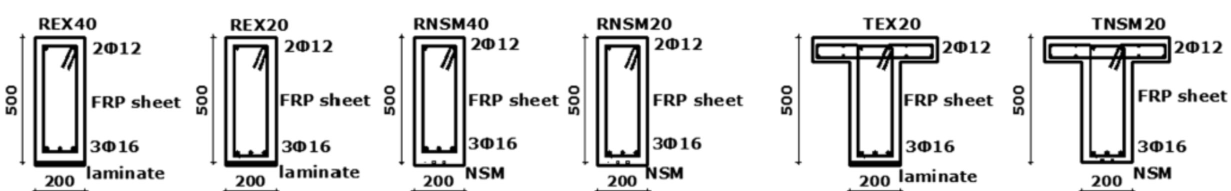


Figure 3-35. Flexural strengthening of rectangular and T-beams using the EB and NSM techniques [142]

Case study 10: Shen et al., [63] used double layer BFRP sheets applied to the bottom (tension side) of 60-year old cracked box beams using epoxy resin. Single layer of BFRP could not provide sufficient modulus of elasticity. The objective of this repair was to increase the flexural capacity of the cracked beams. The beams were also strengthened in shear at the two ends in order to ensure that the failure ode will be in flexure. Double layers of CFRP sheets were used for this purpose. All FRP materials were impregnated with the same epoxy resin, hence the wet layup technique was used. Figure 3-36. shows the detailed implementation of such strengthening technique. As a result of this repair method, load-carrying capacity of the repaired beam was increased at the rate of 27.2% compared with that of the unrepaired beam. Improvements were also achieved in the confinement of concrete crack development.

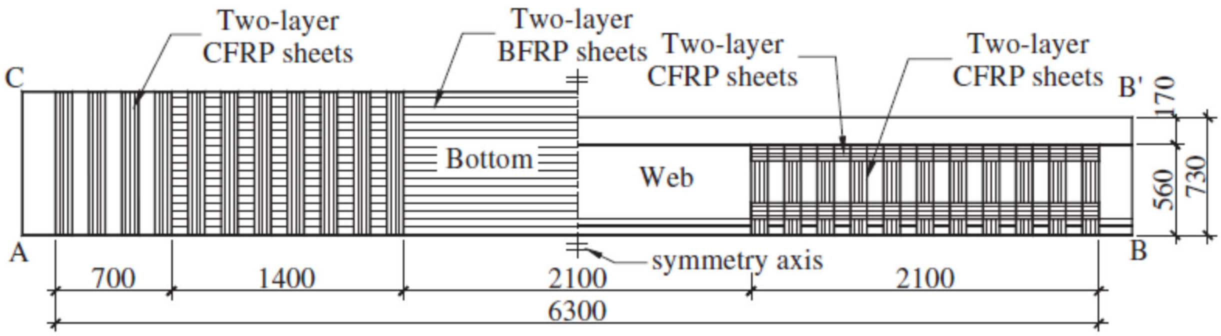


Figure 3-36. Flexural strengthening of RC box beams using CFRP and BFRP sheets [63]

Case study 11: Figure 3-37 shows the flexural strengthening of a rectangular RC beam using CFRP-honeycomb (H-Lam-C) plates. As it can be seen, the plate is applied to the soffit (tension side) of the beam. This method was proved to be effective in increasing the strength and stiffness of the repaired beams. An average gain of 55% and 80% was achieved for beams strengthened with GFRP and CFRP sandwich panels, respectively. However, similar to other conventional FRP strengthening techniques, deflection ductility was reduced [85].

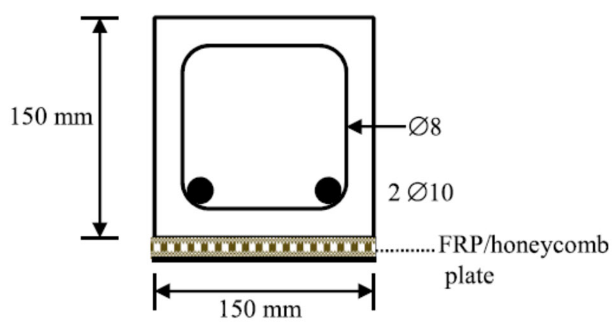


Figure 3-37. Rectangular RC beams strengthened in flexure with H-Lam-C plates [85]

Case study 12: ElSafty et al., [136] used longitudinal soffit laminates for flexural repair of RC girders in combination with evenly spaced transverse U-wraps as the anchorage system. The U-wraps reduce crack propagation and prevent early debonding, and thus increase the ultimate flexural capacity. If shear improvement is not needed, spacing for discrete transverse wraps can be between a distances of one half to one times the depth of girder to constitute a safe CFRP repair. The aforementioned authors demonstrated that repair approaches with two layers of CFRP enhance the flexural capacity by 27.53–45.66 % compared to the control girder. This is while repairs with three levels of CFRP increases the flexural capacity from 60.24 to 68.74 % compared to the control girder.

Case study 13: Babaeidarabad et al., [143] used FRCM fabric applied to the soffit of the beam for flexural strengthening. Experimental results from their study showed that FRCM improves flexural strength of RC beams. The increase in the flexural capacity depends of the amount of FRCM utilized. For low strength concrete, flexural capacity increased between 32% (for 1 ply) and 92%

(for 4 ply) for low-strength concrete. For high strength concrete, the capacity increased between 13% (for 1 ply) and 73% (for 4 ply). However, as the amount of FRCM was increased, the pseudoductility of the section was decreased. Again, based on the amount of FRCM used, two failure modes were observed: (1) fabric slippage within the matrix and (2) FRCM delamination from the substrate.

Case study 14: Hawileh [144] proposed a new FE approach for simulating the behavior of PC beams strengthened with NSM CFRP rods at the soffit of the girder (see Figure 3-38). They concluded that NSM FRP reinforcement of any kind (CFRP, AFRP, or GFRP) increases the flexural strength of the girders. The CFRP rods, however, were the most efficient of all. The increase in the ultimate strength using CFRP rods 18.5% more than AFRP and 43.8% more than GFRP. As can be seen in Figure 3-38, two different rod diameters were used for the repairs. The size of the FRP reinforcement was shown to have a considerable effect on the stiffness and load-carrying capacity of the repaired girders. CFRP rods with larger diameter yielded an increase in the failure load for the girder under repair by 83.6% compared to the smaller CFRP rods.

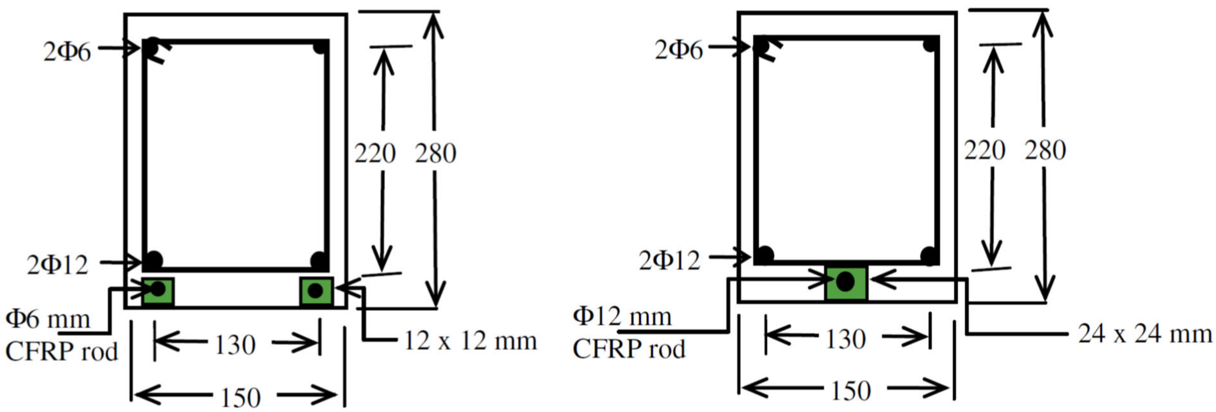


Figure 3-38. Repair configurations used by Hawileh [144] for flexural strengthening of PC girders

Case study 15: Figure 3-39 shows the extent of damage to the bridge 49-4012-0250-1032, located near Sunbury, Northumberland County, Pennsylvania. As it can be seen, the bridge had undergone extensive overall damage. Originally, it was considered for replacement. However, the Pennsylvania Department of Transportation (PennDOT) decided to conduct CFRP repair of the bridge instead. The repair approach included attachment of continuous CFRP sheets to the soffit of the beams, as well as discontinuous CFRP U-wraps as the anchorage system. FRP strips were bonded by using a typical dry application process. In order to quantify the effect of the strengthening technique on the performance of the repaired bridge, FE analyses as well as experimental testing was conducted to investigate the efficiency of the approach utilized for the repair of the bridge. Three different CFRP wrapping approaches were utilized (see Figure 3-40). According to both testing and FE analysis results, they indicated that the overall stiffness of the repaired bridge did not change as much. They also demonstrated that the anchorage system had little effect on the performance of the repaired beams. They concluded that more anchorage would be very beneficial to the long-term durability of an FRP-repair system, as the concrete substrate and FRP-concrete bond is likely to deteriorate over time. Additionally, more anchorage may add ductility to an FRP-repaired structure if concrete debonding begins to occur [35].

Figure 3-39. Extensive damage to the (1) interior and (2) exterior girders of a RC bridge in Pennsylvania [35]

Table 3-2 lists the flexural repair approach used in the literature from year 1991 to year 2019.

Table 3-2. List of different flexural repair approaches used in the literature

No.	Author	Repair approach
1	Shen et al. [59]	EB BFRP sheets on the soffit + EB discontinuous CFRP U-wraps
2	Lee et al. [56]	Post-tensioned NSM CFRP rods with mechanical anchorage at the ends
3	Dias-da-Costa et al. [145]	EB CFRP laminates on the soffit anchored to the beam ends with steel plates
4	Banjara and Ramanjaneyulu [79]	EB CFRP fabric on the soffit
5	Yang and Wang [146]	NSM CFRP strips
6	Peiris and Harik [27]	CRP panels (hybrid composites) on the girder soffit
7	Murthy et al. [58]	UHPFRC (hybrid composites) on the girder soffit
8	Lee et al. [17]	NSM CFRP bar on the girder soffit
9	Kabir et al. [147]	EB CFRP laminate on the girder soffit + CFRP U-wraps at the girder ends and midspan
10	Jawdhari et al. [61]	CRP panels (hybrid composites) on the girder soffit
11	Gangi [60]	Strand splicing, CFRP and FRCM wrap around the girder bulb

12	Woo-tai Jung [57]	NSM CFRP rods
13	Song and Hou [148]	Prestressed EB CFRP sheets on the girder soffit
14	Pino et al. [18]	Strand splicing and/or CFRP and FRCM wrap around the girder bulb
15	Pino, et al. [149]	FRCM EB on the girder soffit
16	Maghsoudi and Maghsoudi [150]	EB CFRP sheets on the girder soffit
17	Lee et al. [151]	Prestressed NSM CFRP bars
18	Lee et al. [152]	Post-tensioned NSM CFRP bars
19	Chen and Cheng [153]	EB CFRP laminates on the girder soffit
20	Al-Saadi et al. [154]	NSM CFRP strips
21	Al-Saadi et al. [155]	NSM CFRP strips
22	Al-Saadi et al. [156]	NSM CFRP strips
23	Pino [157]	Strand splicing, CFRP and FRCM wrap around the girder bulb
24	Peng et al. [62]	Prestressed CFRP plates on the girder soffit
25	Michels et al. [87]	Prestressed CFRP strips on the girder soffit + discontinuous complete wraps with CFRP strips
26	M.Mahal et al. [158]	EB CFRP plates on the girder soffit + CFRP wrap at the girder end, NSM CFRP bars on the girder soffit
27	Huang et al. [81]	EB prestressed CFRP sheets on the girder soffit
28	Gao et al. [140]	Prestressed CFRP laminates on the girder soffit
29	Charalambidi et al. [142]	EB CFRP laminates on the girder soffit, NSM CFRP laminates on the girder soffit
30	Shen et al. [63]	EB BFRP sheets on the girder soffit + discontinuous vertical CFRP U-wraps
31	Pino and Nanni [64]	FRCM EB on the girder soffit

32	Mosallam, et al. [85]	EB CFRP sandwich panels on the girder soffit
33	Kim, et al. [84]	Post-tensioned NSM CFRP strips on the girder soffit
34	Jones [20]	Strand splicing + FRCM on the girder bulb
35	Kasan et al. [139]	EB CFRP fabric on the girder soffit + continuous CFRP U-wrap around the girder bulb
36	ElSafty et al. [136]	EB CFRP laminates on the girder soffit + continuous and discontinuous vertical CFRP U-wraps
37	Bigaud and Ali [159]	EB CFRP laminates on the girder soffit
38	Babaeidarabad et al. [143]	EB FRCM fabrics on the girder soffit
39	Wang et al. [67]	EB CFRP sheets on the girder soffit
40	Choo et al. [28]	EB SFRP sheets on the sides and bottom of the girder
41	Choo et al. [29]	CFRP longitudinal fabric EB on the I-girder's soffit, web, and sides + discontinuous vertical CFRP U-wraps
42	Oudah and El-Hacha [70]	NSM CFRP strips on the girder soffit
43	Oudah and El-Hacha [160]	NSM CFRP strips on the girder soffit
44	Hawileh [144]	NSM CFRP rods
45	Graeff [72]	EB CFRP laminates and strips + continuous and discontinuous CFRP U-wraps
46	ElSafty and Graeff [141]	EB CFRP laminates and strips + continuous and discontinuous CFRP U-wraps
47	Oudah and El-Hacha [161]	Prestressed NSM CFRP strips
48	El-Hacha and Gaafar [162]	Prestressed NSM CFRP bars
49	Dong et al. [163]	EB CFRP fabric to the girder soffit
50	Davalos et al. [35]	EB CFRP strips on the girder soffit alone, or with CFRP U-wraps at the girder end, or with discontinuous CFRP U-wraps along the girder length
51	Bullock et al. [36]	CFRP fabric wrapped around the girder bulb

52	Al-Rousan and Issa [164]	EB CFRP sheets on the girder soffit
53	Ray et al. [165]	EB CFRP sheets on the soffit + EB discontinuous CFRP U-wraps
54	Pantelides et al. [111]	side bonded external post-tensioned carbon fiber rods
55	Martinola et al. [166]	Three sided High Performance Fiber Reinforced Concrete (HPFRC) jacketing
56	Di Ludovico et al. [167]	EB continuous CFRP soffit laminates + discontinuous CFRP U-wraps (around the girder bulb)
57	Davalos et al. [168] and Davalos et al. [169]	EB CFRP sheets on the soffit + EB discontinuous CFRP U-wraps
58	Al-Hammoud et al. [170]	EB CFRP sheets on the girder soffit
59	Rosenboom et al. [171]	EB CFRP and SFRP sheets on the soffit + EB discontinuous CFRP and SFRP U-wraps
60	Pellegrino and Modena [172]	EB CFRP laminates on the soffit with mechanical steel bolted plate anchors at both ends
61	Galal and Mofidi [173]	CFRP sheets (bonded or not bonded) to the girder soffit + hybrid CFRP-steel anchorage system
62	Ekenel and Myers [174]	EB CFRP sheet on the girder soffit
63	Badawi and Soudki [175]	NSM CFR rod at the girder soffit
64	Kim et al. [41]	EB prestressed CFRP sheet on the girder soffit
65	Rosenboom and Rizkalla [176]	EB CFRP sheets on the soffit + EB discontinuous CFRP U-wraps
66	Kim et al. [177]	EB CFRP sheet on the girder soffit + steel anchors at both ends - EB CFRP sheet on the girder soffit + unanchored CFRP U-wraps as end anchor - EB CFRP sheet on the girder soffit + mechanically anchored CFRP U-wraps as end anchor
67	Kim et al. [178]	prestressed CFRP sheets EB at the girder soffit

68	Rosenboom and Rizkalla [179]	CFRP soffit bonding + discontinuous CFRP U-wraps
70	Rosenboom et al. [180]	EB CFRP strips or sheets on the girder soffit + CFRP U-wraps - NSM CFRP bars or strips on the girder soffit
71	Badawi [181]	prestressed NSM CFRP rods
72	Larson et al. [182]	EB CFRP layer wrapped the girder soffit coming up to the web sides a little + external discontinuous CFRP stirrups
73	Gheorghiu et al. [183]	EB CFRP sheets on the girder soffit
74	Czaderski and Motavalli [184]	prestressed EB CFRP plates on the girder soffit
75	Aidoo et al. [185]	EB CFRP strips on the girder soffit - NSM CFRP strips on the girder soffit - Hybrid strips are positioned, predrilled, and fixed to the girder soffit using a commercially available powder actuated fastener system
76	Wenwei and Guo [186]	EB CFRP laminates on the girder soffit
77	Toutanji et al. [187]	EB CFRP sheets on the soffit using an inorganic matrix + EB CFRP strips oriented at 45^{o}
78	Toutanji et al. [188]	EB CFRP sheets on the soffit using an inorganic matrix + EB CFRP strips oriented at 45^{o}
79	Rosenboom and Rizkalla [189]	EB CFRP strips or sheets on the girder soffit + CFRP U-wraps - NSM CFRP bars or strips on the girder soffit
80	Rizkalla et al. [190]	For C-Channel girders: EB CFRP strips or sheets on the girder soffit + CFRP U-wraps - NSM CFRP bars or strips on the girder soffit For I girders: EB CFRP strips or sheets on the girder soffit + CFRP U-wraps
81	Rasheed et al. [191]	EB CFRP sheets on the girder soffit, slightly coming up to the sides

82	Nordin and Täljsten [192]	NSM CFRP quadratic rods on the girder soffit
83	MILLER [193]	EB CFRP sheets on the soffit, and along the web of the girder, and on top of the bottom flange + discontinuous CFRP U-wraps
84	Ekenel et al. [194]	**Rectangular beam:** EB CFRP fabric on the girder soffit wo anchors or with glass fiber anchor spikes - precured CFRP laminates externally bonded with traditional epoxy or with mechanical fasteners
85	Dawood et al. [195]	EB (ordinary and high modulus) CFRP sheets on the girder soffit
87	Rosenboom and Rizkalla [196]	**C-Channel girders:** EB CFRP sheets or strips on the girder soffit - NSM CFRP bars or strips on the girder soffit
88	Quattlebaum et al. [197]	**rectangular girders:** EB CFRP strips on the girder soffit - NSM CFRP strips on the girder soffit - powder-actuated fastener-applied (PAF) CFRP strips
89	Larson et al. [198]	**T-beams:** CFRP sheet wrapped around the girder soffit and slightly up to the web at both sides + CFRP U-wraps
90	Gussenhoven and Brena [199]	**Rectangular girder:** EB CFRP sheet on the girder soffit
91	Ekenel et al. [200]	**Rectangular girder:** EB CFRP fabric on the girder soffit wo anchors or with glass fiber anchor spikes - precured CFRP laminates with mechanical externally bonded with traditional epoxy or with mechanical fasteners
92	Di Ludovico et al. [201]	**I girders:** EB CFRP laminates on the girder soffit + CFRP U-wraps around the girder bulb
93	Carolin et al. [202]	**Rectangular girder:** two EB CFRP strips on the girder soffit – two NSM CFRP rods on the girder soffit
94	Carmichael and Barnes [43]	**T girders:** EB CFRP strips on the girder soffit
95	Calvin E Reed [203]	**T-girders:** EB CFRP sheet on the girder soffit and coming up slightly on both sides of the girder web

96	Brena et al. [204]	**Rectangular beams:** EB CFRP sheets on the girder soffit + CFRP U-wraps, vertical, wo anchorage, to avoid shear failure
97	Pham and Al-Mahaidi [205]	**Rectangular beams:** EB CFRP sheets on the girder soffit
98	Aidoo [206]	**For rectangular girders:** EB CFRP strips on the girder soffit - NSM CFRP strips on the girder soffit - powder-actuated fastener-applied (PAF) CFRP strips
99	El-Hacha and Rizkalla [207]	NSM rebars or strips with CFRP U-wraps at both ends
100	Ekenel et al. [208]	**Rectangular girders:** CFRP laminates on the girder soffit
101	Aidoo et al. [209]	**T-girders:** CFRP sheets on the girder soffit
102	Wipf et al. [210]	**For I girders:** EB CFRP sheet on the girder soffit, alone or in conjunction with transverse continuous CFRP wraps around the bottom flange
103	Ross et al. [211]	**channel beams:** GFRP wraps or GFRP spray applied on the girder soffit, bottom of the flanges and inside surfaces of the web
104	Rosenboom et al. [212]	**C-channel girders:** EB CFRP strips or sheets on the girder soffit + discontinuous CFRP U-wraps – NSM CFRP bars or strips on the girder soffit
105	Reed and Peterman [213]	**T-girders:** CFRP wraps on the girder soffit slightly coming up on the web sides + discontinuous CFRP U-wraps along the girder length or two CFRP U-wraps at both ends
106	Phillips [124]	**T-girders:** CFRP laminates on the girder soffit and slightly coming up on the web with or without CFRP U-wraps
107	Pham and Al-Mahaidi [214]	**rectangular beams:** EB CFRP fabric on the girder soffit
108	Nanni [215]	**I girders:** EB CFRP sheets on the girder soffit + discontinuous CFRP U-wraps

109	Manos et al. [126]	**rectangular beams:** continuous CFRP full wraps for shear repair – for flexural repair: EB CFRP sheets on the girder soffit + continuous CFRP full wraps
110	Heffernan and Erki [216]	**rectangular beams:** EB CFRP sheets on the girder soffit
111	Hassan and Rizkalla [217]	**T-girders:** NSM CFRP bars on the girder soffit
112	Bank et al. [44]	**Flexural repair: Rectangular girders:** CFRP strips on the girder soffit attached using mechanical fasteners
113	Klaiber et al. [45]	**Impact damage, flexural repair: I girders:** strand splicing
114	Hassan and Rizkalla [218]	**T-girders:** NSM CFRP bars on the girder soffit
115	Alkhrdaji [46]	CFRP sheets on the girder soffit
116	Alkhrdaji [46]	**c-channel girders:** Discontinuous CFRP U-wraps
117	Yang and Park [219]	**Rectangular girders:** Polymer Cementitious Mortar and Cement Mortar in the tension zone
118	Rosenboom et al. [220]	**C-channel girders:** EB CFRP strips or sheets on the girder soffit + discontinuous CFRP U-wraps – NSM CFRP bars or strips on the girder soffit
119	Rizkalla and Hassan [221]	**T-girders:** NSM bars and strips and EB sheets and strips on the girder soffit
120	Ghobarah et al. [222]	**rectangular beams:** CFRP and GFRP continuous and discontinuous, vertical and oblique full wraps
121	Arduini et al. [47]	**T-girders:** continuous CFRP U-wraps
122	Hag-Elsafi et al. [48]	**T-girder:** EB CFRP sheets on the girder soffit + discontinuous CFRP U-wraps + discontinuous CFRP strips under the deck in between the girders
123	El-Tawil et al. [223]	**T-girder:** Continuous CFRP U-wraps
124	Deniaud and Cheng [129]	**T-girder:** discontinuous CFRP U-wraps, vertical
125	Wight et al. [224]	**Rectangular girders:** EB CFRP sheets on the girder soffit

126	White et al. [225]	**Rectangular girders:** EB CFRP sheets on the girder soffit
127	Tumialan et al. [49]	**I girders:** EB CFRP sheet on the girder soffit + discontinuous CFRP U-wraps around the girder bottom bulb
128	Spadea et al. [226]	**Rectangular beams:** CFRP plate on the girder soffit with or without discontinuous CFRP U-wraps as anchorage
129	Shahawy et al. [227]	**T-girders:** complete continuous CFRP U-wraps or coming up only slightly on two sides of the web
130	Senthilnath et al. [228]	**Rectangular beams:** CFRP sheets on the girder soffit
131	Sebastian [229]	**Rectangular beams:** CFRP sheets on the girder soffit
132	Schiebel et al. [51]	**I girder:** EB CFRP sheets on the girder soffit + CFRP U-wraps around the girder bottom bulb
133	Rahimi and Hutchinson [230]	**Rectangular beams:** CFRP plates on the girder soffit
134	Papakonstantinou et al. [231]	**Rectangular beams:** GFRP sheets on the girder soffit
135	Nanni et al. [50]	EB CFRP laminates on the girder soffit + discontinuous CFRP U-wraps around the girder bottom bulb
136	Masoud et al. [232]	**Rectangular girders:** discontinuous CFRP U-wraps with or without anchorage. With or without CFRP sheets on the girder soffit. Anchorage is longitudinal CFRP strips at the top of the girder webs.
137	Lamanna et al. [233]	FRP strips bonded or attached using mechanical powder-actuated fasteners to the girder soffit
138	Kachlakev and McCurry [131]	EB CFRP on the girder soffit slightly wrapped up to the sides for flexural repair – continuous GFRP U-wraps for shear repair – combination of the two for both shear and flexural repair
139	Barnes and Mays [234]	**Rectangular beams:** CFRP plates on the girder soffit
140	Naaman [132]	CFRP sheets on the girder soffit + two CFRP wraps at both ends for anchorage

141	Erki and Meier [235]	**rectangular beams:** EB CFRP laminates on the girder soffit – steel plates attached to the sofut of the girder
142	Garden and Hollaway [236]	**Rectangular beams:** EB CFRP plates on the girder soffit
143	Tedesco and Stallings [52]	**T-girders:** EB CFRP plates on the girder soffit with or without continuous CFRP or GFRP side plates
144	Garden et al. [237]	**Rectangular beams:** EB CFRP plates on the girder soffit
145	El-Hacha [238]	EB CFRP straps on the girder soffit - application of post-tensioned CFRP cables to the girder soffit
146	Zobel et al. [239]	strand splicing – repair mortar – prepackaged repair materials
147	Varastehpour and Hamelin [240]	EB CFRP sheets on the girder soffit
148	Norris et al. [134]	**Rectangular beams:** continuous CFRP U-wraps – EB CFRP sheet on the girder soffit +CFRP continuous U-wrap at a distance at both ends of the girder
149	Heffernan [241]	EB CFRP laminates on the girder soffit
150	Picard et al. [242]	EB composite material on the girder soffit
151	Saadatmanesh and Ehsani [243]	EB GFRP plates on the girder soffit

3.3. REPAIR FOR SERVICEABILITY CONCERNS

Serviceability of the nation’s bridge infrastructure is affected by aging and deterioration which can be more critical for bridges subjected to extreme environments and a changing climate. This deterioration can be caused by corrosion and metallic fatigue or the combination of the two which can significantly reduce the strength and serviceability of the bridge [15].

Bigaud and Ali [159] investigated the effect of two degradation factors, corrosion and fatigue on the reliability of concrete bridge girders. They concluded that reliability is highly dependent to the factors governing the corrosion, and that service life after flexural strengthening is strongly related to fatigue damage in concrete. The following two sections explain the effect of corrosion and fatigue on the serviceability performance of the girders in detail.

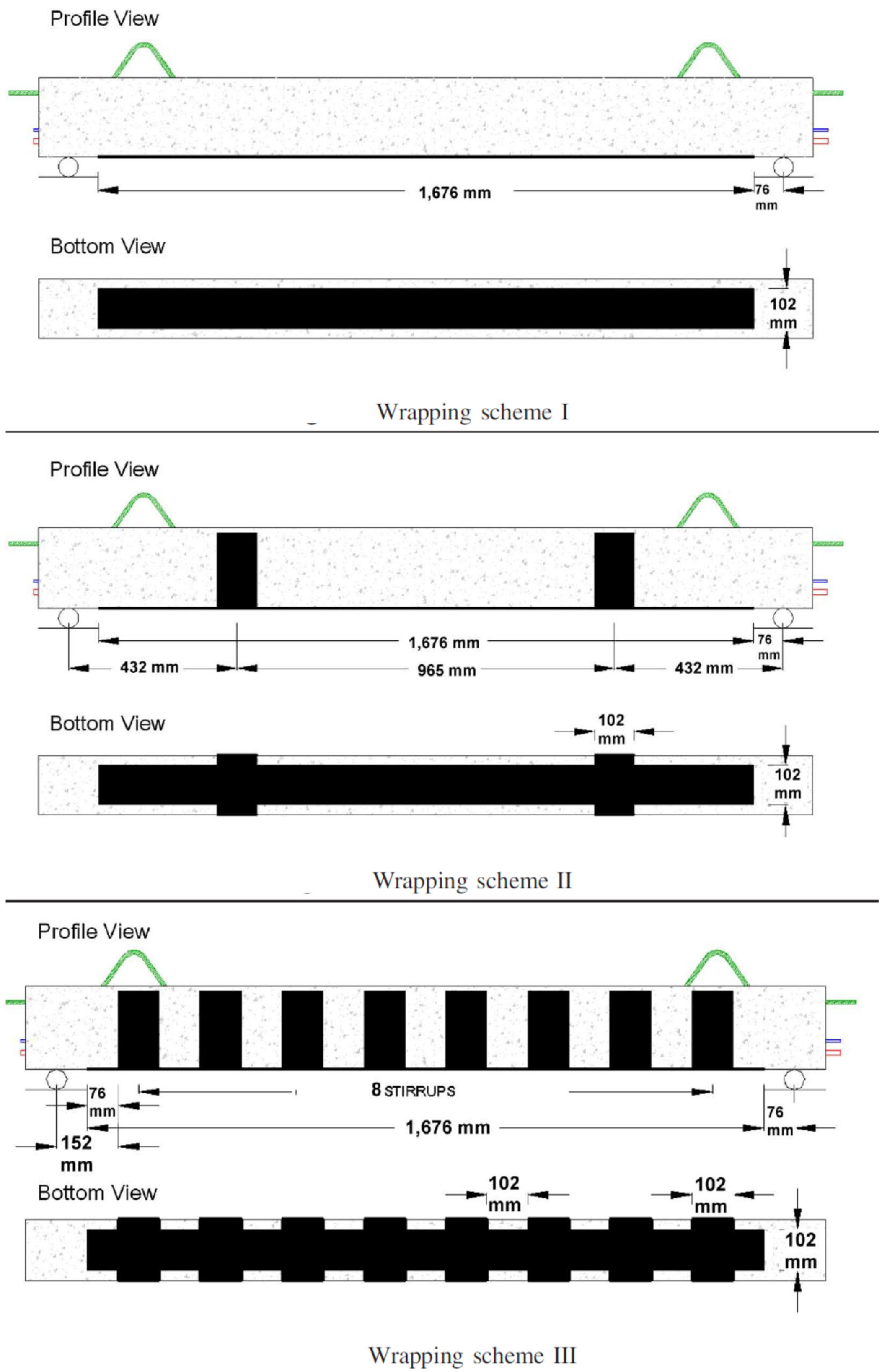


Figure 3-40. Different CFRP wrapping technique used in the study by [35]

3.3.1. Corrosion

3.3.1.1. Causes of damage

Service life of a bridge is improved by increasing the resistance to corrosion, delamination, and concrete cover detachment (CCD), i.e. girder end deterioration (see Figure 3-41), which is initiated by cracking of the concrete. Common causes of prestressed concrete cracking at girder ends are prestressing cut, load hit, diaphragm bond, over-load, insufficient reinforcement, and reinforcement corrosion caused primarily by bridge deck joint leakage and chloride contamination of concrete due to the use of de-icing salts in cold regions and/or windborne salts in coastal/marine environments.

Figure 3-41. Examples of girder end deterioration [19].

Cracking of the concrete can change the dynamic characteristics of the bridge and affect the durability and serviceability of the structure accordingly [63, 75, 244, 245,260]. End-zone cracks parallel or intersecting the prestressing strands can cause debonding. This would result in an increase in transfer and development lengths, consequently reducing the shear and flexural capacity of the girder. If cracks are structurally significant, proper repair approaches should be undertaken to restore their capacity. If the cracks are not significant, and understanding of their effect on the durability of the PC girders is required. This is because cracks expose the strands to chlorides and thus promote corrosion. Chlorides break down the protective passive layer of iron oxides around the internal steel reinforcement and thereby facilitate the corrosion process. Proximity to brackish water environments can also affect the serviceability of the bridge by accelerating corrosion. Figure 3.42 shows the wind-driven waves which splash salt water onto the underside of the bridge girders, accelerating the corrosion. Due to inconsistent exposure of the bridge girders to wind and wave actions, the chloride contamination, and thus corrosion will happen in different locations along the girder. Accordingly, for bridges subjected to wave loads, the damage might not be concentrated on the girder ends only.

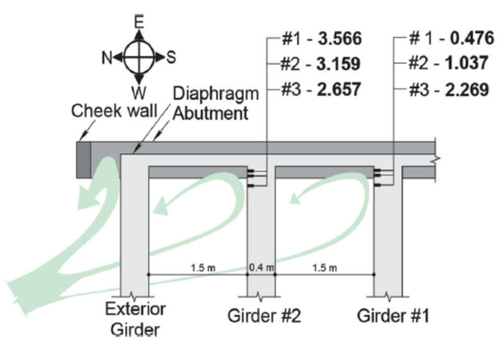


Figure 3-42. Wind and wave action on bridge girders near the abutment [83]

Corrosion is the most important cause of girder end deterioration, and one of the most detrimental sources influencing the performance of reinforced or prestressed concrete structures. Corrosion is more critical in the Midwest and northeast part of the United States due to the harsh climate conditions. In case of steel reinforcement, it reduces the steel area, worsens the steel properties, weakens the bond between the concrete and steel bars, and results in cracking and spalling of the concrete cover. It can also result in the loss of displacement compatibility between steel and concrete [19, 55, 84, 88, 101, 148, 246]. The cost of replacing or repairing corrosion-damaged bridges in the US has been estimated $8.3 billion [101]. Additionally, if corrosion is combined with fatigue, the loss of stiffness and strength can be increased. Effect of fatigue on the performance of the repair scheme is discussed in section 3.3.2.

3.3.1.2. Common solutions

However, previous surveys have indicated that most US states do not repair prestressed girders for end deterioration. Reported repairs have been implemented using coatings, sealers, overlays, electrochemical methods, corrosion inhibitors, admixtures, patching, reinforcing steel protection, membranes, and a combination of treatments. Protective coatings, most of which contain an epoxy resin system, as well as penetrating or surface sealers are the most popular repair approaches especially for low intensity damage levels [19, 88]. Mortar repair, while aesthetically restorative, may not be sufficient in restoring the original shear capacity and stiffness at the end of the beam [55]. Examples of more effective repair schemes used for corrosion such as FRP wraps are discussed in the following section.

Figure 3-43. Example of girder end corrosion (left), and typical mortar repair (right) [55]

3.3.1.3. Case studies

Case study 1: US 150 bridge in Kentucky was repaired using SFRP plates in order to prevent further growth and propagation of diagonal cracks on the girders (see Figure 3-44), which can potentially lead to corrosion of the reinforcing steel, and as a result, undermine the durability of the bridge. The cracks were most likely developed as a results of submergence of the girders during high water-level or flood season. A total of 32 cracked regions were discovered. It was presumed that the cracking started at the soffit and extended up through the entire depth. For the purpose of the rehabilitation of the bridge, SFRP sheets were attached to the soffit and vertical faces of the girder in the cracked regions (see Figure 3-46). Instead of using a continuous long SFRP sheet, splicing at least 24 inches from where cracks were generated was used in construction. Details regarding the implementation of the repair are explained in section 3.1.3.1 [28]

Figure 3-44. Diagonal cracks on the US 150 bridge in Kentucky [28]

Case study 2: Figure 3-45 shows corrosion damage to the girders of the Scheifele Bridge, in the Regional Municipality of Waterloo, Ontario built in 1960. As can be seen, portions of the girders exhibited severe corrosion with evident corrosion-induced cracks and in some cases local concrete spalling. At some regions of the bridge, corroded steel reinforcement was observed as well. However, the bridge inspections and studies showed that strength of the bridge was not affected by corrosion. The bridge was scheduled for full repair after a few years. But, the University of Waterloo research group decided that immediate repair of the bridge is necessary due to the present corrosion level because: (1) serviceability of the bridge could be affected by this level of corrosion as the concrete spalling has led to the complete loss of bond between the steel reinforcement and the concrete (2) the development capacity of the bottom internal steel reinforcement layer would be affected by the spalled concrete at the girder ends (3) the concrete was falling on a horse trail underneath the bridge along the river bank thus presenting a potential danger to the public [34].

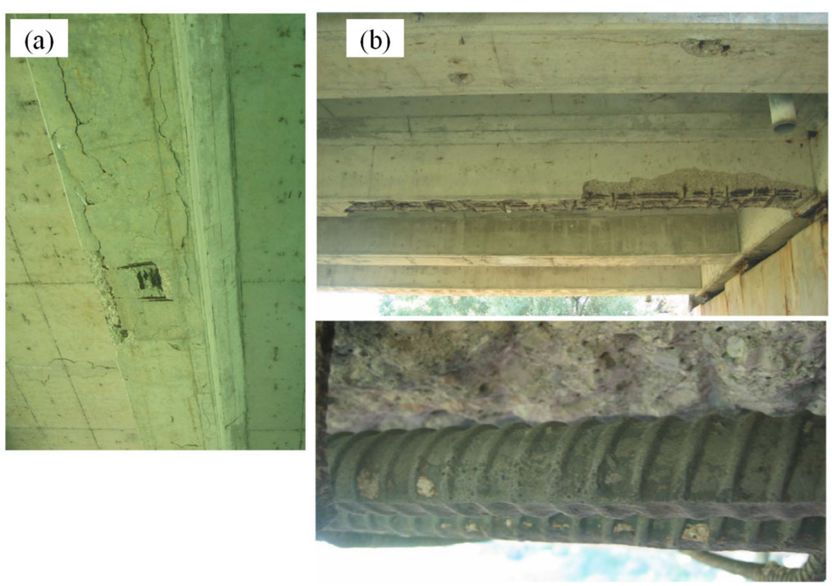


Figure 3-45. Corrosion damage on concrete bridge girder: (a) cracks and spalling (b) corroded steel reinforcement [34]

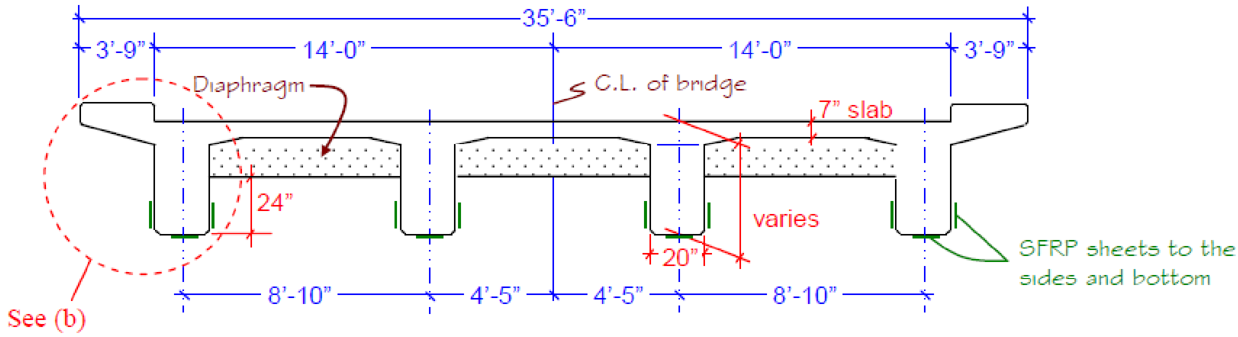


Figure 3-46. An illustration of the SFRP repair approach for corrosion mitigation [28]

The repair approach chosen for the corroded girders was the use of CFRP sheets. First, the cracks were sealed using epoxy injection. Then, the CFRP sheets were applied to the concrete surface (see Figure 3-47). Continuous and discontinuous U-shaped CFRP wraps were used to confine the concrete, minimize or stop the corrosion activity and prevent further spalling. The U shaped sheets were anchored using 2 or 4 longitudinal sheets on the sides. In addition, two longitudinal flexural sheets were attached in all 3 wrapped Sections [34, 247].


Figure 3-47. CFRP repair approach for two different girder sections [34]

Figure 3-48 shows the state of the repaired bridge after 4 years. As can be seen, CFRP repair was able to maintain the structural integrity of the girder with no signs of deterioration. This means that the FRP repair system was able to halt the existing corrosion activity and protect the structural integrity, thus prolonging the bridge service life [34].

Figure 3-48. State of the CFRP repaired bridge in Waterloo after 4 years [34]

Case study 3: Choo et al., [29] used CFRP fabric and CFRP wraps in order to repair cracked PC girders and girders with cracks and concrete spalling, respectively. The two repair schemes are schematically shown in Figure 3-49. The cracking was particularly prevalent near or at fixed end locations where translational movement in the bridge direction is restricted (see Figure 3-50).

Case study 4: As mentioned above, horizontal CFRP fabric in conjunction with vertical CFRP wraps have been utilized to prevent further crack growth and propagation, as well as development of the cracks along the girders. They also provide protection of the steel reinforcement against corrosion since in the absence of this repair scheme the cracks would have started widening and exposing the rebars. Also, they improve the overall aesthetics of the bridge. Figure 3-51 shows the implementation of such repair technique on the cracked girders . Monitoring devices were installed on the bridge which showed that using this repair technique successfully decreases the horizontal deformations of the bridge. The vertical deformations, however, were still apparent [29].

Case study 5: Figure 3-52 shows the state of reinforcement and chloride contents at specified locations along a bridge girder that was repaired in 1999. The hatched areas represents FRP, and the grey areas represent epoxy overlay.

Case study 6: Figure 3-53 shows the repair of a corrosion damaged girders of the Indian bridge in Florida using bidirectional CFRP wraps with the wet layup technique. The CFRP wrap is intended to act as a barrier for the steel reinforcement, in order to prevent further intrusion of chlorides, and thus corrosion damage [83].

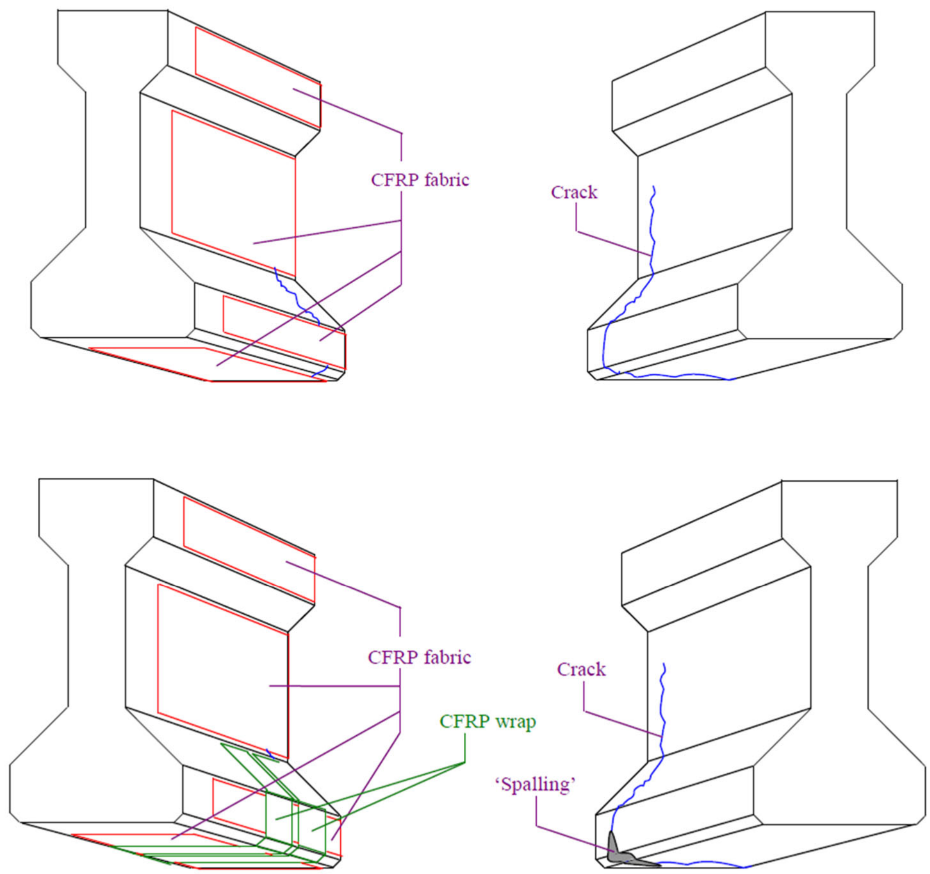


Figure 3-49. schematic of the repair schemes used for cracked PC girders and girders with cracks and spalling [29]

Case study 7: The Ebey Slough Viaduct in Washington was repaired using longitudinal and transverse CFRP plies in order to overcome the problems associated with corrosion of the steel reinforcement as well as spalling of the concrete. The bridge had conventionally reinforced precast concrete double tee concrete units, also known as inverted tub units. Over the years the grout in the keyways had deteriorated allowing water and deicing salt to penetrate between the precast units. This caused the corrosion of the main longitudinal steel reinforcement and spalling of the cover concrete. These damaged areas were generally scattered but mostly predominant in the exterior units. The contract was nearly $7.9 million with 97 days to complete the work. The work began in April 2007 and was completed by November 2007.

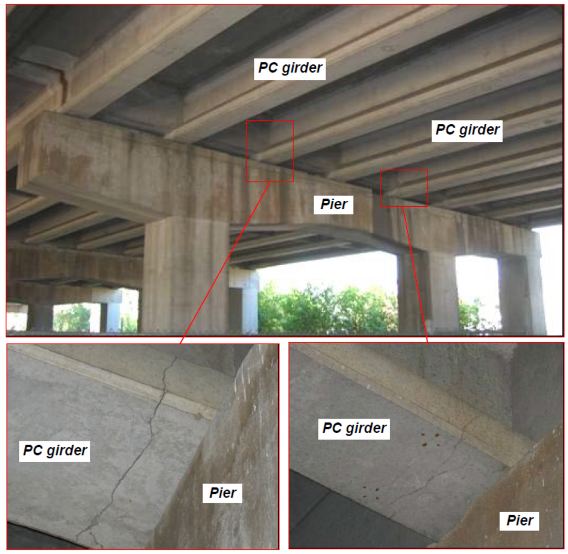


Figure 3-50. Cracking of the PC girders near fixed end locations with two different severities [29]

CFRP fabrics being applied horizontally along the girder

Additional CFRP fabrics were applied vertically

Figure 3-51. Application of horizontal and vertical CFRP fabrics on the PC girders [29]

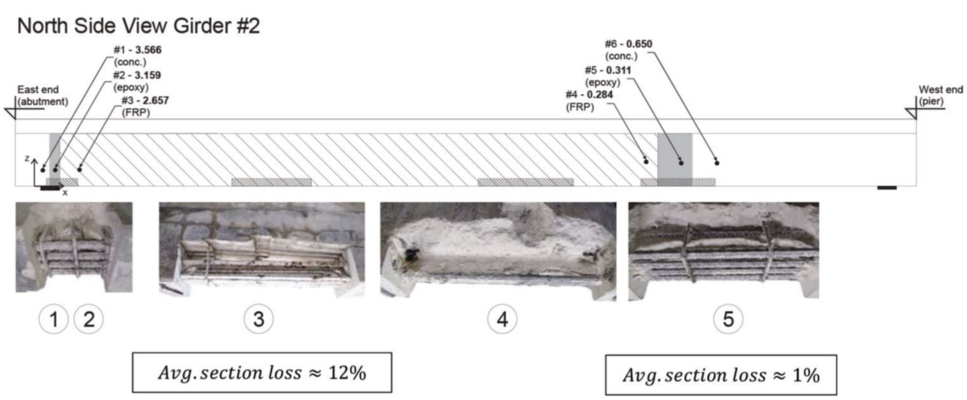


Figure 3-52. The state of reinforcement and chloride contents at different locations of a corroded bridge girder [83]

(a)

(b)

Figure 3-53. (a) Corrosion damage on the Indian bridge in Florida and (b) the CFRP repair for the girders near the abutment implemented in 1999 [83]

3.3.2. Fatigue

3.3.2.1. Causes of damage

Heavy daily traffic on bridges is the main cause of cyclic loading, and thus fatigue in the bridge elements. The cyclic loads produce stresses in the bridge elements well below the ultimate strength, resulting in microscopic damage accumulation until a crack develops. Progressive growth of these cracks can lead to fracture and eventually failure of the component if the stress amplitudes are sufficiently large [5, 248]. Fatigue life of the bridge girders repaired with innovative materials is very important in the service life of the bridges since the cyclic behavior of the new materials is usually not yet well understood. This includes, the fatigue life of the bridges repaired with FRP-based materials.

Fatigue is usually of more importance in the service of the steel bridges. However, it is also of prominent importance in the performance of RC bridges reinforced with steel rebars [5]. FRP materials, particularly CFRP, exhibit excellent performance when subject to fatigue loads. In terms of tensile S-N behavior, CFRP material degrades at a rate approximately one half that of steel. This means that the slope of S-N curve is half that of steel [82]. Oudah and El-Hacha [249] conducted a comprehensive literature review on the fatigue performance of RC beams strengthened in flexure using FRP materials. The following observations were made: (1) The progressive bond degradation and concrete creep lead to the increase in the crack width and the deflection during the fatigue loading. CFRP flexural strengthening of RC beams improves the general serviceability performance in terms of reduced deflection, reduced crack width, etc. However, it will not result in a significant increase in fatigue life if the cyclic steel stress range in the tension steel is maintained the same before and after strengthening. (2) The effect of fatigue loading on the post-fatigue monotonic behavior in terms of yielding and ultimate loads and deflection is insignificant. However, fatigue loading results in a bilinear response as a result of reaching the full cracking stage during cycling. (3) Steel fracture is the primary mode of failure (4) In case the FRP material is prestressed, degradation is significantly limited. However, the increase in the prestress level may result in a transition of the failure mode from steel fracture to FRP ruptures.

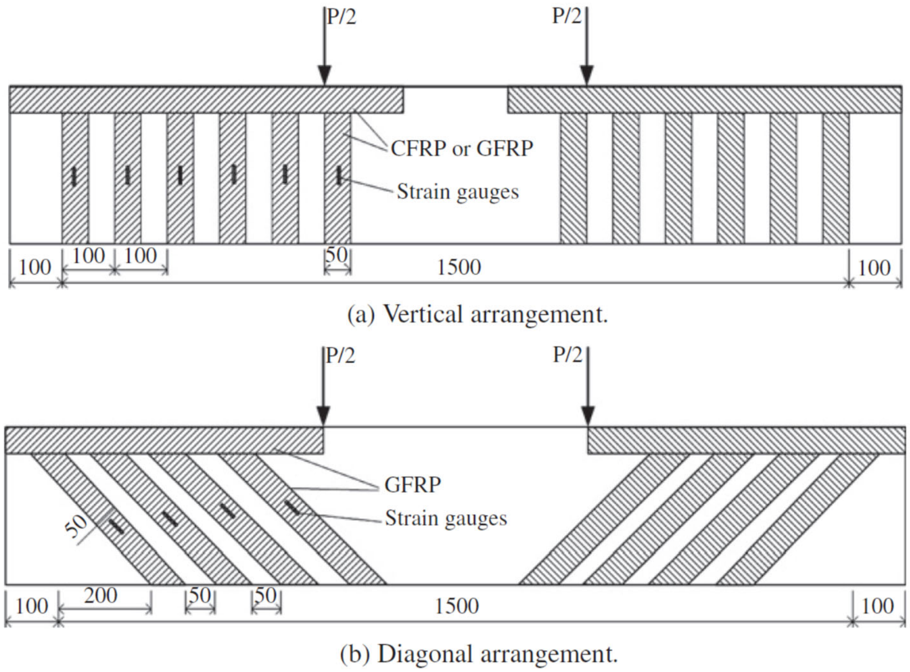
One of the concerns arising from fatigue loads is the relative movement that occurs between the girder substrate and unbonded repair materials. For example in case of unbonded post-tensioned CFRP material or post-tensioned steel material. In these cases, unbonded repair materials must be physically isolated from the substrate girder to avoid the possibility of fretting along this discontinuous interface [82].

3.3.2.2. Common solutions

Fatigue is not actually a deficiency for the structural element by itself. However, fatigue conditions can adversely affect the performance of the repair approach being used. Therefore, finding solutions to reduce the potential adverse effects is needed. For the externally bonded (EB) systems in particular, their performance might be affected by fatigue loading which can lead to system deterioration either by affecting the bond behavior or by reducing ductility (deformation capacity). The former, in a well detailed application, does not lead to a significant reduction in ultimate repaired member capacity. The latter is not of that much concern for prestressed concrete members. Additionally, it is not a concern specific for fatigue loading as even in low stress levels, degradation can happen for RC members. In other words, there is no endurance limit below which fatigue-induced degradation is no longer a concern. The choice of adhesives can be effective in reducing the fatigue effects. For relatively low fatigue stress ranges typical of prestressed girder repairs, a stiffer adhesive will exhibit minimal degradation. At higher stress ranges, however, a softer adhesive will provide greater ductility and may be expected to behave in a more predictable manner. In case of static loads, a stiff adhesive is preferred [82].

3.3.2.3. Case studies

Case study 1: Dong et al., [108] studied the shear fatigue behavior of RC beams strengthened with externally bonded CFRP or GFRP sheets. For this purpose, they conducted a number of tests on RC beams with two different strengthening schemes shown in Figure 3-54. In all the beams, one layer of FRP was applied to the soffit of the beam. The bonding FRP sheets, however, were applied vertically for some beams and obliquely for the others. The results indicated that FRP strengthening was successful in enhancing the fatigue resistance of the beams and increase the first crack load, ultimate strength, and ductility of the beams significantly. It was shown that the diagonal GFRP configuration was more effective compared to the vertical arrangement in increasing the shear strength and stiffness. However, the CFRP strengthened beam had the highest ultimate strength but the lowest deflection.



(a) Vertical arrangement.

(b) Diagonal arrangement.

Figure 3-54. FRP strengthening schemes used by [108]

Case study 2: Oudah and El-Hacha [161] investigated the performance of the RC beams strengthened using NSM CFRP strips at the soffit of the beam (see Figure 3-55) under fatigue loading. The CFRP strips were either not prestressed or had prestressing force equal to 20, 40, and 60% of the CFRP ultimate tensile strength. The experimental were indicative of the occurrence of deboning during the initial cycling of beams prestressed to 0 and 20%, whereas no signs of bond degradation were observed in the other beams. Therefore, it was concluded that prestressing the CFRP strips enhances the bonding properties and results in an overall CFRP strain increase at the completion of the fatigue loading.

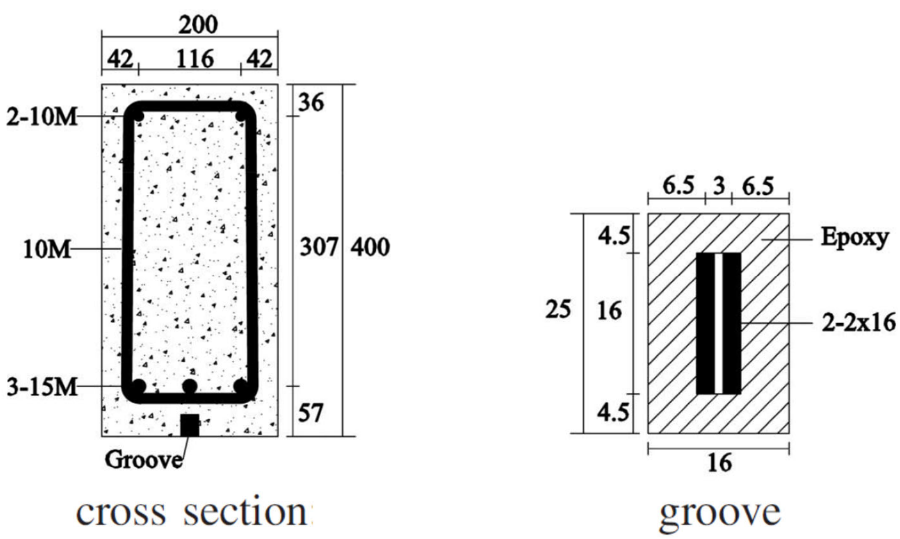


Figure 3-55. Schematic of the NSM mounted CFRP strengthening approach used by [161]

Case study 3: Dong et al., [163] studied the fatigue behavior of CFRP strengthened rectangular beams in flexure using the EB technique. Schematic of the strengthening approach is shown in Figure 3-56. As can be seen, the utilized approach is simply attaching continuous CFRP fabric to the soffit of the beam. The fatigue tests showed that the primary mode of failure is due to fatigue of the steel reinforcement followed by debonding of the CFRP system as a secondary failure mode. Once debonding had started, it propagated quickly with increasing load cycles. The failure was sudden and signs of severe damage appeared only a few cycles before failure. Therefore, the aforementioned authors proposed that the criterion for the fatigue design of RC beams strengthened with CFRP should be to limit the stress range in the steel reinforcement.

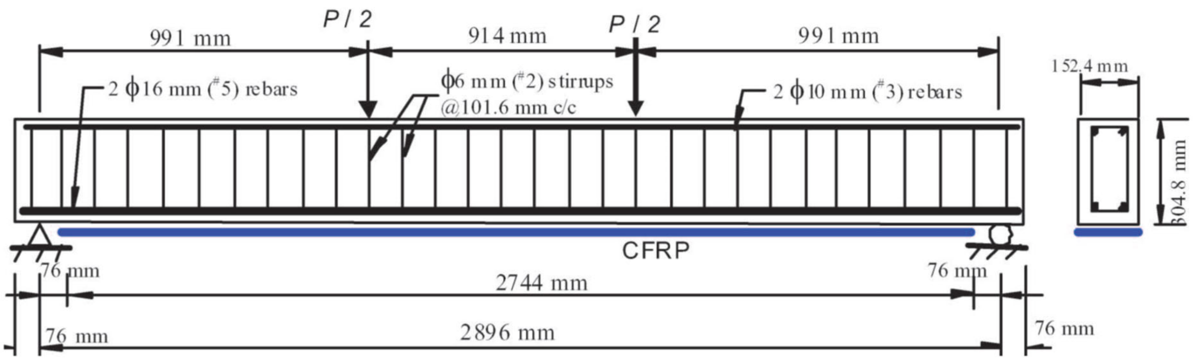


Figure 3-56. Schematic of the flexural strengthening approach used by Dong et al. [163]

Case study 4: Al-Rousan and Issa [164] studied the fatigue behavior of RC rectangular beams with different CFRP configurations. As can be seen in Figure 3-57, this includes different number of CFRP layers, and different CFRP contact area. According to their nonlinear FE analyses, the increase in number of CFRP layers and CFRP contact area with concrete have a considerable decrease on mid-span permanent deflection, and an increase in stiffness and ultimate load. They also demonstrated that strengthening the sides of the beams will improve the effectiveness of CFRP-strengthening through controlling the width and propagation of the shear cracks and providing confinement to the beam [164].

Case study 5: Yu et al., [250] studied the fatigue performance of rectangular RC beams strengthened with GFRP materials through experimental testing. The tested beams were strengthened with two layers of GFRP material applied continuously to the soffit of the girders using epoxy resin. The results indicated that the failure mode of the strengthened beams follows the fracture of steel reinforcement, debonding of the GFRP sheets, and concrete crushing. It was indicated that the GFRP sheets reduced the stress in the reinforcing steel and contributed in bridging the cracks in the concrete. Additionally, the presence of the GFRP sheets, reduced the number of the cracks as well as the crack size, hence, improving serviceability.

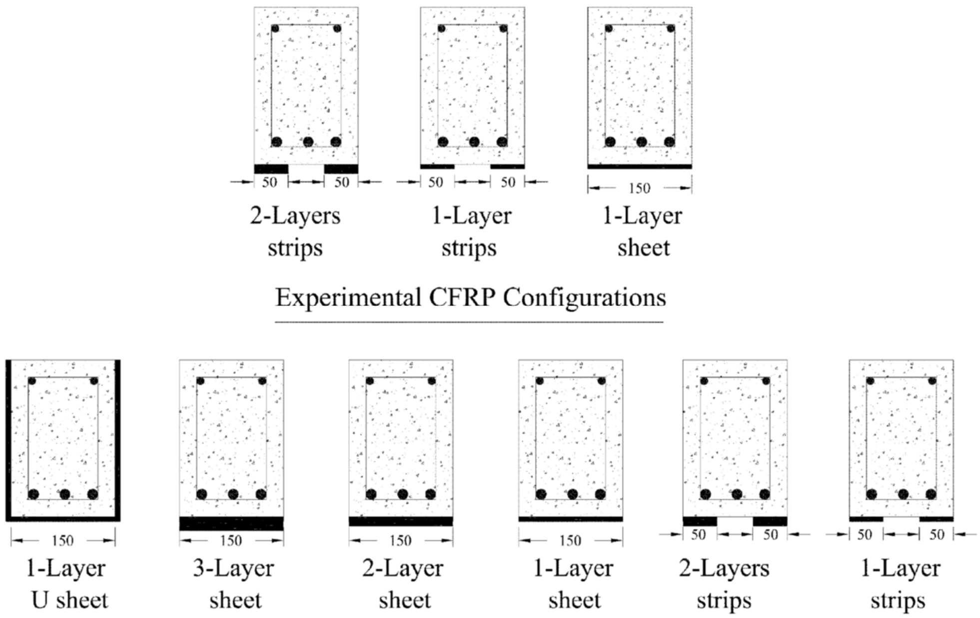


Figure 3-57. Different CFRP configurations for strengthening RC rectangular beams [250]

Case study 6: Al-Hammoud et al., [251] studied the flexural fatigue behavior of corroded RC rectangular beams. The repair scheme is shown in Figure 3-58. As can be seen, the repair approach consists of a continuous CFRP sheet attached to the soffit of the beam for flexural strengthening. The longitudinal sheet is confined by CFRP U-wraps along the length of the beam. The experimental results showed that the failure mode of both strengthened and unstrengthened beams was caused by the rupture of the steel reinforcement. However, Repairing with CFRP sheets increased the average fatigue strength of the beams by reducing the stress range on the steel reinforcing bars. In this study, the effect of additional layers of CFRP was also investigated. It was concluded that, on average, the additional CFRP layer did not make a noticeable increase in the strength of the beams.

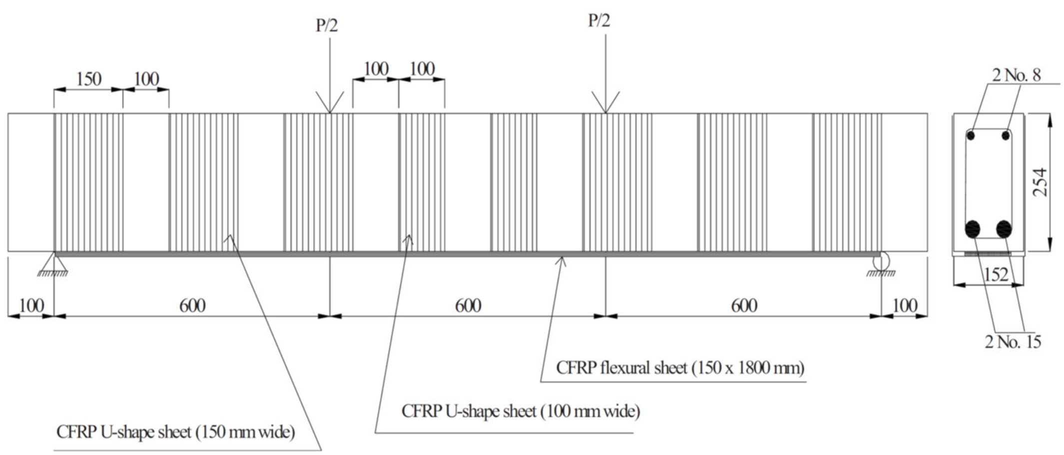


Figure 3-58. CFRP repair scheme for corroded RC rectangular beams [251]

3.4. REPAIR FOR FIRE DAMAGE

3.4.1. Causes of damage

Fire hazard for bridges is caused by crashing vehicles, burning of fuels in the vicinity of the bridges, arson, and wildfire. Fire due to vehicle crashing and burning of the fuels are typically caused by gasoline, also known as hydrocarbon pool fires. The heating rate, intensity, and duration of such fires are different than standard fires and need independent research, and possibly, special fireproofing requirements [252]. Fire damage is rare, but occurs occasionally when the resulting elevated temperature is high enough to damage the concrete cover. The heat dehydrates the concrete, evaporating its stored pore water, which weakens the cover concrete and reduces its compressive strength. This reduction can be up to 70% with further increase of the temperature. The heat may also result in cracking, delamination, and spalling from the expansion of aggregates and steel reinforcement.

3.4.2. Common solutions

Where external FRP wraps are used for strengthening of the bridge girders using epoxy resin as the adhesive, it is important to acknowledge that the mechanical properties of the epoxy resin are influenced by temperature and that they significantly degrade at or above the glass transition temperature. At this temperature, the resin changes from a glassy state to viscoelastic state. That is why, ACI 440 recommends ignoring the capacity contribution of FRP, in such situations. Thus, bridge hydrocarbon fire hazard in the FRP retrofit projects should be considered as an important factor in the repair design in case the bridge is identified as fire-critical. This is important due to the substantial increase of petrochemical transport along the nation's vast highway network and high number of bridge collapses caused by fire which bring up extreme economic impact. Collapse of the two-span MacArthur Maze Bridge in Oakland, California, on April 29, 2007 due to a fire is an example, which caused an estimated $6 million a day total economic impact to the Bay Area [65, 252, 253]. A layer of properly designed insulation over the FRP wraps can be a solution to this problem to avoid debonding of the FRP and concrete spalling, and to slow down the temperature rise in the prestressing strands [253]. Use of cement-based adhesives instead of epoxy could also be an option as they are non-flammable and efficient adhesive materials [154].

3.4.3. Case studies

Case study 1: Beneberu and Yazdani [253] used a cement-based dry-mix fire protection mortar as fire proofing to protect the strengthening CFRP wraps from direct heat exposure. The material contains phyllosilicate aggregates, which are highly effective in resisting fire. They applies a uniform layer of 40 mm to the bridge girders which was challenging in the presence of high winds. The waterproofing was able efficiently protect the CFRP strengthened girders which were subjected to a hydrocarbon pool fire.

Case study 2: Figure 3-59 shows an example of a cast-in-place concrete bridge in Texas damaged by fire. The fire was caused by a tanker truck that went over the bridge rail, then slid under the bridge, and burst into flames. Five beams in addition to other bridge elements were severely damaged. A thorough inspection revealed that the depth of damaged concrete was limited to the concrete cover in most areas. In some areas the depth was slightly deeper than 2 or 3 in. (50 mm or 75 mm) from the original surface. Although no damage was observed in the core concrete, damage to the cover concrete in the compression zones of the girders can significantly affect the performance of the bridge. The steel reinforcement appeared to be undamaged as well, indicating that the concrete cover provided adequate thermal protection. As a solution, TxDOT engineers decided to use CFRP in combination with enhanced concrete repair practices. Before applying the CFRP material, proper surface preparation was implemented. Welded wire mesh was attached to the girders using steel pins, and then shotcrete was applied to the surface and was left to be cured. CFRP fabric was then saturated and applied longitudinally along the soffit of the girders. Discontinuous CFRP U-wraps were also attached around the web of the girders to enhance the integrity of the repaired concrete section as well as to reinforce the shotcrete cover concrete. The bridge was repaired with an emergency maintenance contract in 24 days at a cost of $640,000. An illustration of the complete bridge repair is shown in Figure 3-59 [33].

A fire damaged Bridge in May 2005.

Steel anchors/wire meshes were placed.

CFRP system installed in girders.

Bridge after repair of fire damage (2005).

Figure 3-59. Example of a fire damaged concrete bridge and the utilized CFRP repair [33]

3.5. MISCELLANEOUS REPAIR CASES

Case study 1: Bullock et al., [36] investigated the performance of the FRP repair applied to a PC bridge in Alabama. Wide cracks were observed on the prestressed concrete bulb-tee girders of the bridge shortly after construction. As can be seen in Figure 3-60, some cracks extended through the bottom flange, into the web, and as far as the intersection of the web and upper flange. The cause of the cracking was inspected to be restrained thermal deformations and inadequate reinforcement details.

Initially, epoxy injection was chosen as the repair approach (see Figure 3-61). The objective was to seal existing cracks and prevent future crack growth. However, new cracks often formed near the epoxy-injected cracks, and many epoxy-injected cracks reopened, indicating that this repair technique was ineffective [36].

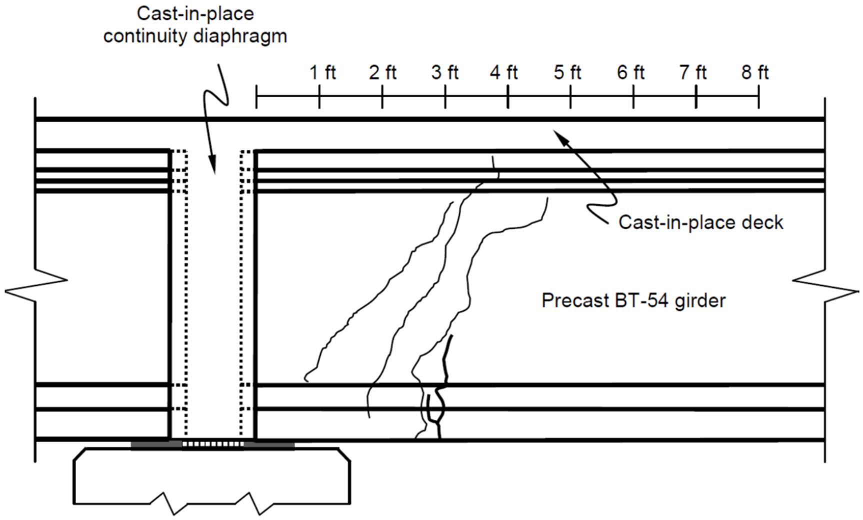


Figure 3-60. Cracking pattern in the end region of a precast girder [36]

Figure 3-61. Epoxy injection of the cracks [36]

Eventually, a 4-ply FRP system applied at the bottom flange of the girders was chosen as the repair approach (see Figure 3-62). The repair approach was expected to provide adequate positive bending resistance, as well as adequate shear resistance, regardless of continuity conditions. Additionally, it was also expected to shift future cracking, associated with the restrained deformations of time- and temperature-dependent effects, to a more acceptable location at the face of, or within, the continuity diaphragm. During post-repair testing, the repair system had been in service for more than 2 years without exhibiting signs of debonding or other deterioration. Also, no additional signs of severe cracking were observed at the repaired region since the installation of the FRP reinforcement [36].

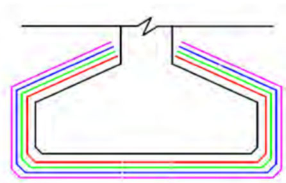


Figure 3-62. FRP repair approach for cracked precast girders [36]

Case study 2: Route 378 Bridge Over Wynantskill Creek, in New York was repaired using FRP laminates in 1999. The objective of the repair was to contain the observed freeze–thaw cracking, as well as to strengthen the girders in flexure and shear. Schematic of the repair approach is shown in Figure 3-63. As can be seen, in this repair approach, continuous FRP laminates attached to the girder soffit in conjunction with discontinuous FRP U-wraps are utilized. Total cost of the rehabilitation was estimated at $300,000, which may be compared to $1.2 million required for replacement of the structure. Load testing of the bridge in 2001 indicated that the quality of the bond between the FRP laminates and concrete, and effectiveness of the retrofit system have not changed after two years in service [37, 38].

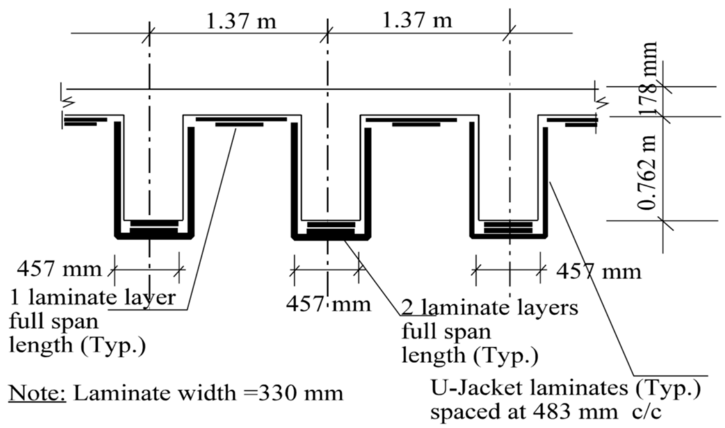


Figure 3-63. Schematic of the repair approach for a bridge in New York [38].

Chapter 4. REPAIR PROCESS

As the first step in the repair process, inspection and monitoring [254, 255] should be done on the bridge. This may be performed on a periodic or usage basis, or motivated by reports of damage or extreme loading to determine the severity of the damage, cause and prognosis. The existing load-carrying capacity of the structure should be determined. Any structural deficiencies and their causes should be identified. The condition of the concrete substrate should also be understood. Other parameters that should be specified as well include: the existing dimensions of the structural members; the location, size, and causes of cracks and spalls; the location and extent of any corrosion of reinforcing steel; the presence of any active corrosion; the quality and location of existing reinforcing steel; the in-place compressive strength of the concrete; and the soundness of the concrete, particularly the concrete cover in all areas where the strengthening material is going to be bonded to the concrete. Then, a decision is made about the type of action needed for the bridge which can be: repair, demolish, or leave alone and keep monitoring [1, 72]. If repair is needed, then the next step is to choose an appropriate repair material. Availability and durability of the material, ease of handling on site, cost-effectiveness, type and condition of the structural element, and the targeted enhancement in the structure are factors that should be considered in making this decision. The resulting change in the size of the element that is being repaired is also an important factor as it affects the overall aesthetics of the element and might enforce additional labor cost and disruption of the structure's service. This is controlled by the thickness of the strengthening material used [78]. Another important factor is the shape of the girder cross section is important in the choice of the repair technique. For example, for rectangular beams, the most common way of repair is fully wrapping of the member. For T-beams, however, this solution is impractical due to the presence of the flange. Therefore, U-wraps and side-bonding configurations as well as the use of mechanical anchorage systems are to address the issue of debonding commonly used for such beams. This is an important research topic since most RC bridge girders have a T-shaped section [95]. Harries et al., [82] provided a repair technique selection criteria based on a number of parameters including: (1) is it commercially available? (2) girder type (box girder or I-girder) (3) dominant repair limit state (4) severity of the damage that it can repair (5) fatigue performance (6) strengthening beyond undamaged capacity? (7) can be combined with strand splicing? (8) speed of mobilization (9) constructability (10) specialized labor required? (11) proprietary tools required? (12) lift equipment required? (13) closure below bridge? (14) time for typical repair (15) environmental impact of repair process (16) durability (17) cost (18) aesthetics.

For precast, prestressed concrete girders, methods such as shotcrete or patching with repair grouts might be used if the damage is minor. Internal strand splices, strengthening with steel plates, and external posttensioning have been shown be partially satisfactory as they are often unable to restore complete ultimate capacity of the damaged member. That is why fiber reinforced composites and other innovative methods have recently gained popularity for more extensive repair problems [64].

In case FRP based materials are used for repair, the following codes can be used to provide recommendations on the repair process:

- AASHTO (2013), Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements.
- AC125 (2012), Acceptance Criteria for Concrete and Reinforced and Unreinforced Masonry Strengthening Using Externally Bonded Fiber-Reinforced Polymer (FRP)

Composite Systems. AC125 is issued by ICC Evaluation Service to establish minimum requirements for the issuance of evaluation reports on fiber-reinforced polymer (FRP) composite systems under the 2012, 2009 and 2006 International Building Code (IBC) and the 1997 Uniform Building Code (UBC).
- ACI 440.3R (2004), Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures.
- ACI 440R (2007), Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures.
- ACI SP-215 (2003), Field Applications of FRP Reinforcement: Case Studies.
- ISIS (2008), Design Manual No. 4, FRP Rehabilitation of Reinforced Concrete Structures, issued by the Canadian Network of Centers of Excellence on Intelligent Sensing for Innovative Structures.

In practice, most of the repair methods might cause concerns for the industry and DOT decision makers regarding their performance in effectively strengthening the deficient bridge girders. This is because for most repair technique, there is a lack of readily available laboratory results. [26, 88]. Concerns that may arise for a chosen strengthening method are: bond performance which in turn affects the failure mode. Bond strength requirements of the strengthening methods are difficult to calculate, and depend on the exact geometry of the repaired element [26]. In order to mitigate such concerns, in many rehabilitation projects, gradual monitoring through proper instrumentations are used to make sure the desired performance criteria are met [25, 26].

After choosing the appropriate repair method, repair design, implementation, and post-repair assessment are the final steps. This section focuses on the implementation procedure for different repair methods. First, special considerations that might exist in any process are explained. Then, different approaches of surface preparation are identified and briefly explained. Three different technique for the application of the repair material along with application examples are then introduced. Finally, optional procedures that might be used depending on the type of the damage including pre-stressing of the material, anchorage system, and strand splicing are discussed.

4.1. Special considerations

The following special consideration might exist for some repair methods:

Material toxicity: Resins that are commonly used to bond FRP materials to the concrete surface concrete can cause skin irritation and are harmful to breathe. Therefore, disposable suits, gloves, dust masks or respirators, and safety glasses or goggles are recommended during mixing and placing of resins [20].

Temperature: Additionally, FRP installation should not be done on cold surfaces without an auxiliary heat source. Therefore, the FRP system manufacturer should specify a minimum temperature for installation [20]. When the surface temperature of the concrete surface falls below this minimum level, improper saturation of the fibers and improper curing of the resin constituent materials can occur, compromising the integrity of the system. Application difficulties may also occur due to a deceleration of the rate of curing. Additionally, the presence of frost or ice crystals may be detrimental to the bond between the FRP and the concrete. ACI suggests that a non-contaminating heat source can be used to raise the ambient and surface temperatures during installation. ISIS (Intelligent Sensing for Innovative Structures) suggests that in general, primers, saturating resins and adhesives should not be applied to cold or frozen surfaces. Similarly, in high temperatures, the epoxy may be difficult to apply due to an accelerated hardening rate. AASHTO thus recommends to stop the work in such high temperatures. In case that is not possible, the work should be supervised by a person experienced in applying epoxy under such conditions [66].

Moisture: FRP resins should not be applied to wet or damp surfaces, as it might have adverse effects on the bond between the FRP and the surface. Accordingly, weather conditions can might delay the project [20]. ACI and ISIS state that resins and adhesives should generally not be applied to damp or wet surfaces unless they have been formulated for such applications. Also, ACI demonstrates that FRP systems should not be applied to concrete surfaces that are subject to moisture vapor transmission, condensation, or water ingression unless such issues are clearly addressed by the system design and the resin systems are specifically formulated for use in such conditions. Transmission of moisture vapor from a concrete surface through the uncured resin materials typically appears as surface bubbles and can compromise the bond between the FRP system and the substrate [66].

Transient loads: Wang, et al. [67] investigated whether the transient vehicle loads present at the time of the installation of the FRP flexural strengthening system (sheets attached to the girder soffit) adversely affect the bond performance between the CFRP and the concrete surface. It was shown that a 1-Hz sinusoidal transient load varying between 30 and 50% of the ultimate capacity of the unstrengthened beam during the installation and curing of the CFRP sheets does not affect the structural performance. This proves the efficiency of CFRP sheets for flexural strengthening of bridge girders in the presence of continuous vehicle loads.

4.2. Surface preparation

Surface preparation, i.e. cleaning and roughening the surfaces of composites is a critical step in the application process which can improve bond strength. Successful strengthening with FRP systems is dependent on a sound concrete substrate and proper preparation of the concrete surface. An improperly prepared surface can result in debonding or delamination. Sandblasting, water jetting, grinding, brushing, air pressure, rounding of corners, pressure washing the concrete surface, surface patching, and nylon peel-ply techniques are commonly used for this purpose. Failure in proper surface preparation can result in damage to the repair material such as FRP due the the delamination of the concrete substrate [20, 36, 77, 154] [65, 66].

The required steps for surface preparation are as follows:

Removal of all unsound concrete: It is recommended to remove slightly more concrete rather than too little, unless it affects the bond of prestressed strands. If patching is going to be done after unsound concrete removal, the chipped area should at least be 1 in. deep and should have edges as straight as possible, at right angles to the surface. Air driven chipping guns or a portable power saw can be used for cutting the concrete. However, care should be taken not to damage the strands or the reinforcement [82].

In case of concrete corrosion, the first step in the repair process is to locate the corroded and hollow areas by sounding the concrete surface. The next step is to remove the delaminated, loose or weak concrete as well as any non-cementitious contaminants or geometric inconsistencies. Then, the repair area should be sandblasted and possibly pressure washed in order to allow for the base repair material to penetrate best inside the damaged area [18, 26]. Figure 4-1 shows cutting out the damaged area of a RC girder as well as the sawed and chipped girder, ready for the repair process to begin.

Figure 4-1. Cutting out the damaged area of the girder (a) process (b) final results [20]

Select a patching method (if needed): in order to choose a proper patching technique and material, several parameters should be taken into account: (1) rheology of the patch material (the material must thoroughly fill or pack into the void being patched), (2) bond strength to the concrete substrate and the steel reinforcement traversing patch, (3) compressive and tensile strength of the patch material, (4) and durability of the patch material. Examples of common patching methods are: (1) Drypack Method: suitable for holes having a depth nearly equal to the smallest dimension of the section, such as core or bolt holes. The method should not be used on shallow surfaces or for filling a hole that extends entirely through the section or member, (2) Mortar Patch Method: appropriate for concrete members with shallow defects, which require a thin layer of patching material such as in honeycombs, surface voids or areas where concrete has been pulled away with the formwork, (3) Concrete Replacement Method: the defective concrete is replaced with machine-mixed concrete that will become integral with the base concrete. This is preferred when there is a void extending entirely through the section, or if the defect goes beyond the reinforcement layer, or in general if the volume is large. Concrete replacement will also provide the best substrate for eventual EB-CFRP, bPT-CFRP or even NSM-CFRP repairs, (4) Synthetic Patching: This method is beneficial where Portland cement patches are difficult or impractical to apply. Examples are patching at freezing temperatures or patching very shallow surface defects. In these situations, epoxy and latex based products can be used. Epoxies can be used for a variety of purposes: a bonding agent, a binder for patching mortar, an adhesive for replacing large broken pieces, or as a crack repair material. Small deep holes can be patched with low-viscosity epoxy and sand whereas shallower patches require higher viscosity epoxy and are more expensive. Although epoxies offer excellent bond and rapid strength development, they are hard to finish and usually result in a color difference between the patch and the base concrete. Therefore, it is suggested that epoxy mortars be used only in situations where exceptional durability and strength are required. Latex materials are used in mortar to increase its tensile strength, decrease its shrinkage and improve its bond to the base concrete, thus helping to avoid patch failure due to differential shrinkage of the patch. Latex is especially useful in situations where feathered edges cannot be avoided, (5) Epoxy Injection: This method is used to repair cracks or fill honeycombed areas of moderate size and depth. It becomes an important part of the repair process specifically for corrosion damaged girders in which cracking and spalling of the concrete is commonplace. Epoxy injection should be done only appropriately trained personnel [34, 82]. Figure 4-2 shows an example of a concrete girder surface after epoxy injection.

Figure 4-2. Concrete surface after epoxy injection [34]

Figure 4-3. Epoxy injection in cracks before surface preparation [28]

In case this repair technique includes the application of the repair material on the surface of the concrete, putty filler can be used to fill small voids in the concrete surface to provide a smooth surface for the FRP to bond to. This also prevents bubbles from forming during curing [20].

In case there are cracks on the girder, prior to surface preparation, they should be filled with proper materials. Figure 4-3 shows the process for injecting high strength epoxy into the diagonal cracks of an RC bridge in Kentucky. First, crack injection ports are placed and secured along the crack. Then, the crack is covered with high strength structural epoxy. Then, the injection process starts on the sealed crack. Covering the crack is important as it prevents the filler material from being forced out of the crack before reaching the core, when injection starts. Figure 4-3 shows the injection of epoxy into a crack at the bottom of the girder. The injection from a specific port continues until excess material is forced out from an adjoining injection port. Then, the injection port is sealed off and the process is continued from the next open port. Figure 4-4 shows the closed crack injection ports after the completion of low viscosity crack filling process. The epoxy should be left to be cured, before any other repair techniques such as FRP sheets etc. can be applied [28].

Shotcreting is another way of patching the concrete (see Figure 4-5) [33].

Figure 4-4. View of the crack filled with low viscosity epoxy [28]

Figure 4-5. Shotcreting to patch the concrete [33]

Sometimes, the state of the damage to the girder causes intense concrete crushing and thus requires more than patching in order to restore the original shape of the section. Pino et al., [18] utilized mortar as the base repair material, which is common in other applications as well, to restore the original shape of impact damaged bridge girders. Then, they performed a hammer test was to ensure sufficient bond between repair mortar and the girder concrete prior to the application of the main repair material.

Figure 4-6. Mortar application of an impact damaged bridge girder [18]

Surface polishing (roughening): As part of the surface preparation, the surface of the concrete is usually polished until fine aggregates are exposed [108]. This improves the bond between the main strengthening material and the concrete surface. Abrasive blasting or sand blasting is one way of surface roughening [33]. Diamond grinding is another technique utilized for this purpose [39]. It can also be done using high pressure waterjetting (see Figure 4-7) [87] or using a grinder. the roughening can be implemented to the aggregate level [18]. Tetta et al., [4] used a grinder to create a grid of grooves, 2-3 mm deep, in order to roughen the surface of concrete girders.

Cleaning: The concrete surface should be cleaned before the application of the repair material. This can be done using a variety of methods including pressurized air and acetone or water jetting and pressure washing [108]. It is usually done using compressed air or water [92]. It can also be done using a wire brush. It is also important to make sure that the surface is free from any oil, or greasy substances [101]. As shown in Figure 4-8, sandblasting can also be used to clean the repair area to enhance the bond between the concrete and the repair material [33,261]. Compressed air (see Figure 4-9) is also widely used for cleaning the concrete surface from dust and debris [36].

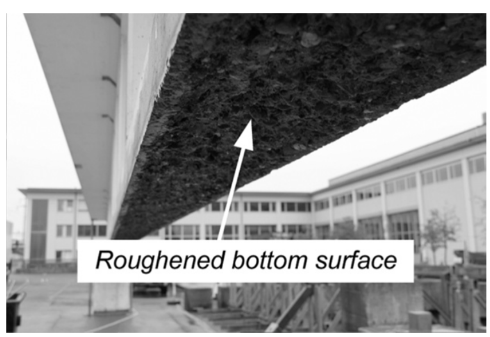


Figure 4-7. Roughened surface using waterjetting [87]

Figure 4-8. Sandblasting to clean the repair area [33]

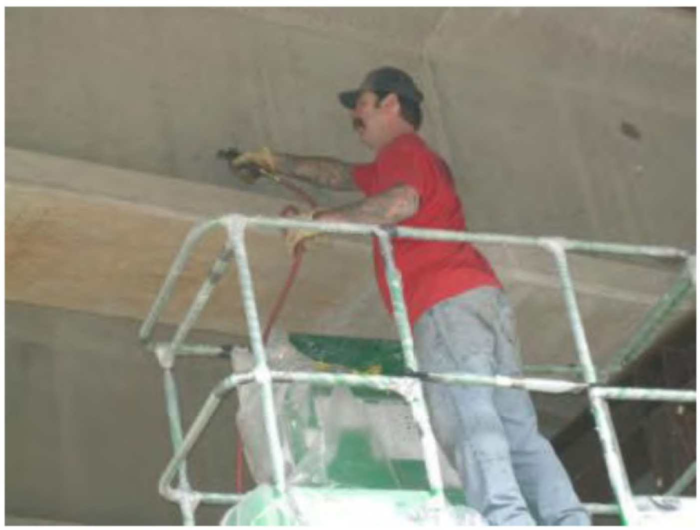


Figure 4-9. Surface cleaning using compressed air [36]

Priming: In order to increase the performance of the repair that will be applied on the concrete substrate, a primer might be applied to the concrete surface. [108] applied a two-part primer to the prepared concrete surface, left it to be dried, and then applied a two-part epoxy resin to the primed concrete surface prior to the application of the FRP material.

Primers have been used in many different repair projects [39].

Figure 4-10 shows the application of the primer to the surface of a concrete bridge girder prior to the application of epoxy putty and the CFRP fabric [33].

Figure 4-10. Application of the primer to the prepared concrete surface [33]

In case FRP material are being used for the repair, according to ACI, ISIS, and AASHTO: surface preparation should be done according to the FRP system manufacturer's guidelines. It can be done using abrasive or water-blasting techniques. All contaminants that could interfere with the bond between the FRP system and concrete substrate should be removed. Before the repair process, the concrete surface must be free of debris that no longer adhere to the structure, and cleaned from dirt, oil and other contaminants as well as existing coatings, or other matter that could interfere with the bond of the FRP. Bug holes and voids should be filled with epoxy putty. Larger cracks should be pressure injected with epoxy. Smaller cracks in aggressive environments may also require epoxy injection to prevent corrosion of steel reinforcement. Where required, primer should be applied uniformly and at the manufacturer's specified rate of coverage to all areas on the concrete surface where the FRP system is to be placed. The primer should have sufficiently low viscosity to penetrate the surface of the concrete substrate. Putty should be used in an appropriate thickness and sequence with the primer as recommended by the FRP manufacturer, and only to fill voids and smooth surface discontinuities. Before applying the FRP system, dust, moisture, and other contaminants should be removed from the surface. Primer and putty should be cured as specified by the FRP system manufacturer. Other surface reparation procedures, if required by the manufacturer should also be implemented before resin or adhesive is applied [66]

The next step after surface preparation is the application of the repair material. Figure 4-11 shows the repair location of the impact damaged girder after formwork removal and at the final stage of surface preparation.

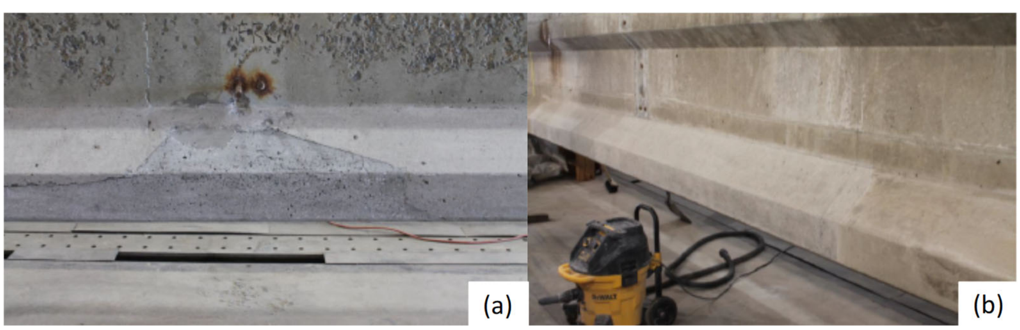


Figure 4-11. Repair location of an impact damaged bridge (a) after formwork removal and (b) final surface preparation [20]

4.3. Application of the repair material

The strengthening material should be applied to the concrete surface using the externally bonded (EB) technique, near surface mounted (NSM) method, or as embedded reinforcement. As the naming suggests, in the first method, the strengthening material is attached to the external surface of the beam using an appropriate adhesive material or mechanical fastener, whereas in the second method, the strengthening material is embedded into grooves or precuts made in the concrete cover using an adhesive material. The performance of the beam strengthening technique highly depends on the efficiency of the application method used. Selection of an appropriate application method depends on the availability of the product and trained application personnel, the ease and simplicity of application, and of course the condition and needs of the element being repaired [5]. More information on each method is provided in the following sections.

4.3.1. Externally bonded (EB) technique

This is the most efficient and popular method for strengthening of RC beams using FRP materials. External FRP wraps are currently used by twenty four highway departments in the US, and several other states are in the process of adopting it [61, 252, 253].

One of the advantages of this method over other techniques is that there is no need to remove concrete parts or drill into the section, hence, the ease of application and less risk of exposing or damaging the existing reinforcement [6]. Another benefit of this method is that it provides protection for the patch concrete and the reinforcing steel from ingress of water and salts and thus corrosion and deterioration. Otherwise, the repairs implemented by concrete patch alone are prone to crack under the combination of shrinkage and service loadings [64]. However, in this method, the performance of the strengthened element is highly dependent on the bonding between the concrete and the strengthening material. This is specifically important for FRP strengthened elements where debonding failure occurs at an effective strain much lower than the ultimate strain achievable by the FRP composite materials. Therefore, the full capacity of the FRP is not used. Additionally, the failure would be in a brittle manner. In order to effectively use the externally bonded technique, the debonding failure mode should be overcome [17, 73, 92, 146]. Additionally, this method also has low fire resistance and high vulnerability to vehicle collisions and bond failure [151]. The saturating resins in the EB techniques can be adversely affected by the ultraviolet light over time. Additionally, their characteristics degrade when exposed to high temperatures. To partially overcome this issue, protective coatings can be applied to limit the exposure to ultraviolet light and to also provide some fire protection [20]. The aforementioned issues with the EB method has caused attraction to the near surface mounted method explained next.

Initially, the EB method was applied using adhesively bonded steel plates. But gradually, use of FRP-based materials took over the steel due to their superior characteristics mentioned in section 2.1 [61]. The EB repair techniques using FRP materials are usually implemented in three ways: (1) wet layup (2) prepreg, or (3) pre-cured.

In the wet layup approach, the resin serves to both saturate the fibers and bind the sheet to the concrete surface. Dry fiber sheets impregnated with a saturating resin on site and bonded to the concrete substrate using the same resin. Usually, the saturating and the curing process are done on site. But, they also might be implemented at the manufacturer's facility off site as well. This method has the advantage of the flexibility of the FRP sheets. Thus, it is appropriate for application on surfaces that are relatively smooth, but have an abrupt or curved geometry. The relatively smooth surface is a requirement here to make sure that proper bond is achieved between the concrete and the strengthening material. Wet layup applications are suitable for column wrapping and U-wrap applications, however are not generally recommended for flexural repair for prestressed concrete girders. In this method, the strengthening material is saturated in the field and is then applied in the structure's surface to be cured [5, 20, 55, 82].

In the prepeg approach, the fiber sheets are saturated offsite and also partially cured. On the site, they are bonded to the concrete surface using resin and they often require additional heating to complete the curing [20].

In the pre-cured approach, the resin is only used for gluing the procured (fiber and matrix already combined) laminates, strips, or sheets to the concrete surface. The fibers are saturated and cured offsite like precast concrete members. Pre-cured strips are available from a variety of manufacturers in discrete sizes and a number of 'grades. As for CFRP strips, high strength (HS), high modulus (HM) and ultra-high modulus (UHM) grades are commercially available. In this method, the repair material is rigid and cannot be bended if a more flexible application is needed. Therefore, the application is limited to straight or slightly curves surfaces. This method is used when the surface of the structure is smooth and flat or when using the wet layup method is not practical [5, 20, 55, 65, 82].

In this matter, EB, ACI and ISIS and AASHTO provide the following recommendations for the application of the material to the concrete surface:

The first step in the application of any of these methods is the mixing of the resins. All the comprising components of the resin should be mixed at a proper temperature and in the correct ratio until there is uniform and complete mixing and the product is free from trapped air. Also, the resin mixing should be done in quantities sufficiently small to ensure that all mixed resin will be used within the resin's pot life. The resin should have sufficiently low viscosity to be able to get the fibers fully impregnated prior to curing [66].

In the wet lay-up FRP method, the installation is done by hand using dry fiber sheets and a saturating resin. Generally, saturating resin is applied uniformly to all prepared surfaces where the system is to be placed. Then, the reinforcing fibers are gently pressed into the resin. Sufficient resin should be applied to achieve full saturation of the fibers. Before the resin sets, the entrapped air between layers should be released or rolled out. For this purpose, it is recommended to work the FRP materials parallel to the fibers, proceeding in one direction from the center or one extremity and to avoid any backward and forward movements. Application of each layer of the saturating resin and fiber should be done before the complete cure of the previous resin layer. If previous layers have cured, interlayer surface preparation, such as light sanding or solvent application as recommended by the system manufacturer, may be required [66].

Wrapping machines might be used for installation. Machine-applied systems can use resin pre-impregnated tows or dry-fiber tows. The former is the prepreg approach in which prepreg tows are impregnated with saturating resin off-site and delivered to the work site as spools. While dry fibers are impregnated at the job site during the winding process. After wrapping, prepreg systems should be cured at an elevated temperature in accordance with the manufacturer's recommendations [66].

The last method is the precured approach which includes shells, strips, and open grid forms that are typically installed with an adhesive. After proper surface preparation, similar to the wet layup technique, the adhesive should be applied uniformly at the rate recommended by the FRP manufacturer. The precured sheets are cleaned and prepared in accordance with the manufacturer's recommendations and are then placed into the wet adhesive, and entrapped air between layers is released or rolled out before the adhesive sets. Air trapped under the laminates is difficult to detect and rectify. Therefore, care should be taken to use an application method to avoid entrapping air under the laminates. As opposed to the wet lay-up method, stacking multiple layers of FRP is usually not permitted, except for the overlapping portion of prefabricated L-shaped stirrups. At intersections of FRP plates, care should be exercised to minimize curvature; grooving the concrete for the layer underneath is sometimes used to allow full contact between the plate and the concrete surface underneath. Any protective coatings that are used should be compatible with the FRP strengthening system and applied in accordance with the manufacturer's recommendations [66].

In all the EB approaches mentioned earlier (wet layup, prepreg, and pre-cured), the primer is often applied to the surface of the concrete anyways to improve bond for the adhesive or the saturating resin used [20]. Figure 4-12 shows a typical saturator machine for saturating CFRP sheets in the wet layup approach [33].

Figure 4-12. An illustration of a saturator machine [33]

Example application 1: Pino et al., [18] used the wet layup approach for the application of CFRP sheets as means of flexural strengthening. Figure 4-13 shows the steps for this process. First, epoxy resin was applied as a surface primer to the concrete substrate, filling the voids, minimizing surface discontinuity, and providing a good bond between the concrete and the CFRP sheets. CFRP sheets were then run through a saturator to ensure proper fiber impregnation while removing excess resin. The impregnated sheet was then applied to the bottom of the girder in the longitudinal direction (see Figure 4-13 and Figure 4-14). A ribbed roller was used to bond the fabric to the epoxy. Another layer of resin followed by longitudinal CFRP sheets were then applied. A third layer of resin was also applied followed by transverse CFRP sheets (see Figure 4-13 and Figure 4-14), and finally, a last layer of epoxy for a smoothed finished surface. It should be mentioned that the transverse CFRP sheets act as confinement for the longitudinal sheets and to avoid their delamination.

Figure 4-13. Application of CFRP sheets for flexural strengthening [18]

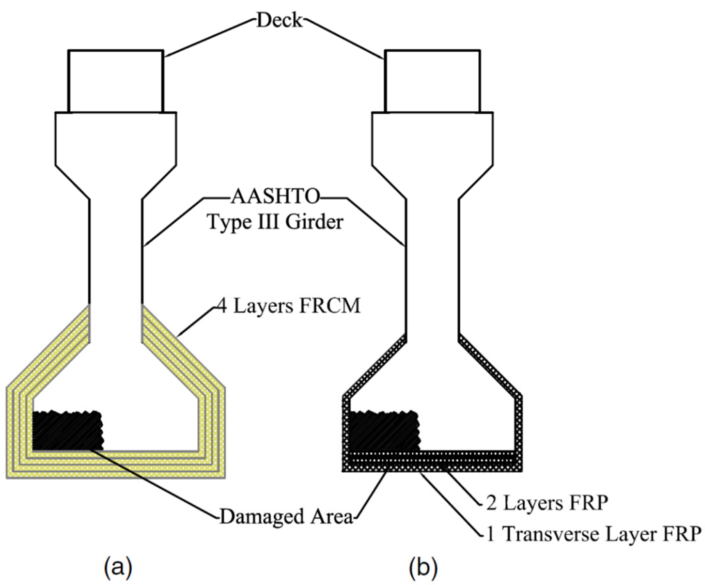


Figure 4-14. Repair configuration for impact damaged girders using (a) FRCM (b) FRP [18]

Example application 2: Figure 4-15 shows another procedure for flexural strengthening of a girder using CFRP sheets at the girder soffit and CFRP wraps as end anchorage systems.

Example application 3: Figure 4-16 shows an example application of bridge girder shear strengthening using CFRP U-wraps where trench cuts on top of the beam web are used as anchorage for the wraps. This repair approach, as can be seen in Figure 4-16, included the following steps: (a) the loose concrete is removed from the girders (b) rapid set cement is used to repair where there was significant amount of concrete missing in the girder (c) cracks are epoxy injected. For this purpose, first, toothpicks are placed inside the cracks where injection will be taking place. Then, small tubes are placed over the toothpicks. Putty is added to seal off the cracks and hold the tubes in place. When the putty was cured the toothpicks are removed and epoxy is injected through the tubes. The tubes are then capped off. (d) the epoxy should be left to be cured, and then the tubes are removes and the surface is ground off (e) two trenches were cut on top of the girder wen on the intersection with the girder flange. This will be used to anchor the CFRP wraps and to hold them in place. (d) Finally, the CFRP wraps are soaked in a saturate and are then placed over the primer and the putty on the girder surface. Then, rollers are used to remove surface imperfections [23].

(a) Loose debris removed from the top (b) Gaps filled with repair mortar (c) Exposing the concrete substrate

(d) Gaps filled in after exposing the concrete substrate (e) Rounding off the corners (f) applying pressure with a roller

Figure 4-15. Flexural strengthening of the beam using CFRP wraps [147]

Example application 4: ElSafty and Graeff [141] used a wet layup approach for the CFRP repair of the impact damaged bridge girders. The first step after surface preparation was to apply a priming layer of mixed epoxy to the concrete surface using a regular paint roller. The CFRP laminate used in this study were pre-cut. The pre-cut laminates were drawn through a poll of epoxy in a paint tray. The excess epoxy of the laminates was squeezed out of the material by hand. The saturated laminates were then placed on the proper positions on the girder surface. Then, a plastic trowel was used to straighten the fibers and for force out any air pockets trapped behind the laminates.

Example application 5: Figure 4-17 shows the application of CFRP and GFRP sheets for shear strengthening of concrete girders. In both cases, longitudinal strips of CFRP or GFRP are used as the anchorage system [55].

Example application 6: FRP material preparation and installation can be done through the following steps: (1) the fiber sheet roll is set up on the pre-impregnation frame following the manufacturer's specifications and equipment (2) fiber sheets are cut to the appropriate dimensions (see Figure 4-18.) (3) epoxy resin is mixed and poured into the reservoir of the frame. Then, the fiber roll is fed through the resin bath of the frame to get saturated (see Figure 4-19.) (4) the individual FRP sheets are then placed on non-stick sheets on a flat surface. Another non-stick sheet is used on top of the sheets to sandwich the CFRP ensuring a flat panel is produced. A plastic trowel is then used to remove the excess resin. After 24 hours, the non-stick sheets are removed (see Figure 4-20.) (5) moving to the concrete substrate, the concrete surface is primed with resin, thickened epoxy (resin mixed with fumed silica) is applied to fill in the holes on the concrete and to enable the FRP material to be attached to the surface (6) the impregnated FRP sheets are then installed on the prepared substrate (6) Finally, the FRP is rolled with a ribbed roller and left to be cured.

Figure 4-16. Strengthening of PC girders using CFRP wraps [23]

Example application 7: Michels et al., [87] used a commercially available two component epoxy resin for the application of prestressed CFRP strips for flexural strengthening. The strips were also anchored to the girder at the ends using a gradient anchorage system. The nonmechanical anchorage system avoids the installation of metallic bolts and plates, with the exception of a temporary support frame. Debonding and cracking are two problems that can be caused during the installation and release of the prestressed CFRP strips. If debonding occurs, the installation process should be repeated. Cracks, however, if they do not include bonding failure, might be injected with resin.

Figure 4-17. application of CFRP and GFRP sheets for shear strengthening of the beams [55]

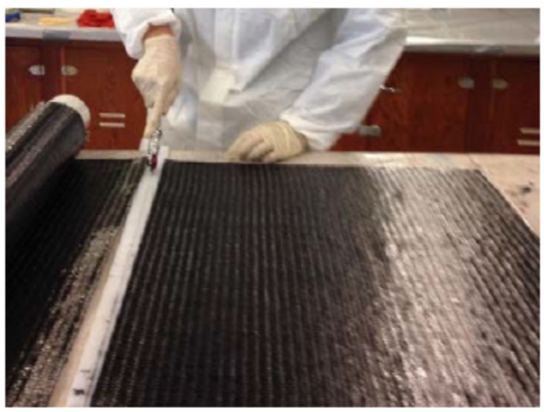


Figure 4-18. cutting the FRP sheets prior to impregnation with resin [64]

Figure 4-19. Fiber impregnation [64]

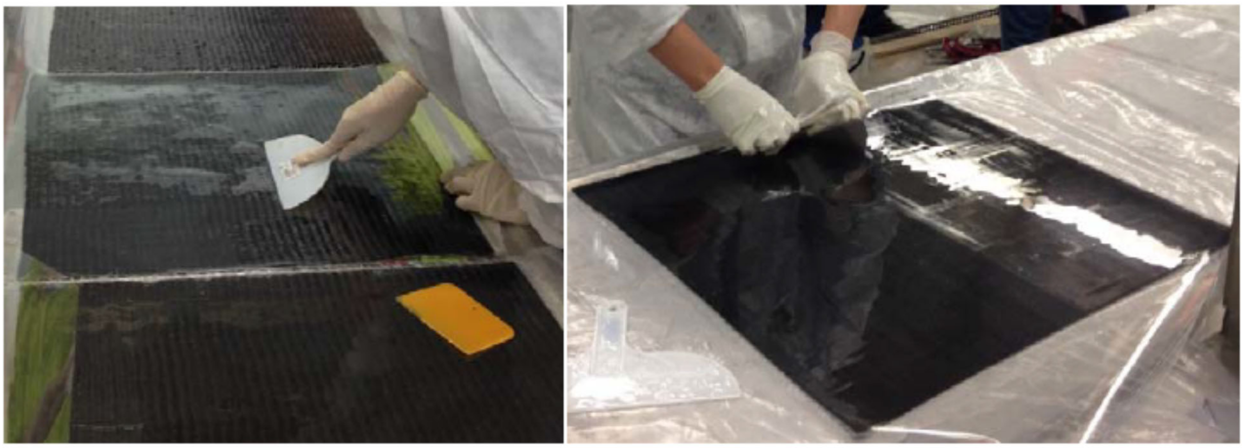


Figure 4-20. Panel fabrication [64]

Figure 4-21. Application of impregnated FRP sheets to the concrete substrate [64]

Example application 8: Figure 4-22 shows the step by step application of L-shaped CFRP laminates for shear strengthening of RC T-girders. The procedure is as follows: (1) the end part of the laminates goes inside the grooves made in the girder flanges, at the intersection with the web. In order to increase the bond between the CFRP laminates and the concrete, the ends of the laminates are coated with epoxy paste adhesive at both sides, 24 hours before installation. The adhesive was applied using a V-notch adhesive spreader shown in Figure 4-22 (2) Grooves are made on both sides of the flange at the intersection with the girder's web (3) surfaces on both sides and underneath of the web of the girders where the laminates will be bonded are sandblasted (3) grooves are filled with epoxy adhesive (4) finally, the L-shaped laminates are epoxy bonded into the grooves and to the sides and the soffit of the girder (5) the second L-shaped laminates are then bonded to the opposite side of the girders to form a U-wrap envelope around the web at one cross section. It was shown by [98, 106] that this shear strengthening technique can be a potentially efficient method in extending the service life of RC beams subjected to fatigue loading for increased live load. During the tests that were performes by them, no signs of debonding was observed. Also, the use of CFRP L-shaped laminates to shear-strengthen RC beams with steel stirrups changed the failure mode from brittle to ductile behavior under static loading.

Example application 9: The EB CFRP U-wraps used by Qin et al., [101] were installed in the following manner: after proper surface preparation, (1) CFRP sheets were impregnated with two component epoxy resin (2) a uniform layer of epoxy was applied to the web. Also, any pores on the concrete surface were filled with epoxy (3) then, a layer of the epoxy-impregnated CFRP sheets are pressed gently onto the web (4) air bubbles beneath the CFRP sheets are removed using a plastic trowel (5) finally, a layer of epoxy is applied to the CFRP sheets as a protectant (6) the entire system is then left at the room temperature to be cured.

Example application 10: Choo et al., [28] used SFRP sheets for the rehabilitation of an RC bridge in Kentucky. The implementation of such repair was done using scaffolding that hangs from sides of the bridge (see Figure 4-23). This is because most of the spans are over waterway. The scaffolding used is completely adjustable and movable along a bridge span between two piers. It can also be disassembled, moved, and reassembled at another span, if needed [28].

Figure 4-24 shows the process for application of the SFRP plates to RC girders. The procedure is as follows: (1) first, epoxy with a specific thickness is applied to the concrete surface using a trowel or spatula (Figure 4-24 (a)) (2) then, SFRP sheets are applied to the required regions (Figure 4-24 (b)) (3) the SFRP sheets are then pressed using a hard roller until epoxy is completely forced out on both sides of the sheet and has fully saturated the sheet on the outside (Figure 4-24 (c)). Please note that based on the project requirements, application of multiple layers of SFRP is possible (4) finally, protective coating is applied onto the SFRP sheets.

Example application 11: Some repair projects might have special condition that require additional steps in the repair process. One example can be corrosion of the reinforcement in the brackish water environments. For the repair of the girders in such environment, surface preparation involves removal of the corrosion product from the steel reinforcement, in addition to the removal of the spalled and contaminated concrete. Then, before restoring the section with new concrete or mortar, and the application of the repair material (such as CFRP wraps), the steel reinforcement should be coated with proper material such as polymeric coatings [83].

Implementation of the CFRP-honeycomb (H-Lam-C) plates to the soffit of a rectangular beam is shown in Figures 4-25 through 4-27. As can be seen: (1) first, the sandblasted concrete surface is saturated with epoxy (2) Then, a hammer drill was used to make pilot holes on the concrete surface to place the concrete screws attached to the panels which act as an anchorage system. The CFRP panel and the three screws attached to it are placed on the beam soffit (3) Finally, the screws are tightened to enhance the bond between the concrete and the panel [85].

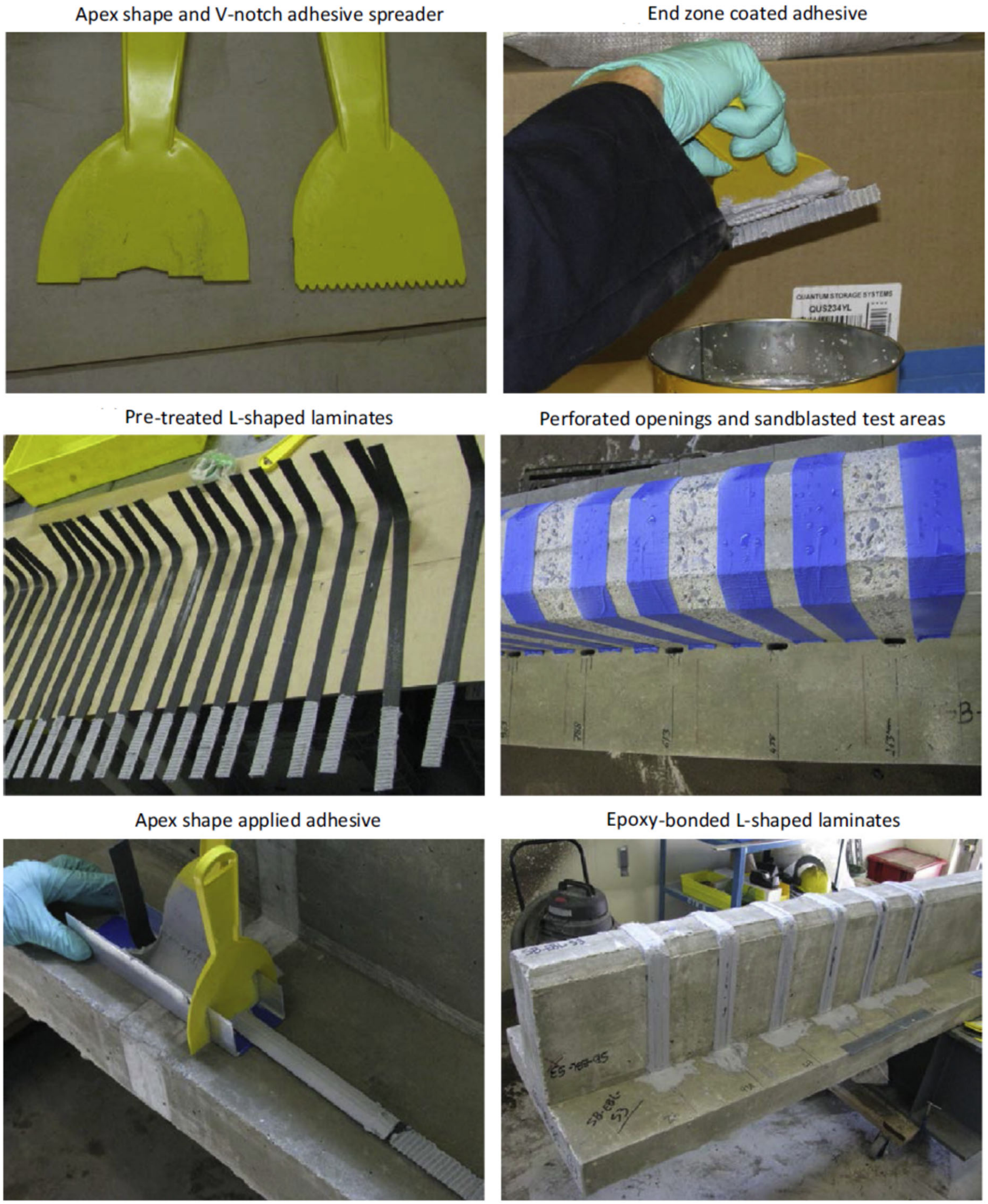


Figure 4-22. Procedure for the application of precured L-shaped CFRP laminates [98]

Figure 4-23. Implementation of the SFRP repair using adjustable and movable scaffolding [28]

Figure 4-24. Application of the SFRP plates on a RC girder in a bridge in Kentucky [28]

Figure 4-25. Saturating the concrete surface [85]

Figure 4-26. Bonding the CFRP sandwich panel to the concrete surface [85]

Figure 4-27. Tightening the screws for bond enhancement [85]

For the traditional EB-CFRP repair methods, the dominant limit state is debonding of the CFRP from the substrate concrete. In a sound CFRP application, debonding failure is characterized by cohesive failure through a thin layer of cover concrete immediately adjacent to the CFRP. Therefore, it would be difficult to improve the debonding capacity by enhancing the characteristics of the adhesives since failure is governed by the substrate concrete, not the adhesive. The properties of the concrete substrate which is in control of the failure mode are not affected by the repair approach. With the occurrence of the debonding failure mode, the CFRP material does not reach its full capacity. Therefore, if CFRP is used in small amounts, they might debond before they can increase the capacity of the damaged girder. For such cases, the capacity of the strengthened girder would be even less than the damaged girder capacity [53].

Example application 12: All the previous examples used some sort of a resin as the adhesive. However, as mentioned in section 2.1.2., FRP materials can also be used with a cementitious matrix, one of the most common of which is FRCM. Figure 4-28. Shows the procedure for the application of FRCM wraps for flexural strengthening of an impact damaged bridge girder. In this specific application, four layers of fabric were needed. This is because according to the previous studies, a four-ply configuration using FRCM, leads to the failure of the system due to the delamination of the concrete, which is desirable. To achieve this, the mortar was mixed and applied to the bottom bulb of the girder using a trowel, followed by a layer of the fabric. This procedure is repeated until the four layers were applied. Eventually, the fabric is covered by mortar to have a clean finished look [18].

Figure 4-28. process for the application of FRCM for flexural strengthening [18]

Example application 13: Application of the FRCM material can be done in four steps (see Figure 4-29.): (1) the first layer of matrix is applied with a trowel; (2) a pre-cut fiber mesh with the appropriate fiber orientation is placed on top of the matrix and is pressed lightly with the bottom of the towel to embed the fabric in the matrix (3) a second layer of matrix is added with the trowel to cover the fiber mesh (4) steps 2 and 3 are repeated until desired number of layers is reached [64].

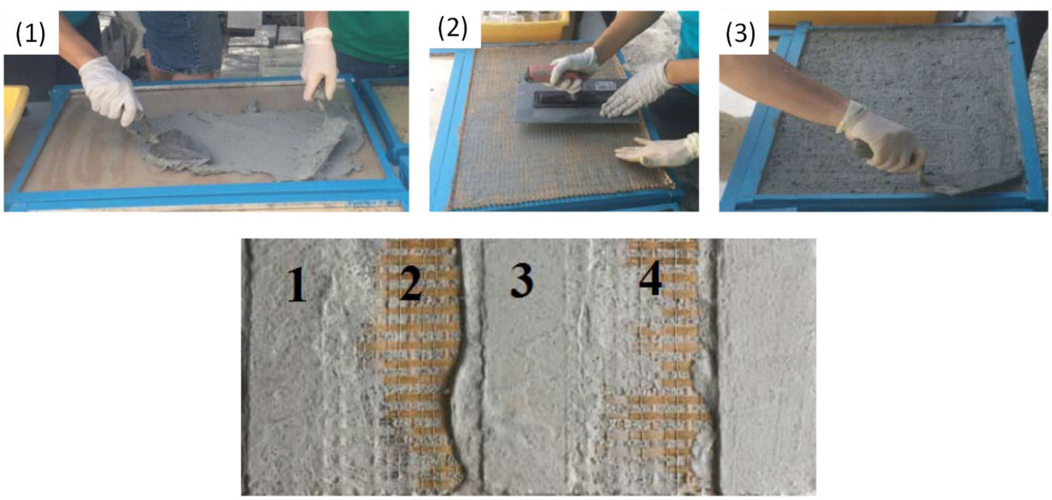


Figure 4-29. Details of the implementation of the FRCM material [64]

Example application 14:

Figure 4-30 also shows application of the TRM repair method for a RC girder, where the repairing textile is being pushed to the mortar by hand pressure in order to create the necessary bond. Prior to the application of the mortar, the concrete surface was dampened [4].

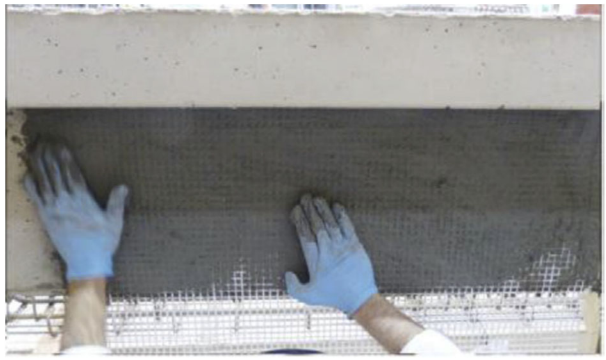


Figure 4-30. Bonding the repair textile into the mortar by hand pressure [4]

Example application 15: Application of the hybrid fiber reinforced method explained in section 2.1.3 is different than the examples explained above. For the application of regular CFRP plates, setup of the scaffolding or access platform for the entire length of the strengthened beam is required. As mentioned before, this can be cumbersome for bridges over waterways or multilane roads. However, in case of using CRPs, the application can be done using one set of scaffolding or access platform (see Figure 4-31.), which moves along the length of the bridge span, applying one panel at a time. The procedure for the application of such repair approach is shown in Figures 4-32 and 4-33 [27].

Figure 4-31. Beam strengthening using CRP over waterway [27]

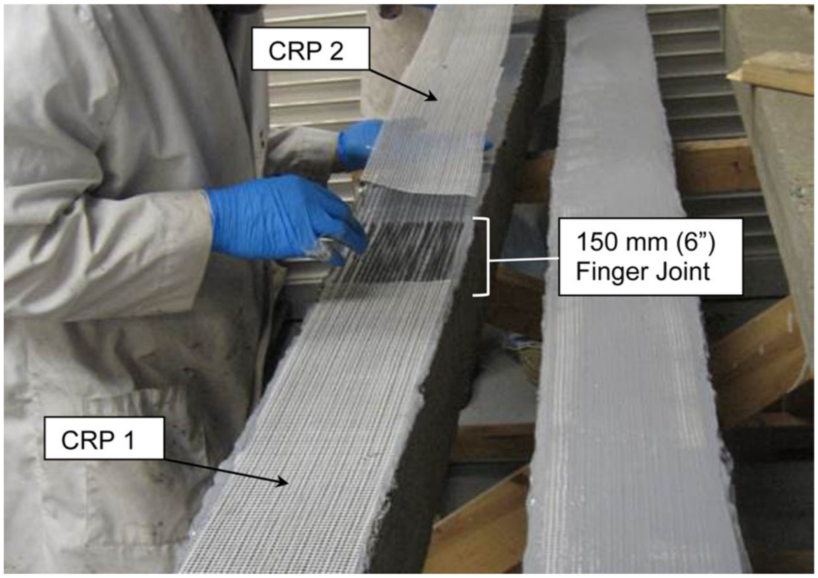


Figure 4-32. CRPs joined together in a finger joint in a test beam [27]

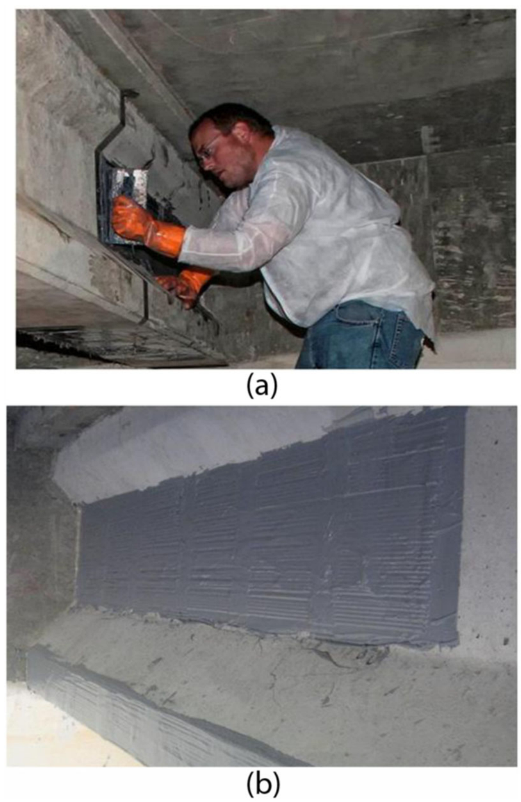


Figure 4-33. CRP application on KY 218 Bridge: (a) application of epoxy for CRPs and (b) CRP-strengthened girder [27]

4.3.2. Near surface mounted (NSM) technique

This method was initially presented in 1940. It is a construction technique that embeds FRP bars in the concrete surface and pre-stresses anchorage devices to improve the performance of the reinforced concrete (RC) structure. Although initially steel cables were used as part of the strengthening process, later on they were replaced with FRP materials due to the corrosion of steel. The FRP material is typically used in the form of bars with rectangular or circular cross sections, manufactured using the pultrusion process. Additionally, the use of NSM approach is limited to RC structures since it requires cutting a groove into the surface of the element being repaired [56],[54],[5].

In this method, first, grooves are made into the concrete surface, and the concrete in between the cuts is chiseled away. Then, the groove is cleaned and dust is removed using compressed air. In order to have a clean final appearance, tape can be applied to the sides of the grooves. The strengthening material (bar or thin strip, etc.) is then fastened into the groove using a filler material (epoxy resin, cement grout, etc.). Finally, the adhesive surface is leveled using a trowel and the tape is removed (prior to curing of adhesive) [55]. Either bars or strips are commonly used in this methods. Bars can be sandblasted or deformed. But studies have indicated that deformed bars have a better bond performance. Also, it has been demonstrated by some researchers that strips can lead to a more effective repair since they provide an increased surface area between the FRP-adhesive interface, with strips failing in tension rupture and achieving full composite action with the concrete [20]. Figure 4-34 shows the schematic of the NSM method technique.

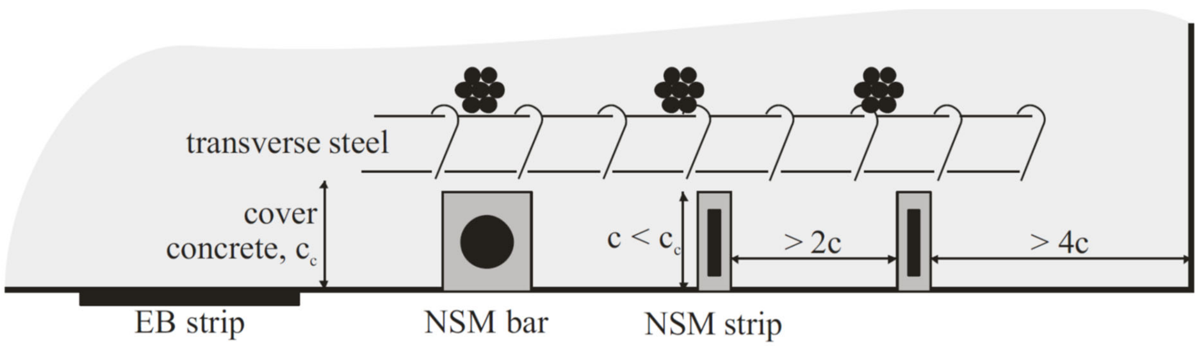


Figure 4-34. Schematic of the EB and NSM bar and NSM strips for strengthening of RC members [82].

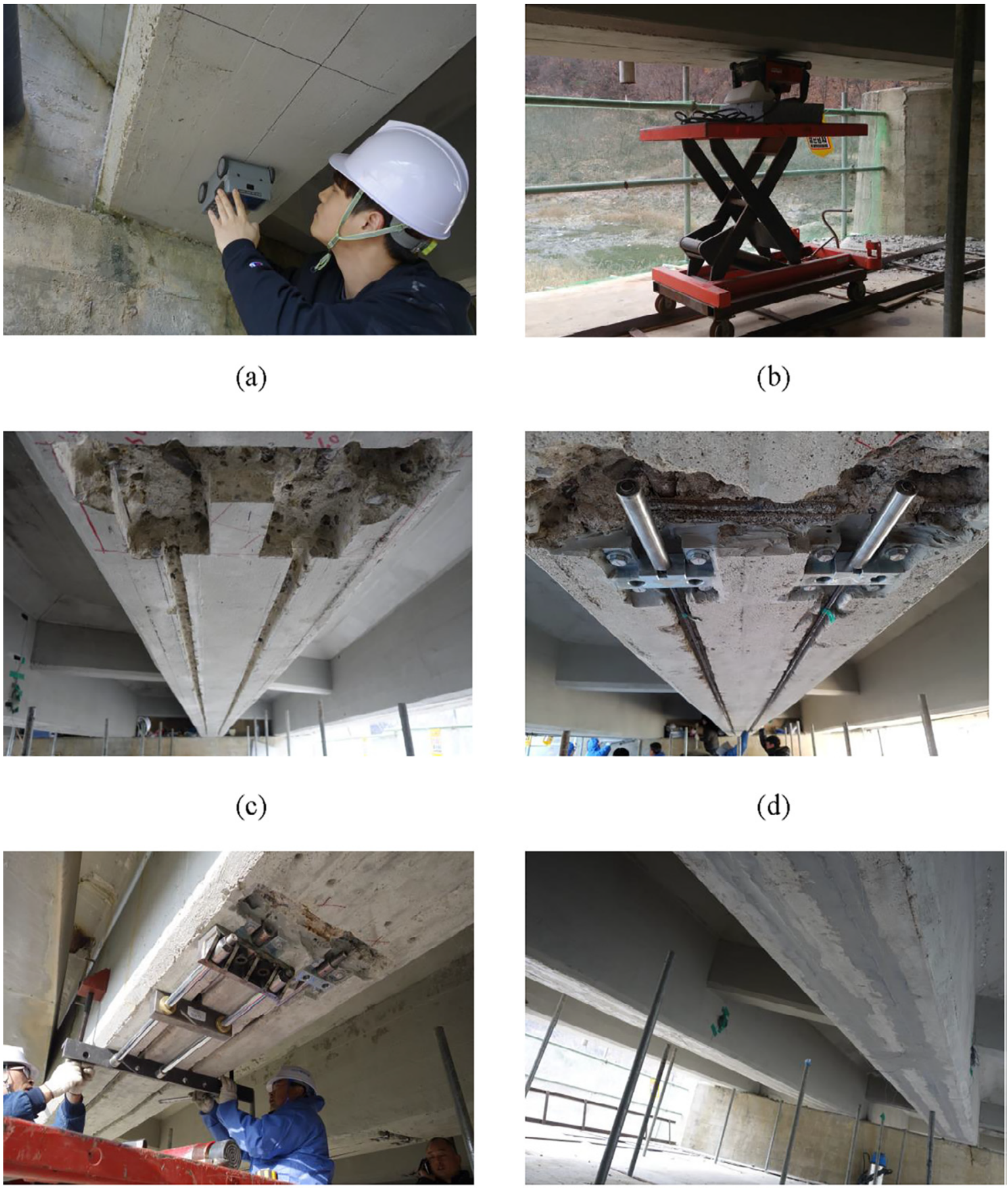
The two main advantages of this method are: (1) higher bond strength can be achieved compared to the EB method since the repaired material is completely enclosed in epoxy, which means a larger surface area is bonded. (2) due to the enhancement in the bond behavior, this method typically requires less material use [82]. Also, the NSM method improves the fire resistance, and impact damage resistance of the strengthened member compared to the EB method since the repair material is placed inside of the concrete instead of being exposed on the concrete surface, and also as a result of the increased contact area. Although FRP-based materials are generally considered to be corrosion resistant, the bond between the concrete substrate and the FRP material can be adversely affected by the exposure to high levels of water, deicing salts, and freeze/thaw cycling applied to the end regions of these concrete bridge girders. Additionally, it technique requires less labor and does not change the dimensions, and thus the cross section of the strengthened element [56],[55, 56, 146].

The additional time and effort that is spent on surface preparation for making the grooves will usually be compensated with the increase in the flexural properties in case the NSM rods are pretensioned [5]. However, Jones [20] indicated that although this technique leads to decreased material use, the increased labor cost might offset the savings in the material cost. An example is cutting in grooves overhead which is difficult to implement for the workers. Also, in case of overheight vehicle collision and damage to the prestressed girder strands, NSM might not be the best repair choice. This is because the thickness of the strand splicing equipment used for repairing the prestressing strands can conflict with cutting grooves into the concrete surface in particular locations [20]. Additionally, although the bond behavior is improved in this technique, but the effectiveness of the method is affected by the amount of material that can be used for the repair. The minimum spacing between the grooves that the repair materials are placed in is one example of the reasons that limits the amount of material that can be applied to the structure in this method. The NSM method is most effective when it is used in the negative moment region of a structure, so that it can remain protected from wear and abrasion. It is not recommended to be used in the positive bending region of the structure [53]. The NSM method is also sensitive to the amount of concrete cover and is not a viable option when cover is not sufficient [82].

Example application 1: Figure 4-35 shows the application of the NSM method using prestressed CFRP rods [17].

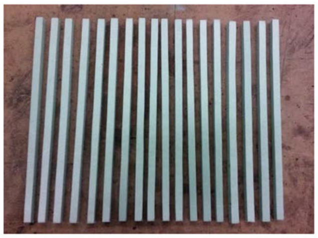
Example application 2: Figure 4-36 shows the implementation of the CFRP NSM technique for concrete girder repair for shear strengthening implemented by [55]. First, grooves were cut into the girder. Then, notch fillers (see Figure 4-36) were placed inside the grooves and mortar was applied. The foam filler were removed using a flathead screwdriver. The interior surfaces of the grooves were vacuumed and air blasted to remove dust and laitance. Masking tapes were applied between the grooves for a more clean application. The grooves were filled halfway with epoxy, the CFRP bars were inserted, and then the groove was completely filled. The excess epoxy was then troweled away and the tape removed. In order to provide increased bond with the epoxy filler, the CFRP bars were sandblasted [55]. Surface treatment of the CFRP rods in NSM strengthening method for increasing the bond performance is common practice. Figure 4-37 shows two types of such treatments. Figure 4-37 (a) shows a CFRP bar that was grinded with sandpaper. Figure 4-37 (b) shows a sand coated CFRP bar which was obtained from a ground CFRP bar after the application of a coating agent and being sprayed by sand [151].

Example application 3: The adhesive used to fill in the grooves can either be epoxy or cement-based adhesives. Use of organic adhesives (epoxy adhesives) in the NSM FRP technique increases the ultimate capacity and fatigue life of the strengthened element. However, these materials are highly flammable, when exposed to temperatures more than 70 ºC, they lose their properties. Additionally, they cause emission of toxic fumes throughout the curing process. Cement-based adhesives have good bonding properties and can withstand high temperatures. They are also non-flammable and there is no emission of toxic fumes. Therefore, they can be a good alternative for organic adhesives. Figure 4-38 shows the procedure for strengthening PC beams with CFRP NSM strips and a cement-based filler. First, grooves are made into the concrete surface using a concrete saw. Prior to the application of the cement-based adhesive, the grooves were wetted with water. After the adhesive was applied using an injection gun, the CFRP strips were placed into the grooves to the required depth. Finally, any excess filler material was removed and the surface of the concrete was levelled [154].



(a) (b) (c) (d) (e) (f)

Figure 4-35. Fabrication process for the test: (a) nondestructive inspection, (b) identify the location of the rebar and the thickness of the covering, (c) form the groove, (d) place the anchorage device, (e) apply pre-stress, (f) inject the filler [17].



Foam notch fillers cut

Mortar repair with foam notch placed

Foam removed and longitudinal notches marked

Notches taped after cutting longitudinal notches

Applying Hilti HIT-RE 500 epoxy

Final repair after troweling and removing tape

Figure 4-36. FRP NSM repair process [55]

Grind

Sand coating

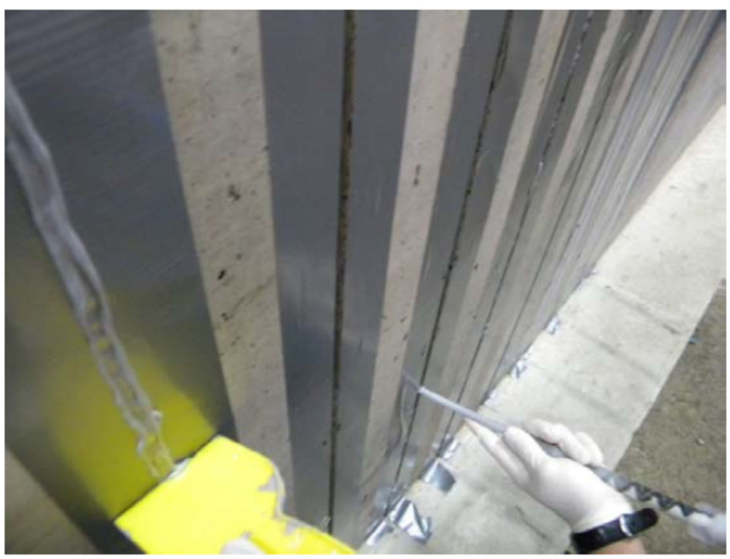
Figure 4-37. Surface treatment of CFRP bars for NSM strengthening approach [151]

Example application 4: Dias and Barros [96] used NSM CFRP laminates for shear strengthening of T-shaped RC beams. The laminates were placed into vertical and inclined grooves on the web of the beams. The procedure for the implementation of such strengthening technique is as follows: (1) first, grooves were made on the lateral faces of the beam web using a diamond cutter, and according to the vertical or inclined orientation. (2) the grooves were then cleaned using compressed air. (3) the laminates which came in the form of rolls were then cut with the desired dimensions and cleaned with acetone. (4) the grooves were filled with adhesive (5) a layer of adhesive was applied to the laminates (6) finally, the laminates were placed into the grooves and the excess adhesive was removed. Everything was then left for one week, allowing the adhesive to be cured.

Figure 4-38. Procedure for NSM CFRP strengthening using a cement-based filler [154]

Example application 5: Goebel et al., [97] implemented a NSM CFRP shear strengthening technique by cutting out grooves on the web of the RC girders as shown in Figure 4-39. The grooves were filled half way with epoxy. The CFRP strips were placed in the center of the epoxy filled grooves without using any centering devices. Then, additional epoxy was applied in the grooves to ensure that the CFRP strips are fully covered with adhesive. Finally, the excess epoxy was removed using a trowel.

Typical vertical groove cutting technique and finished grooves



Epoxy placement over CFRP in saw cut grooves

Figure 4-39. Procedure for the implementation of NSM CFRO shear strengthening used by Goebel et al., [97]

Example application 5: Figure 4-40 shows the schematic of the flexural strengthening approach used by Oudah and El-Hacha [160] which used CFRP rods as NSM reinforcement placed in a groove at the soffit of the beam. The test results conducted by the aforementioned authors showed that the NSM CFRP rods were able to successfully reduce the deflections and damage accumulation of the beams. The indicated that the amount of damage accumulation is independent of the prestress level. They also concluded that presstressing enhances the bond at the epoxy–concrete interface. However, as the prestress level increases, anchor slippage is more likely to happen. But it does not have a major effect on the bond behavior along the length of the beam. It was also demonstrated that the groove dimensionality, rather than the CFRP geometry, has a detrimental effect on the bond behavior. The larger interfacial area, the higher bond strength.

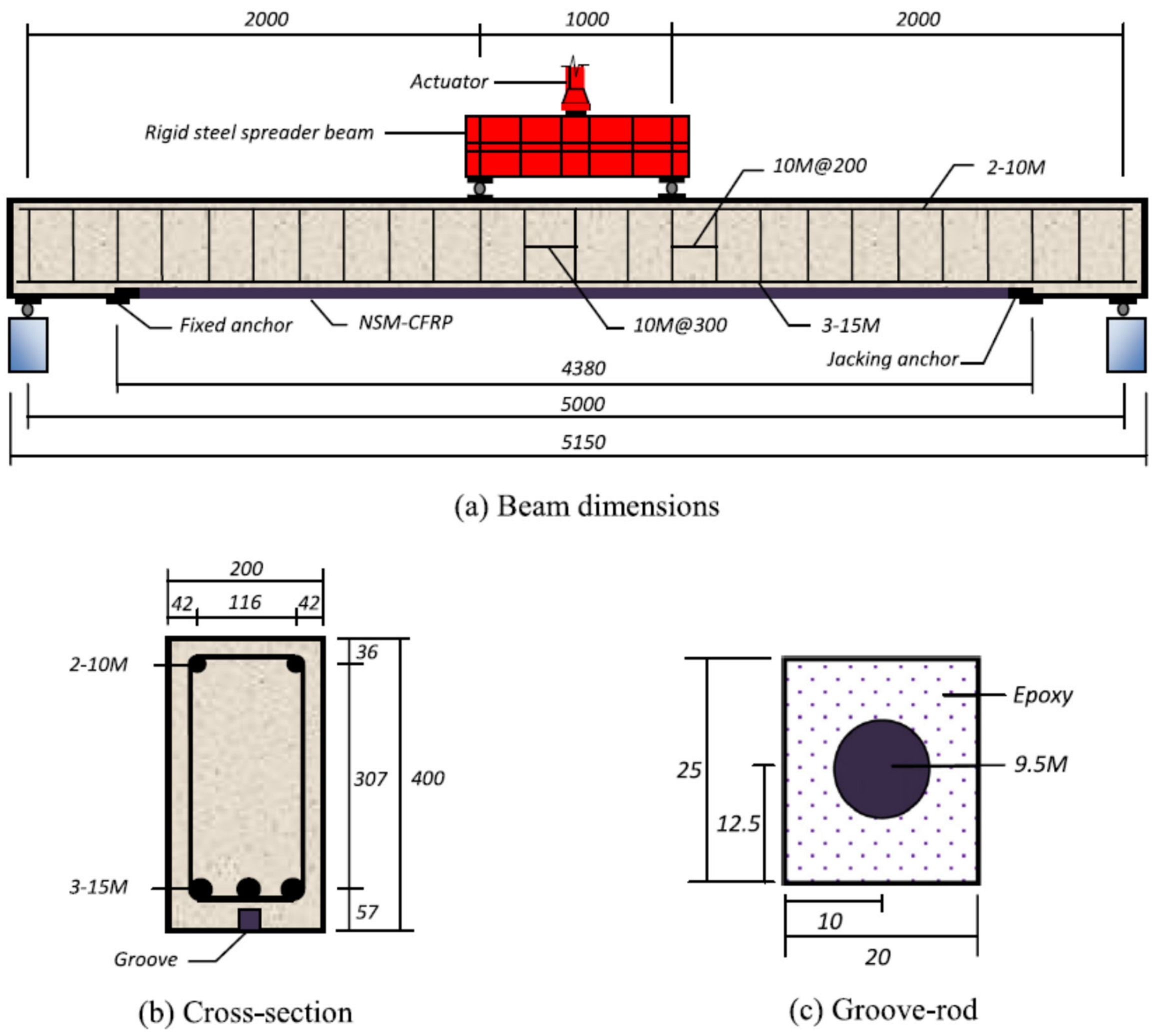


Figure 4-40. Schematic of the prestressed NSM CFRP rods for flexural strengthening of rectangular beams [160]

4.3.3. Embedded reinforcement

Even when using the NSM method, premature debonding can still occur, resulting in incomplete use of the tensile capacity of the repair material (such as FRP). This is more likely to happen in beams with T-shaped or I-shaped cross sections. Additionally, studies have indicated that in the NSM method, detachment of the cover concrete in which the NSM reinforcement is used might occur which prevents the repair approach to work in full capacity. Therefore, it might not be possible to fully utilize the tensile strength of the repair material using the NSM or EB methods, unless proper anchorage is provided. Embedding the reinforcing material inside the girder will increase the bonding. This is because the concrete core handles the stress transfer to the strengthening material, and compared to the concrete cover, it can provide better confinement, and thus improved bond behavior. Additionally, in this technique, protection against fire and vandalism is even more than the NSM method [80, 90].

Example application 1: One example of the embedded approach is the deep embedment (DE) technique, also called the embedded through-section (ETS) method. In this technique, the strengthening bars are placed into the vertical or inclined holes drilled into the section of the beam through epoxy material (see Figure 4-41.).

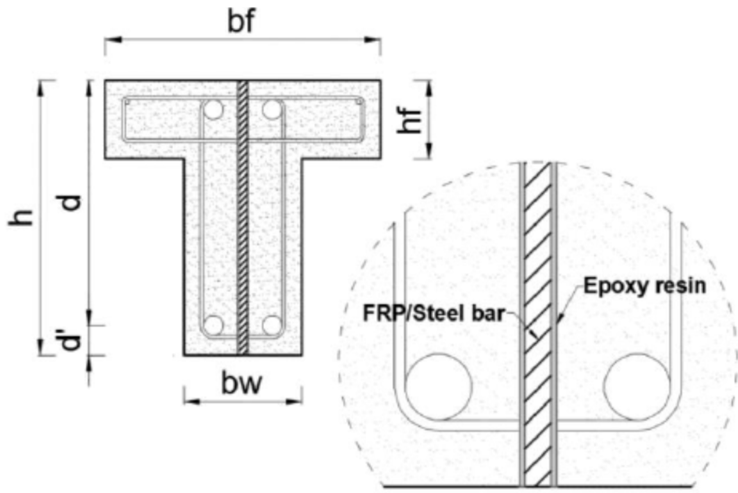


Figure 4-41. Schematic of the deep embedment technique for T-beams [105]

Figure4-42 shows the implementation of the DE technique, including drilling the holes, injecting epoxy in them, and placement of the bars inside the holes.

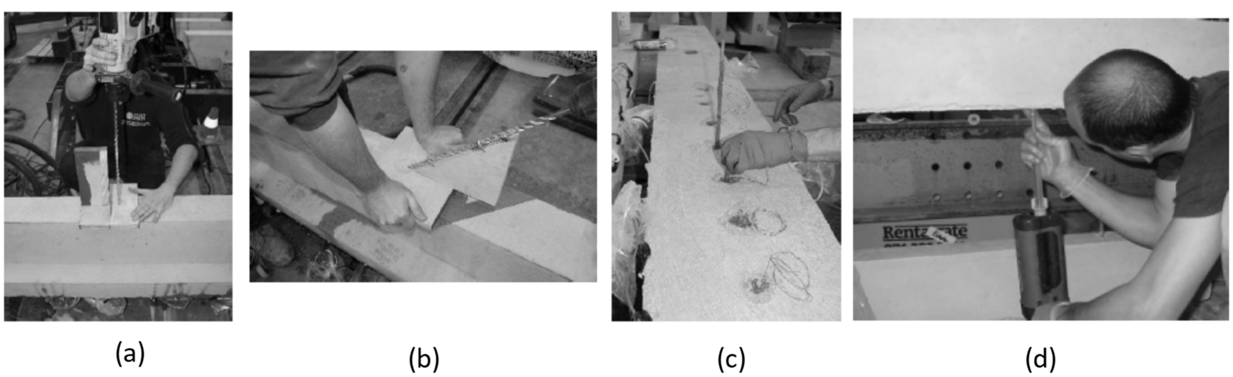


Figure 4-42. Implementation of the DE technique: drilling (a) vertical and (b) inclined holes, (c) injecting epoxy into the holes, and (d) placement of the bars inside the holes [90, 105]

Example application 2: Another similar repair technique of this type can be removing the entire damaged concrete and then placing reinforcing materials inside the damaged area of the section. Yazdani and Montero [3] implemented such technique for the repair of an impact damaged girder. The implementation procedure is similar to the EB and the NSM techniques. They used GFRP bars for the repair of an impact damaged girder through the following procedure after surface preparation (removing the loose concrete and roughening the surface): first, they drilled holes into the girders for bar placement. After cleaning, they placed the bars inside the holes and applied bonding agent. Then, they installed formwork for filling the damaged area with repair mortar. However, this method might not be the most convenient approach for girder repair projects on older bridges as in the most of such cases, only the surface of the girder is accessible [5].

4.4. Pre-stressing of the repair material (optional)

Pre-stressing was first utilized for strengthening bridges in 1950s [54]. It enables the member to sustain higher loads and cover a longer span length due to the negative moment that is generated in the element. It is relatively fast and that it can be done without impacting traffic [25]. It also helps to upgrade the performance of the member in terms of both load-carrying capacity and serviceability (for instance, controlled deflections and crack initiation) that could not be achieved otherwise [57].

Some of the advantages of prestressing the FRP repair material are: Fully utilizing the high strength of FRP, improving the serviceability of RC beams, limiting the propagation of old cracks, delaying the formation of new cracks, and enhancing the stiffness of RC beams, better utilization of the strengthening material, smaller and better distributed cracks in concrete, unloading (stress relief) of the steel reinforcement, resulting in higher steel yielding loads, potential for the restoration of service level displacements or performance of the structure, confining effect on concrete (and, significantly, any patch material) because they place the concrete into compression, and thus, they cause a delay in the onset of cracking and a reduction of crack widths [53, 81]. El-Hacha and Gaafar [162] indicated that prestressing the CFRP bars used for flexural strengthening of beams using the NSM technique enhances the overall performance of the strengthened beam by decreasing deflections and crack widths; delaying the formation of new cracks; and increasing the cracking, yielding, and ultimate loads. They indicated that increasing the prestressing levels, improved the overall flexural behavior of the beams at service and ultimate conditions, but also decreased the ductility. It should be noted that generally, different levels of prestressed forces will result in different failure modes. Despite all the advantages of prestressing the repair material, design of the end anchorage system requires accurate and expensive analysis due to the presence of large shear forces, large concentrated compressive forces, and induced moments due to the eccentric post-tensioning forces. If needed, the anchorage system should also be post-tensioned itself [20].

There are different approaches to prestressing the CFRP material for girder repair. Figure 4-43 shows schematic of these methods. Inconsistent terms are used in the literature for these methods. Herein, the CFRP applications are divided into prestressed and non-prestressed. The prestressed applications are further divided into pre-tensioned and post-tensioned methods. Finally, the post-tensioned methods can be applied either in an unbonded or bonded manner [82].

Each of EB CFRP approach depicted in Figure 4-43 are briefly described below and their advantages and disadvantages are explained:

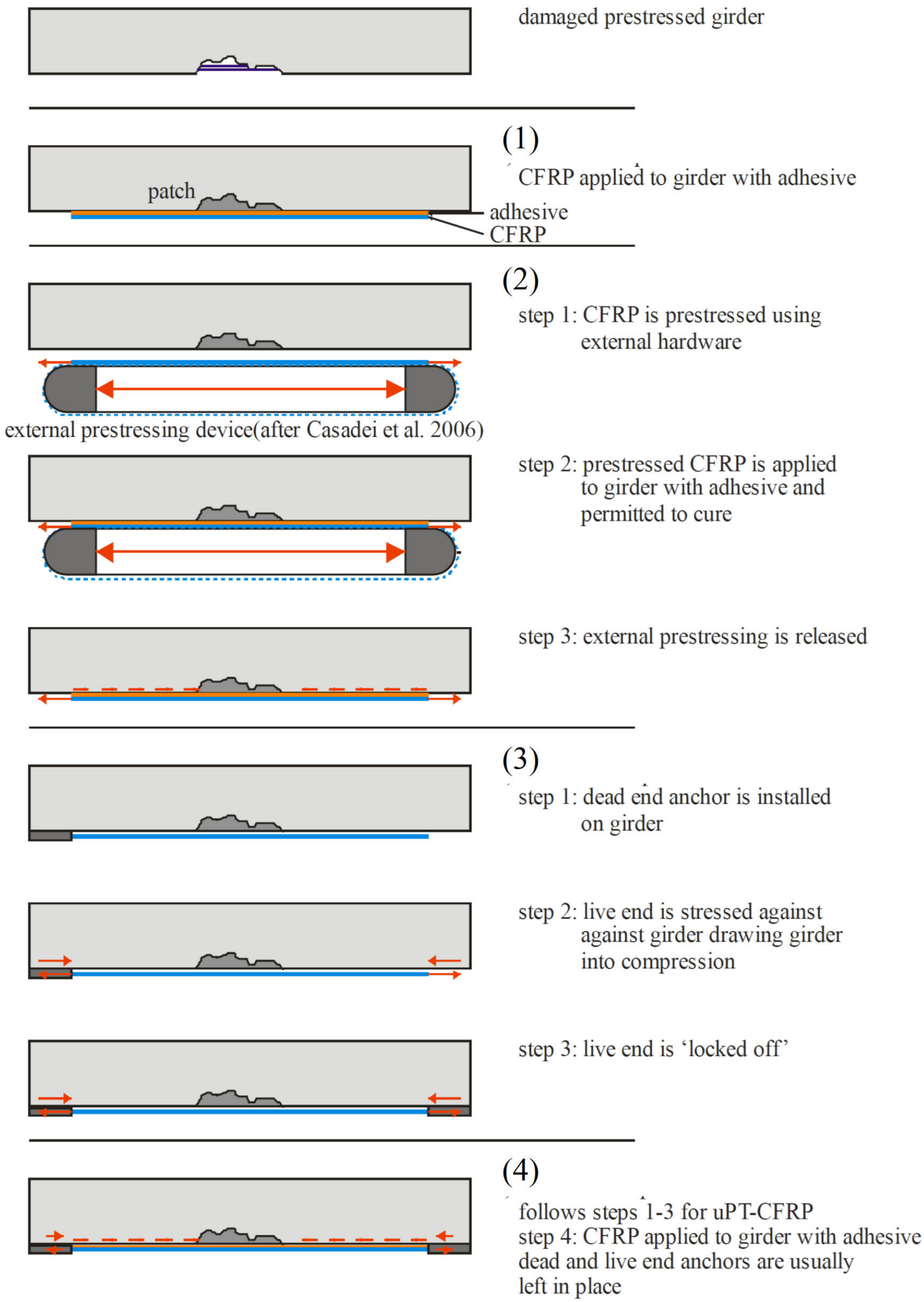


Figure 4-43. Four different approaches for EB CFRP application: (1) non-prestressed (2) Pre-tensioned (3) Unbonded post-tensioned (4) Bonded post-tensioned [82]

(1) Non-prestressed CFRP: advantages are the reduced labor and expenses in the application of the repair. Disadvantages are the inability to fully utilize the strength of the repair material.

(2) Pre-tensioned CFRP: in this method, the CFRP material is put into tension using external reaction hardware (see Figure 4-43) and is adhesively bonded to the concrete substrate while under stress. The stress is maintained using the external reaction until the bonding adhesive is cured. Then, the reacting stress is released and the 'prestress' force is transferred to the substrate concrete. This method results to losses both at stress transfer and due to the creep of the adhesive system. Therefore, only relatively low levels of prestress may be achieved. Furthermore, since the prestressed force is transferred to the concrete through the adhesive, bond behavior becomes of great importance. Additional details (such as FRP U-wraps) might be necessary to mitigate debonding at the termination of the CFRP strips [82].

(3) Unbonded post-tensioned CFRP: as it can be seen in Figure 4-43, in this method, when putting the CFRP into tension, the girder being repaired provides the reaction. Typically, a hydraulic or mechanical stressing system will be installed on the girder to apply the tension. The tension is transferred to the girder through mechanical anchorage. Finally, the stressing system will be 'locked off' at the stressing anchorage. This final step can lead to prestress losses. Additionally, depending on the anchorage method, long term losses due to creep in the anchorage are also a consideration. Harries et al., [82] reviewed the available methods for the repair of impact damaged bridge girders. They demonstrated that the unbonded post-tensioned CFRP is not recommended as a repair method for impact-damaged prestressed concrete girders. To reduce this drawback, sufficient clearance between the CFRP and the substrate should be considered. The drawbacks of this method are overcome by the bonded post-tensioned method explained next, at little additional cost.

(4) Bonded post-tensioned CFRP: this is the method recommended by [82] for repairing impact-damaged prestressed girders requiring the restoration of some prestress force. In this method, the CFRP is stressed and anchored in the same way as the unbonded post-tensioned CFRP method. However, following the anchorage, the CFRP is bonded to the concrete substrate resulting in a composite system with respect to loads applied following CFRP anchorage. The advantage of this technique is that adhesive creep is not critical here since the adhesive is not under stress due to the post-tension force. In fact, the bonding between the CFRP and the concrete substrate might help in mitigating the creep losses associated with the anchorage.

Example application 1: High strength steel tendons or rods have been traditionally used in this technique (see Figure 4-44) [82]. However, in case of harsh environmental conditions, carbon fiber composite cables (CFCC) might be preferred over steel material owing to their corrosion resistance [25]. FRP-based materials, have desirable properties in prestressed conditions which leads to a better performance compared to prestressed steel material [54], and also compared to their non-prestressed conditions. For example, in case of EB CFRP strips, researchers have demonstrated that the strengthened element uses only 20-30 percent of its total strength. Prestressing can improve the performance of the EB FRP strengthened elements by reducing crack widths, deflections, stress in the internal steel, and by increasing fatigue resistance [148].

As can be seen in Figure 4-44, the pre-stressed steel material is applied on the surface of the concrete. For more efficient retrofit results, NSM technique can be used. Figure 4-45 shows the procedure for prestressing (post-tensioning) FRP reinforcement for strengthening of RC beams using the NSM technique.

Figure 4-44. Real-life application of the externally post-tensioned technique for bridge girder repair [54]

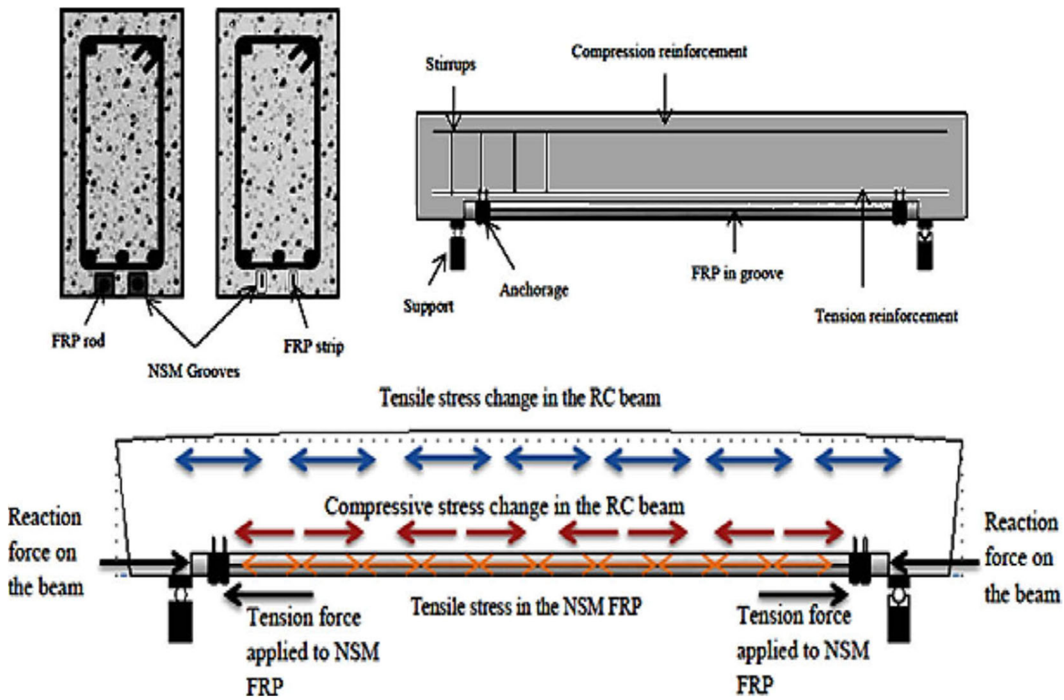


Figure 4-45. Schematic diagram of near surface mounted (NSM) prestressed FRP reinforcement [54].

Example application 2: Figure 4-46 through Figure 4-48 show the steps for installation and post tensioning of CFRP rods for strengthening of concrete girders. The procedure is clear. It involves: making the grooves, installing the CFRPP rods and the anchorage system (see section 4.3. on the anchorage system), mounting the jacking device and application of the post-tensioning force, removal of the jacking device and filling the grooves with proper filling material. The filling material of the grooves, however, can be different based on the project requirements and availabilities. Either mortar or epoxy can be used. The post-tensioning device is shown in Figure 4-47.

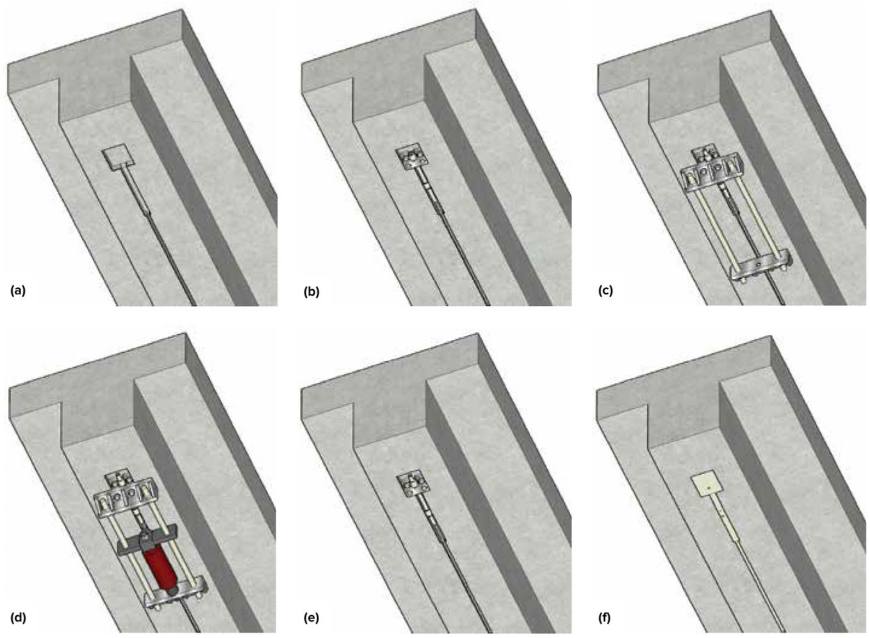


Figure 4-46. Strengthening scheme: (a) groove and anchorage zone are cut into the girder; (b) anchorage and CFRP rod are installed; (c) jacking apparatus is mounted; (d) post-tensioning force is applied to anchorage sleeve on the CFRP rod; (e) force is transferred from the jacking pparatus to a fastening nut on the end of the anchorage sleeve; and (f) the groove and anchorage zones are grouted [57]

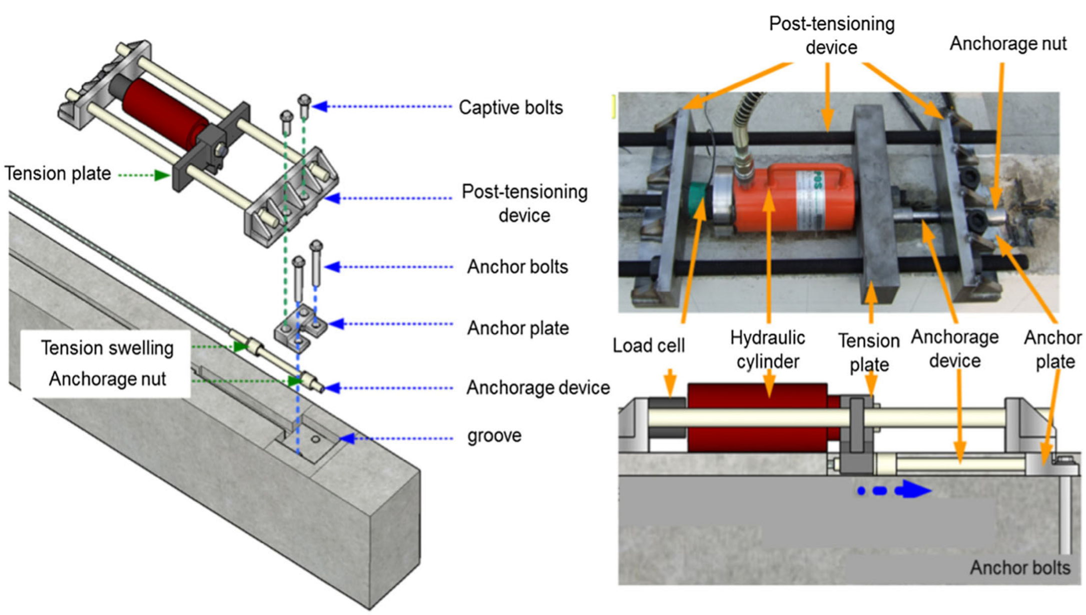


Figure 4-47. Details of the post-tensioning device system [152].

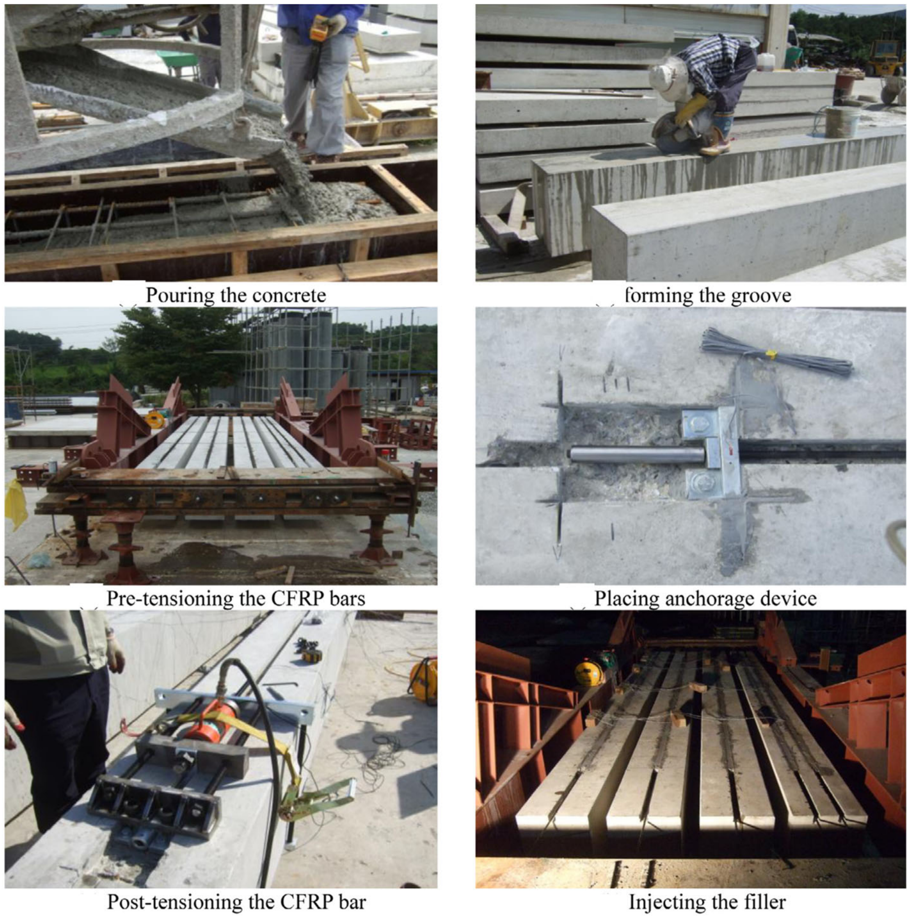


Figure 4-48. Application of the NSM post-tensioning strengthening method using CFRP bars [151]

Example application 3: Figure 4-49, shows the post tensioning system used by Huang et al., [81] for prestressing CFRP sheets. As can be seen, they used two end anchorage systems: a pulled-end anchorage and a fixed-end anchorage. They also used a tensioning equipment, a steel frame, and a series of bolts. The anchorages at both ends were two steel plates, which clamped the impregnated CFRP sheet tightly using four bolts. At the tension end, a load sensor was includind in the tensioning equipment to monitor the variation in the prestress force. A hydraulic oil jack was used for applying the prestress force [81].

Example application 4: Gao et al., [140] used steel anchors, bonded to the CFRP laminates through adhesive, for post-tensioning of the laminates. Figure 4-50 shows the installation of such anchors to the beam. The anchors are first bonded to the CFRP laminates. Then, the bottom of the girder is grinded and coated with epoxy. The laminates are then attached to the bottom of the girder by mounting the steel anchors on the steel angles at both ends. These steel angles act as reaction supports to the hydraulic jack’s applied pre-tensioning forces.

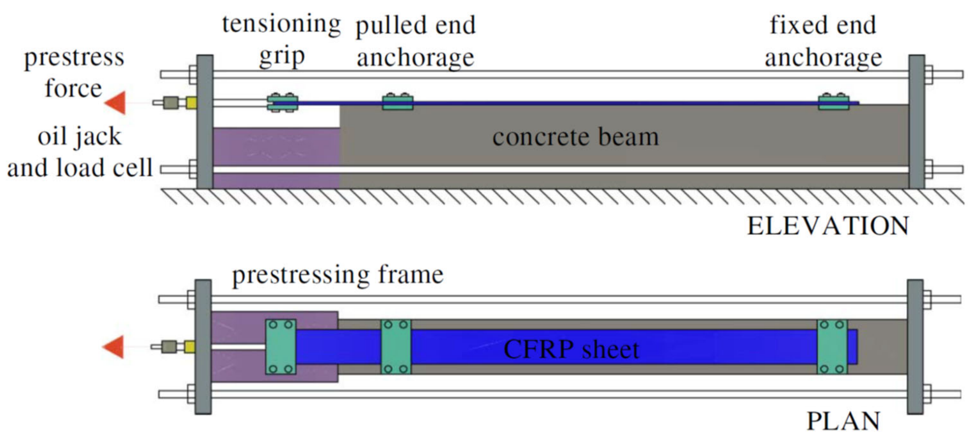


Figure 4-49. Post tensioning system used by Huang et al., [81] for prestressing CFRP sheets

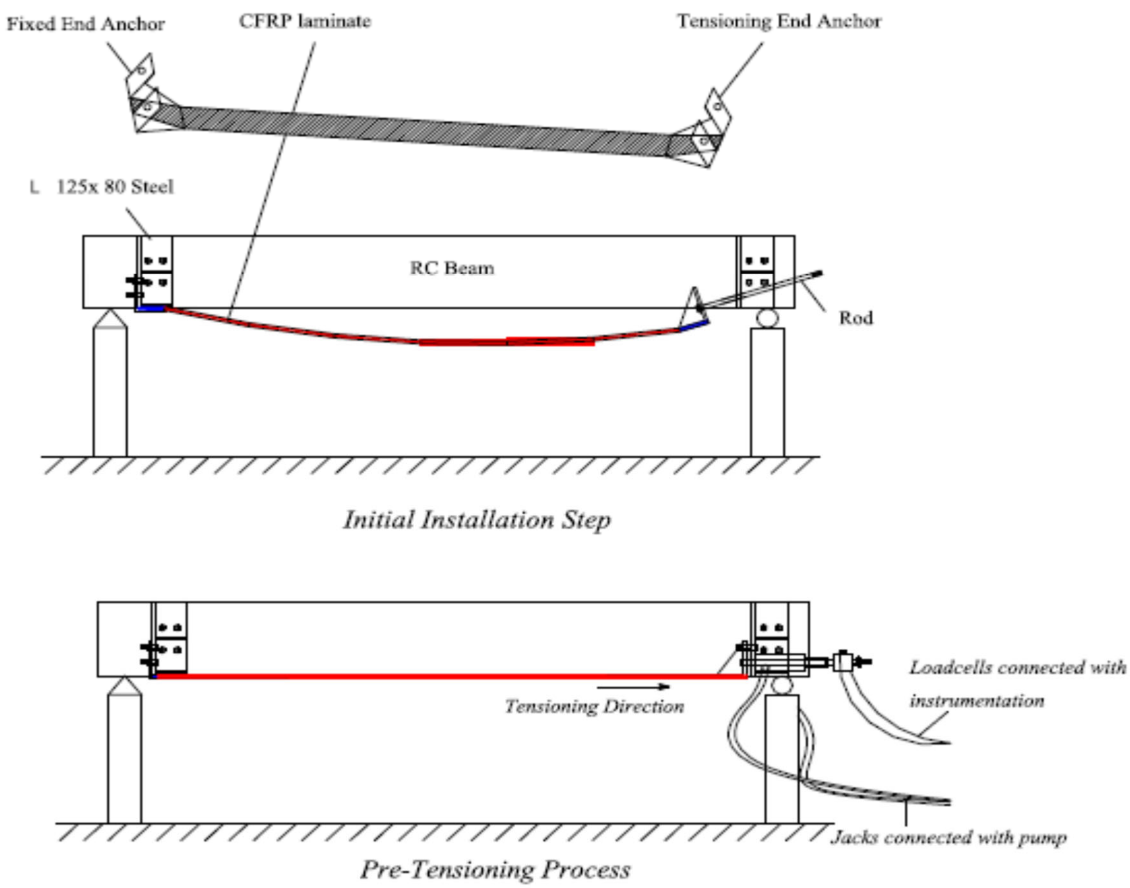


Figure 4-50. Post-tensioning of the CFRP laminates

4.5. Anchorage system

For cases of high peeling or shear stress, an anchorage system might be used in order to delay debonding of the strengthening system such as FRP materials. A proper anchorage system might allow the use of a FRP strengthening plan that otherwise would not meet design code provisions. i.e. greater strengthening or the use of a wider range of possible FRP geometries and material properties. It can also be used in order to enable post tensioning or prestressing of the strengthening material to grip the two ends of the repair material to induce the prestressing force. Different anchorage systems has been introduced so far depending on the strengthening approach that they are used with. The types of anchorage systems investigated in the existing research studies for shear strengthening include additional horizontal strips of FRP sheets, FRP anchor spikes, near-surface mounted (NSM) systems, embedment of FRP sheets into the beam flange through precut grooves with adhesive bonding, mechanical strengthening of the concrete substrate over the anchorage zone of the FRP sheets, and various mechanical anchorage systems involving bolts and plates. An effective anchorage system allows externally bonded FRP reinforcements to continue carrying load, even after debonding occurs and thereby increase the shear contribution provided by the FRP sheets [55, 57, 66, 93]. Metallic anchors, FRP-based anchors, and textile-based anchors are examples of such systems. The last two repair methods have the advantage of being light-weight and non-corrosive. Additionally, since the use of FRP-based or textile-based materials are commonplace for girder repair, using a compatible anchor material is also advantageous [4]. Some other methods simply involve embedding part of the strengthening material such as FRP into holes or grooves made inside the girder section using adhesive material. A drawback of the use of many anchorage systems is the added cost and complexity of installation [66].

Common anchorage methods used in conjunction with shear strengthening systems are shown in Figure 4-51. Examples of each anchoring technique in practice or research is provided afterwards.

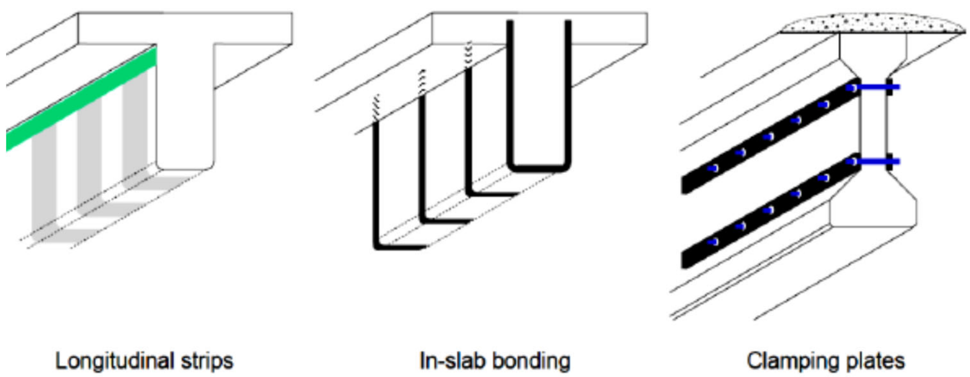


Figure 4-51. Common anchorage methods used in conjunction with shear strengthening systems

Example application 1: Foster et al., [6] compared performance of the CFRP U-wrapping technique for the shear strengthening of T-beams in two formats: externally bonded continuous CFRP sheets without end anchorage and CFRP sheets anchored with a near-surface-mounted bar-in-slot anchorage system. The anchorage bars, also made from CFRP, are spiral-wound sand coated bars. In their study, it was observed that the anchored CFR strengthening lead to moderate increases in shear capacity compared with both uncontrolled and unanchored EB CFRP-strengthened beams.

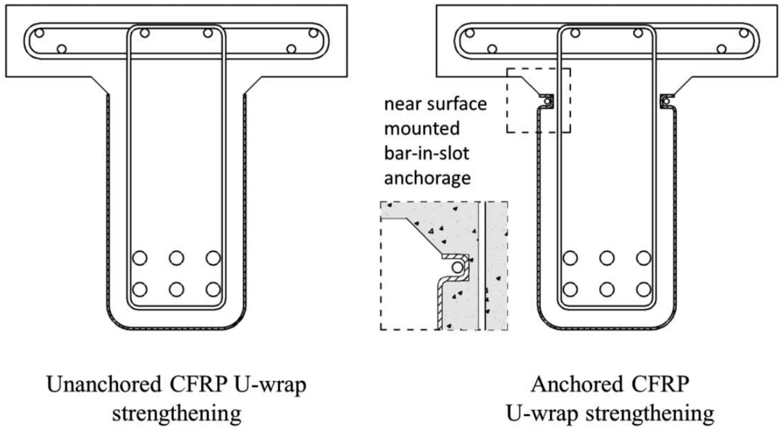


Figure 4-52. CFRP U-wrapping arrangements [6]

Example application 2: Figure 4-53 shows a common longitudinal anchorage system used in conjunction with CFRP and GFRP shear repair of RC girders.

Figure 4-53. End anchorage system using CFRP or GFRP strips [55].

Example application 3: Figure 4-54 shows the schematic and geometry of a fan-shaped textile based anchorage system. The fan-shaped part serves for the distribution of stresses between the textile reinforcement to be anchored and the anchor itself. The dowel part serves for its installation into holes and anchorage into the concrete mass [4].

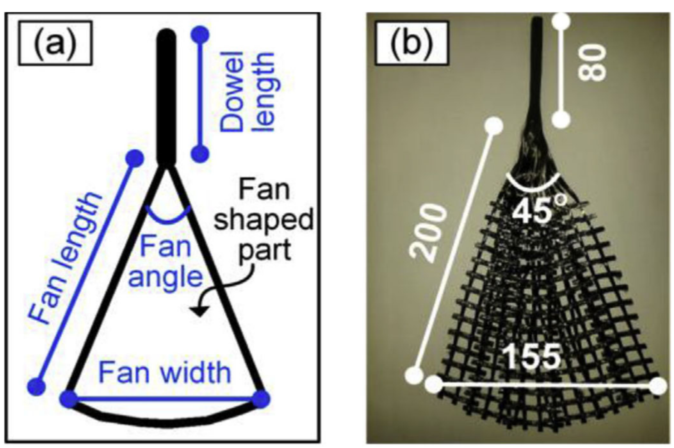


Figure 4-54. Fan-shaped textile-based anchors [4]

Figure 4-55 shows some steps in the implementation of the textile-based anchors for the repair of a RC T-shaped girder. First, holes are drilled into the flanges of the beam. Dust is then removed from the holes using compressed air. As shown in Figure 4-55, the holes are then filled with low viscosity epoxy resin, dry fiber anchors are impregnated in a two-part epoxy resin, and are then installed into the holes. The fan-shaped part of the anchors are bonded to the impregnated textile layer on the beam surface by hand pressure.

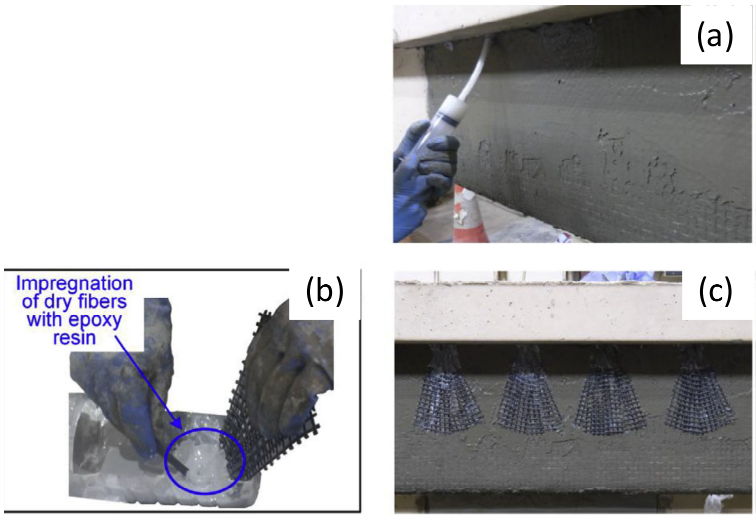


Figure 4-55. implementation of the textile-based anchors [4]

Example application 4: Figure 4-56 shows strengthening of shear deficient RC beams using CFRP U-wraps bonded to the concrete surface by epoxy used by TexasDOT. The horizontal layers of CFRP are meant to act as part of the anchorage system for the U-wraps. Instead of using mechanical anchorage, which is considered by TexasDOT as a potential cause of damage to the CFRP material, an FRP-based anchorage system is used. In this method, holes are drilled into the beam in the region where horizontal CFRP strips are located. Then, plugs of CFRP material (See Figure 4-57 and Figure 4-58) are epoxied in and placed into the holes through their upper part. The lower part of the CFRP anchors is attached to the horizontal CFRP strips. This anchoring technique was able to increase the efficiency of the strengthening technique by allowing the CFRP to reach its full capacity. Accordingly, shear strengthening up to 50% was be achieved, which might not be possible if the absence of a proper anchoring technique [256].

Figure 4-56. Strengthening of shear deficient beams using CFRP U-wraps [256]

Figure 4-57. Plugs of CFRP anchors inserted into holes inside the concrete surface [256]

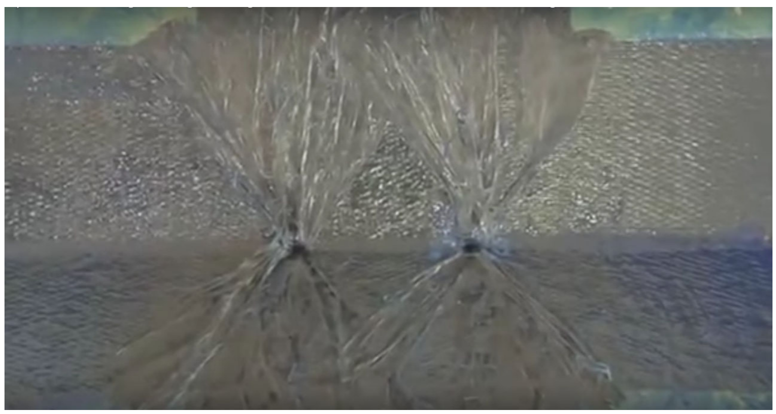


Figure 4-58. Top view of the CFRP anchors [256]

Example application 5: Figure 4-59 shows the anchorage system used with CFRP-honeycomb (H-Lam-C) and GFRP-hon eycomb (H-Lam-G) composite panels. The panels are pre-equipped with such anchorage systems in order to improve the bond with the concrete surface. The anchorage system, in form of concrete low carbon steel screws, will assist in precluding or even delaying the unfavorable interfacial debonding failure modes commonly encountered in RC beams repaired with externally bonded FRP laminates. The implementation details of CFRP sandwich panels pre-equipped with these mechanical anchors was explained in detail in section 3.1.2.1. Their study showed that the bolted/bonded joint between the strengthening panels and the concrete surface was able to prevent the typical interfacial panel debonding that is common for conventional FRP flat laminates strengthening technique [85].

Example application 6: Figure 4-60 shows two L-shaped CFRP laminates that are embedded into the grooves made in both sides of the girder flange, at the intersection with the web, as an anchorage system to increase the bond. Note that the anchorage length of the CFRP laminates in this configuration is almost the whole height of the girder's flange, i.e., full embedment length [98].

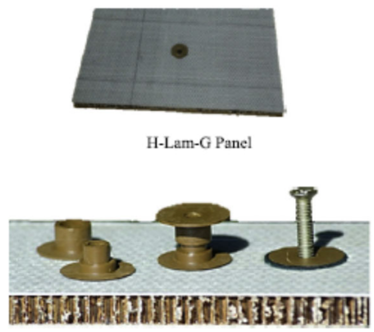


Figure 4-59. anchorage system pre-installed on the honeycomb panels [85]

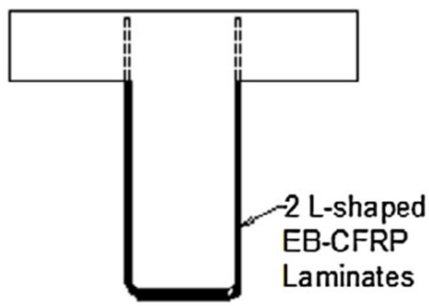


Figure 4-60. Two L-shaped CFRP laminates as the anchorage system [98].

Example application 7: Bae and Belarbi [93] and Belarbi et al., [95] used different mechanical anchorage systems in conjunction with CFRP U-wraps for shear strengthening of T-beams. The anchorage systems used included a discontinuous mechanical anchorage (DMA) system, sandwich discontinuous mechanical anchorage (SDMA) system, and additional horizontal strips (HS) system (see Example application 8).

Additional horizontal FRP strips are very easy to install and require the least amount of labor among all anchorage systems; however, different levels of effectiveness have been observed from them in various studies. As can be seen in Figure 3-61, the basic mechanical anchorage used in this study is comprised of two CFRP pre-cured laminate plates bonded to each FRP strip with epoxy resin and anchored firmly in place with concrete wedge anchors and steel bolts. The experimental results indicated that use of a mechanical anchorage system can provide additional shear strength. The FRP-strengthened beams with mechanical anchorage showed 7–48% higher shear strength than the beams without mechanical anchorage, depending on the types of mechanical anchorages used.

Example application 8: Similarly, You et al., [109] studied different types of anchorage systems used in conjunction with CFRP U-wraps for shear strengthening of AASHTO-type PC girders using nonlinear FE analysis. These anchorage systems shown in Figure 4-62 included horizontal FRP strips, as well as continuous and discontinuous mechanical anchorage systems.

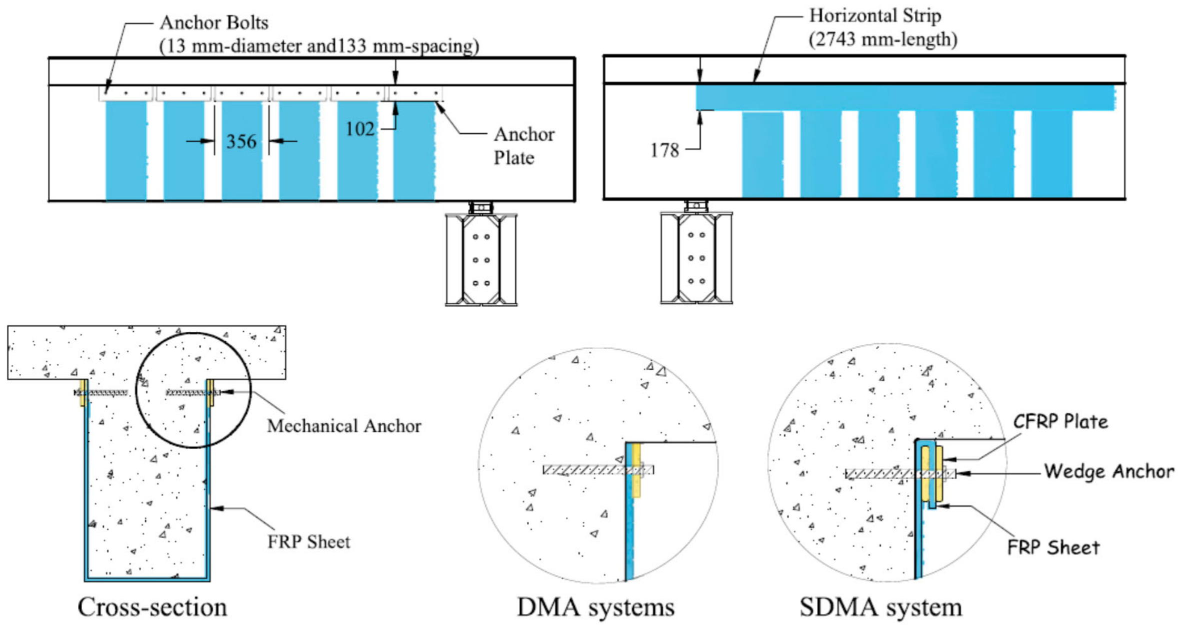


Figure 4-61. Different anchorage systems used in conjunction with CFRP U-wraps [93]

Example application 9: Petty et al., [110] investigated the performance of two different anchorage systems used in conjunction with a shear strengthening approach (vertical or inclined CFRP strips). The first anchorage system is comprised of a horizontal CFRP strip epoxied over vertical shear strengthening strips. The second approach used CFRP laminates epoxied into grooves over the vertical strips that were cut at the web-to-flange interface (see Figure 4-63). Experimental results showed that a CFRP scheme of vertical strips and horizontal anchorage strip provides the highest shear resistance [110].

Example application 10: El-Saikaly et al., [92] proposed a new anchorage system using CFRP ropes, which consist of a bundle of flexible CFRP strands held together using a thin tissue net (see Figure 4-64). To implement this method, holes are drilled through the web at the web-flange intersection. Then, CFRP ropes are inserted and flared onto the two free ends of the U-wrap scheme used (see Figure 4-65). This way, the U-wrap scheme is transformed into a full-wrap scheme which enhanced the shear resistances of the repaired girders.

Figure 4-66 shows the procedure for installation of the CFRP rope anchorage system including: (1) drilling holes in accordance with CSA/S806-12 (2) cleaning the holes using compressed air or water (3) impregnating the CFRP ropes for 30 minutes in a low-viscosity epoxy to enhance the bonding performance (4) partially filling the hole with epoxy adhesive using a beaker with a narrow spout, starting (5) inserting the ropes inside the holes while being extended to both sides (6) epoxy adhesive was again injected into the hole, and the excess epoxy at the hole surface was removed, just to ensure that no air pockets remain inside the holes (7) the two ends of the rope were flared onto the L-strips and are gently pressed to ensure proper bond [92].

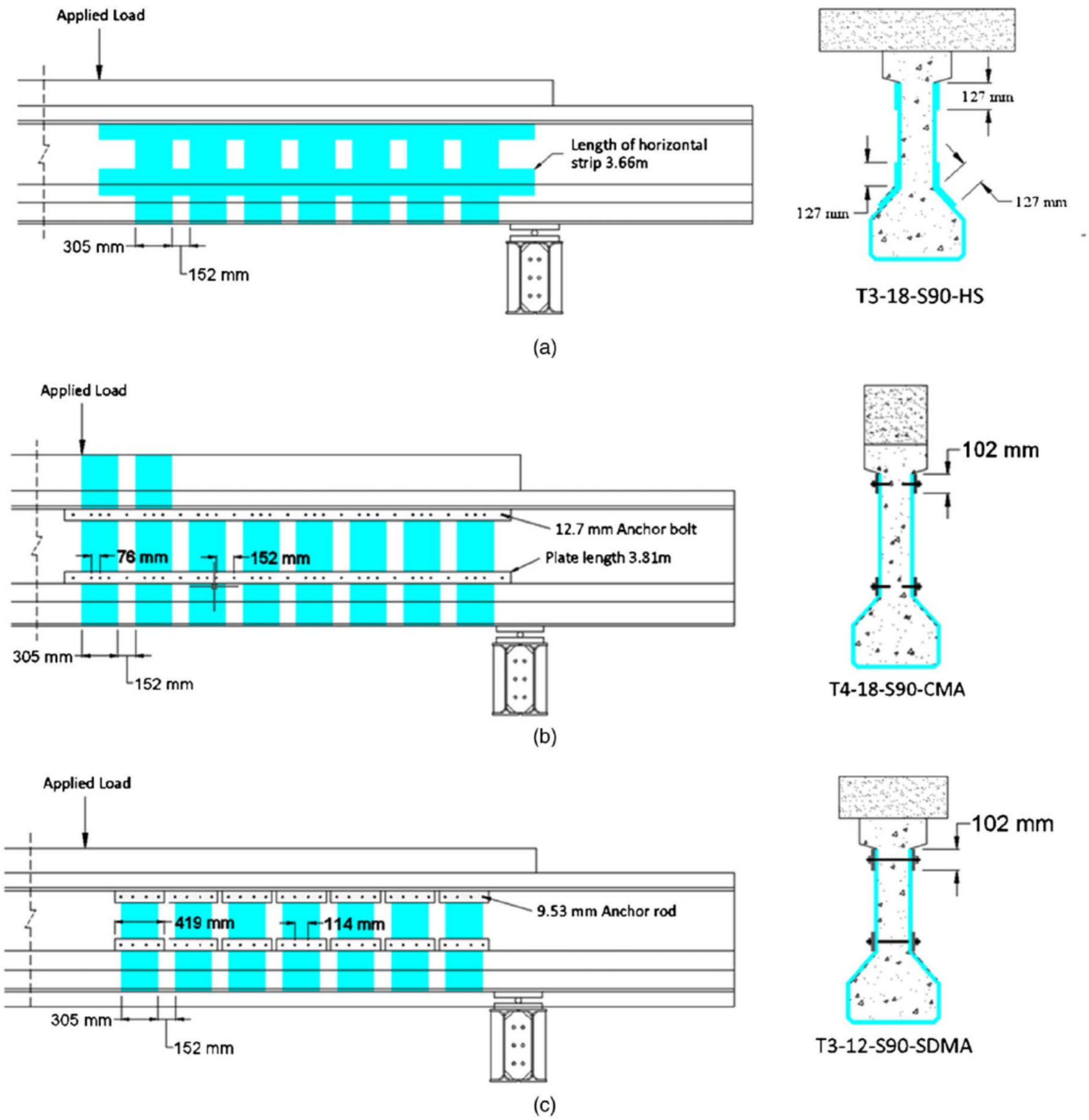


Figure 4-62. Different anchorage systems used in conjunction with CFRP U-wraps for shear strengthening of AASHTO-type PC girders: (a) horizontal FRP strips (b) continuous mechanical anchorage (c) discontinuous mechanical anchorage [109]

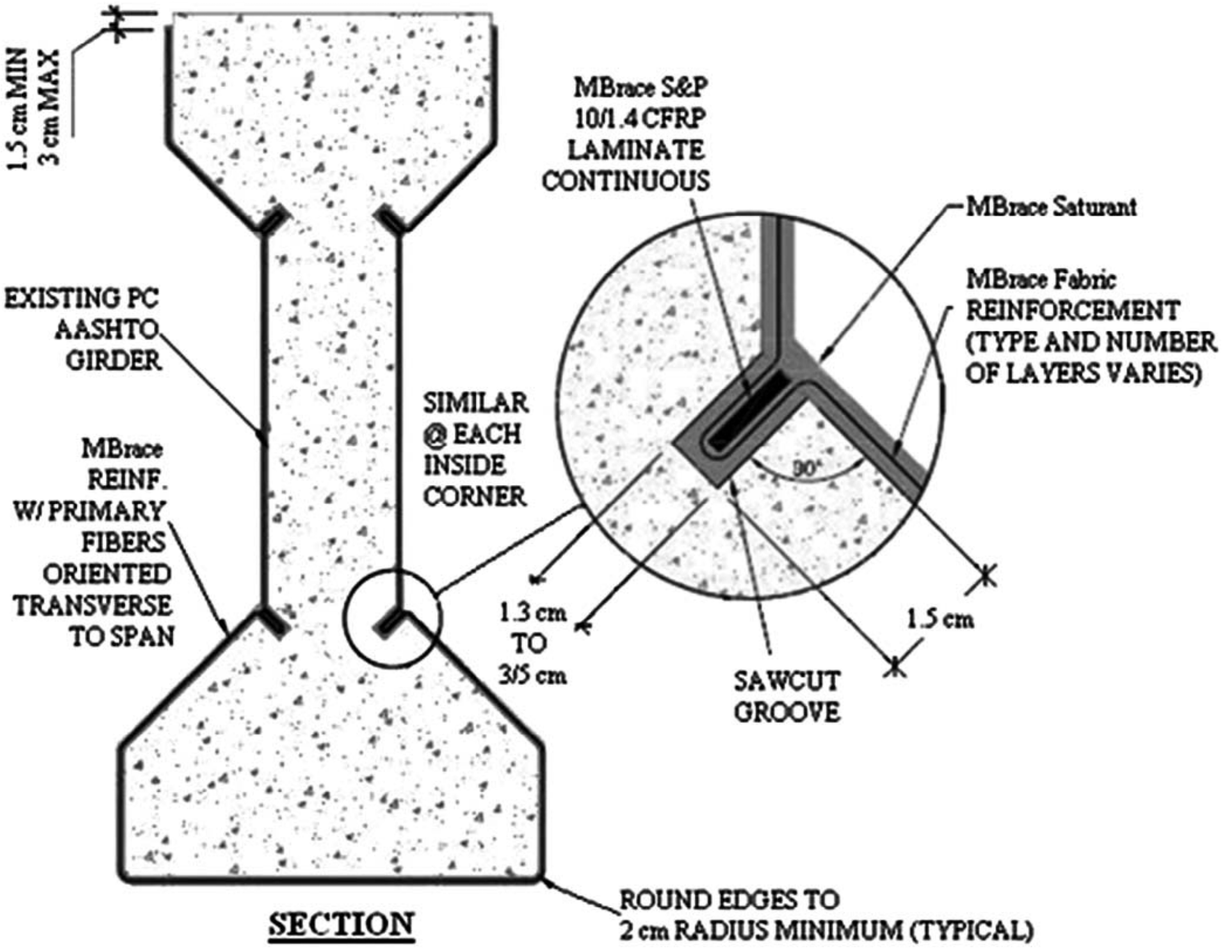


Figure 4-63. Details of the laminate anchorage system [110]

Figure 4-64. CFRP ropes as anchorage system [92]

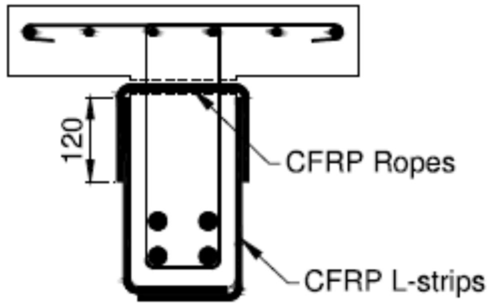


Figure 4-65. CFRP rope anchorage system used in conjunction with two L-shaped CFRP sheets [92]

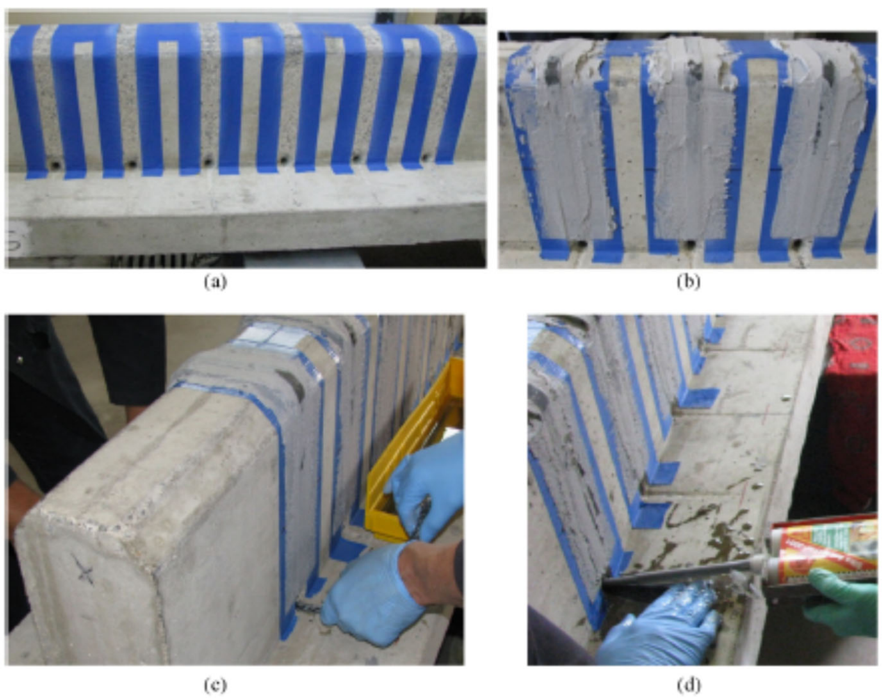
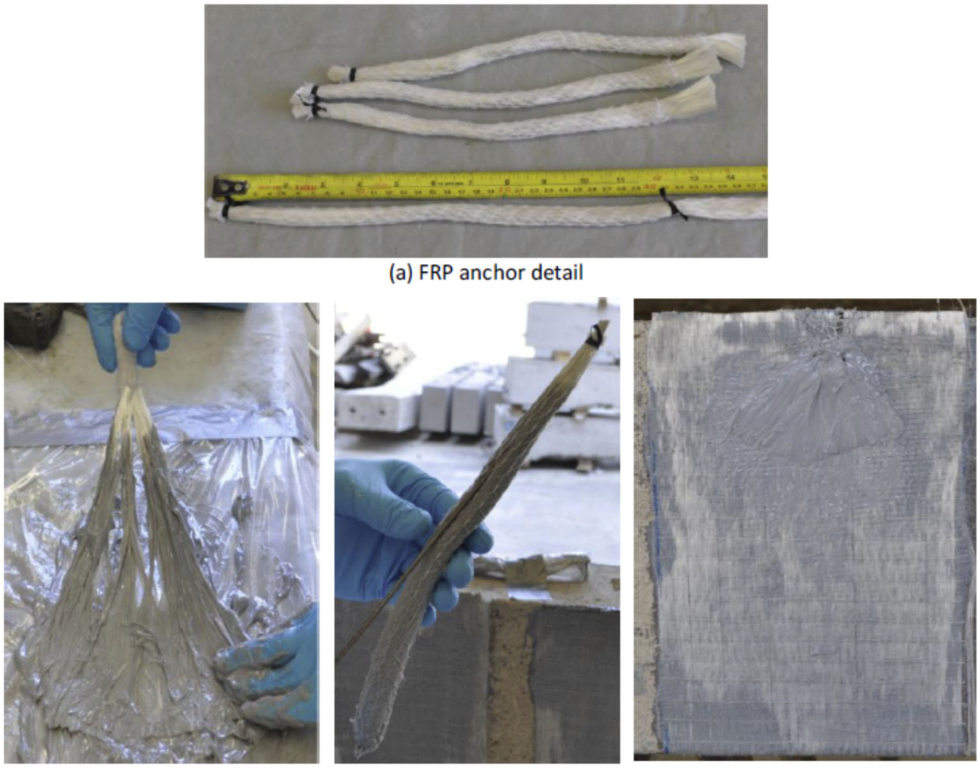


Figure 4-66. Installation procedure for the CFRP rope anchorage system [92]

Example application 11: Figure 4-67 shows the installation procedure for a commercially available FRP anchor system. First, holes are located and drilled at mid-width in the FRP sheet. The FRP sheets are then installed on the girder and finishing nails are inserted through the weave of the FRP to mark the location of each pre-drilled hole. Then, the sheets are sprayed so the predrilled hole opening was visible. The nails are removed after 24 hours and the holes are re-opened by drilling through the gap in the hardened FRP sheet. Finally, FRP anchors are installed and fanned out to secure the u-wrapped strengthening sheets [16].



(a) FRP anchor detail

(b) FRP anchor impregnation (c) FRP anchor installation rod (d) FRP anchor fan detail

Figure 4-67. FRP anchorage system installation [16].

Example application 12: Murphy et al., [71] used four different anchorage systems in conjunction with CFRP U-wraps that were used as a means of shear strengthening (see Figure 4-68): (1) continuous mechanical anchorage system (CMA): continuous precured CFRP plates anchored in place with concrete wedge anchors (2) discontinuous mechanical anchorage system (DMA): discontinuous precured CFRP plates anchored in place with bolts running through the web (3) sandwich panel discontinuous anchorage system (SDMA): discontinuous precured CFRP plates with sandwich wrapped ends anchored in place with bolts running through the web (4) additional horizontal CFRP strips (HS): strips of bidirectional CFRP strips applied parallel to the longitudinal axis of the beam and covering all of the free edges of the vertical CFRP strips as well as along the interface of the web and bottom flange. These are the locations where debonding is expected to initiate. In order to ensure a better bond between the vertical and horizontal CFRP sheets, this anchorage system was installed immediately after application of the vertical CFRP shear reinforcement.

It was shown that the anchorage systems were able to successfully delay the debonding of the FRP strengthening material, which leads to more shear resistance. Discontinuous CFRP plates attached with epoxy and anchored in place with bolts running through the web was the most effective anchorage system. Horizontal FRP strips provided little additional shear capacity. Continuous CFRP plates with anchorage bolts were also ineffective in anchoring the CFRP sheets. The reason was buckling of the plates and insufficient embedment length to prevent pullout of the anchor bolts [71].

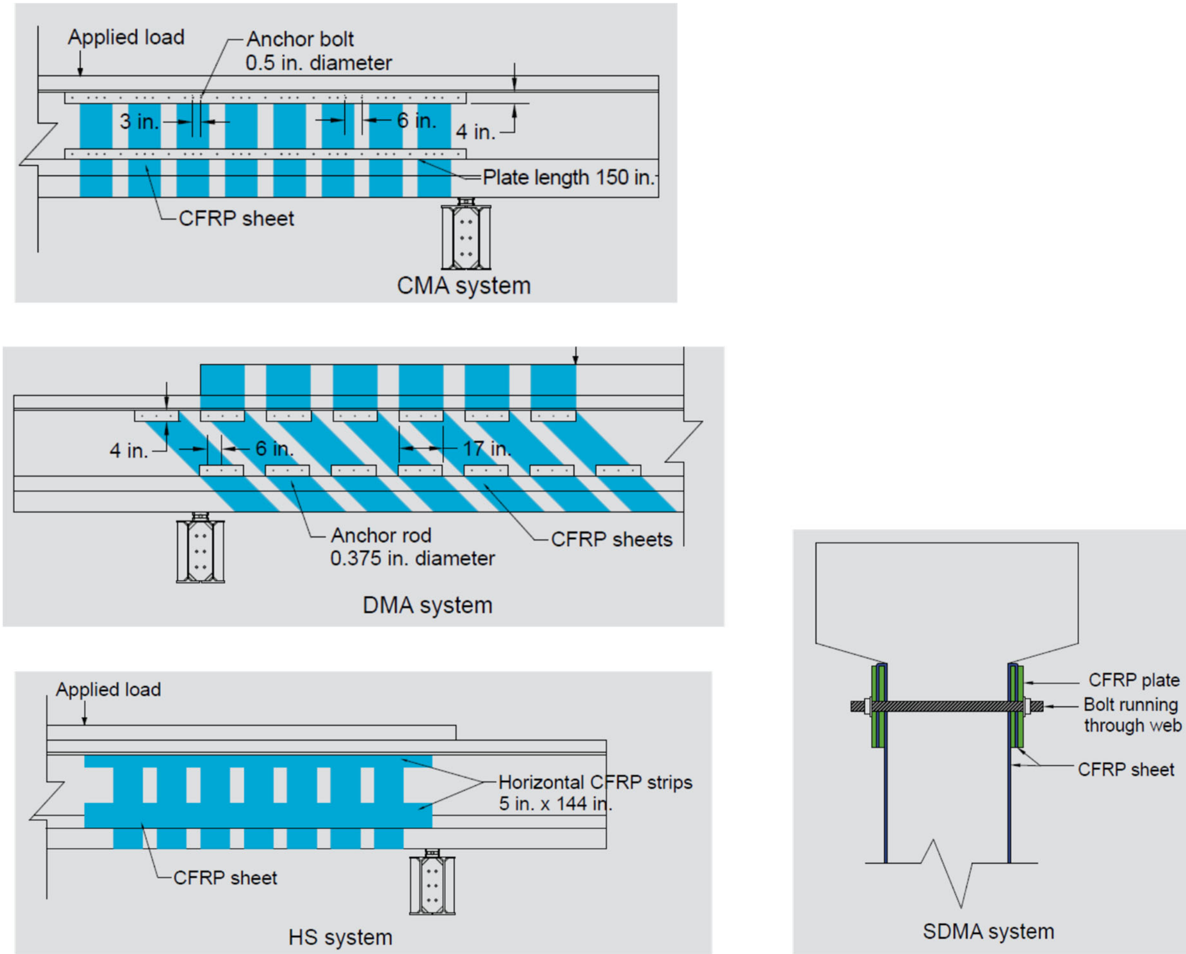


Figure 4-68. different types of anchorage systems used in conjunction with CFRP U-wraps [71]

4.6. Strand splicing (if needed)

When one or more prestressing strands in a prestressed girder are damaged, strand splicing can be used to repair the girder. It is a fast and efficient repair method for reconnecting damage or broken prestressing strands in order to restore the prestressing force. Commercially available strand splices (see Figure 4-69) have been reported to be adequate in providing $0.96f_{pu}$. Typically, a re-tensioning operation will aim to restore $0.60f_{pu}$ which will generally be close to the long-term effective prestress in a strand. It should be mentioned that commercially available splices are available for strand diameters only up to 0.5 in [82], [20, 137]. Additionally, strand splices are internal applications and therefore may be used with almost any external application. NSM method might be an exception since interference between the strand chucks and NSM slots might happen [82]. However, they can be combined with an externally bonded repair method using FRP or FRCM [60]. Strand splices are one of the cheapest and easiest methods (to design and install) for repair of damaged prestressed girders [137]. Figure 4-70 shows the installation of the splice chunks. Also, Figure 4-71 shows the complete procedure for the prestressed concrete girder repair using strand splicing.

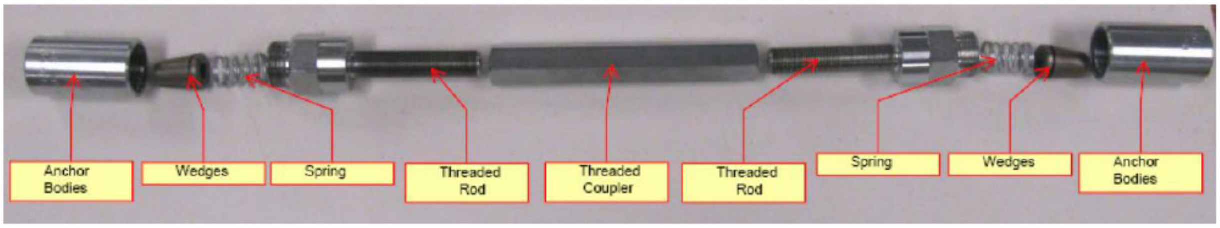


Figure 4-69. Components of a typical strand splice [82]

Figure 4-70. Installation of the splice chunks [60]

Figure 4-71. Repair procedure using strand splices: (a) installation of the strand splices (b) completed installation of the strand splices (c) placing the repair concrete (d) completed repair after concrete placement and form removal [20]

Using strand splicing for restoring the original beam strength is recommended when: (1) the ultimate flexural strength of the beam with the remaining undamaged strands is greater than the factored design moment; (2) fatigue is not a major concern; (3) repairs consist of less than 10-15% of the total number of strands in the girder [239].

There are three methods for doing strand splicing: (1) in the first method, bridge is first be preloaded introducing a negative moment, or upward camber. Then, the strands are connected and the load is removed, resulting in tension inside the repaired strands. (2) in the second method, the strands are heated and elongated. Then, the splice is connected. After the strands are cooled, they shrink and tension is introduced. (3) the last technique uses a wrench to torque the strand splice chuck and induce tension. This is the most common technique used to introduce tension in the severe strands. The first method might be inconvenient as producing a negative moment is not always possible. In the second method, heating might change the material properties of the strands and thus is not an ideal option [137].

As mentioned before, strand splices alone cannot be relied on for fully restoring the ultimate strength of the strands or the element that is being repaired as they are limited to developing 85% of the nominal strength of the strands they are joining ($0.85fpu$), i.e. the advertised minimum strength of a strand splice. In order to increase their efficiency, the splices should be staggered (see Figure 4-72.) and limited to splicing 15% of strands in a girder, regardless of staggering [137, 139].

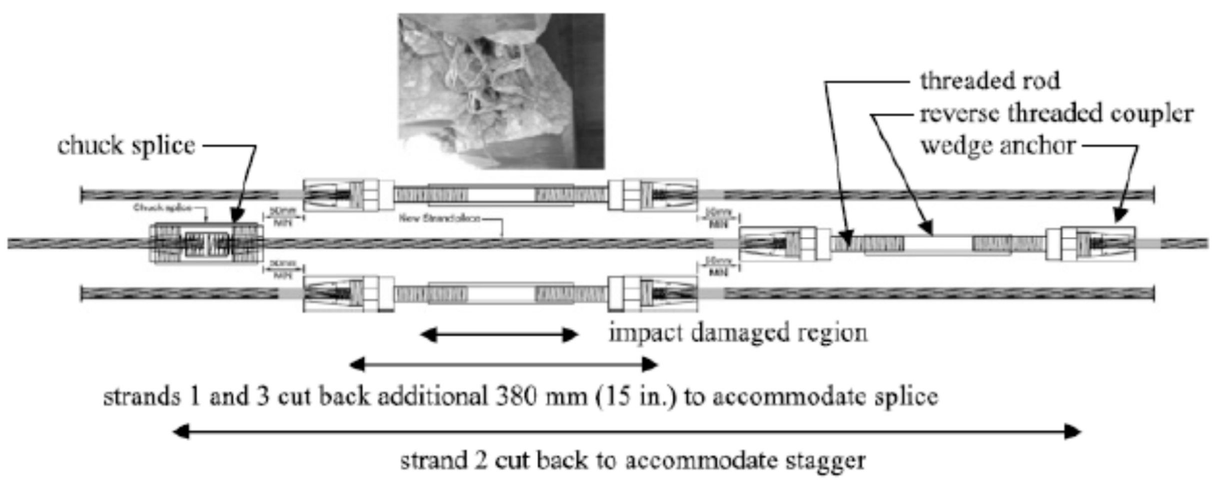


Figure 4-72. Staggering of the strand splices [137]

For box girders, Kasan et al., [139] do not recommend using strand splicing for repair of impact damaged girders, especially for older girders. Splicing adjacent strands in a box girder will result in significantly reduced concrete cover and interference. Furthermore, issues of splitting associated with strand splices cannot be adequately addressed in such girders because the top of the bottom flange (in the box void) is inaccessible. The aforementioned authors believe that in box sections, strand splicing is only practical for the repair of a few isolated strands. Strand splicing is more practically applied to flanged members. In order to improve the long term durability, confinement of the spliced region is recommended since the reduced cover, spacing, and interference with adjacent strands and splices affect development, crack control, and the likelihood of splitting, and also to enhance the performance of supplementary longitudinally oriented CFRP materials as introduced in this work. Splicing adjacent strands requires a longer repair region and thus may not be practical for cases of very local damage. One solution is to use a hybrid repair approach with strand splices and an externally bonded alternative. Such hybrid repair technique was proposed and investigated by [139]. Strand splices are internal applications and therefore may be used with almost any supplementary external application.

Chapter 5. RECOMMENDATIONS

In this chapter, based on the comprehensive literature review presented in the previous chapters, recommendations for choosing efficient repair techniques, where the state of damage requires structural repair, are provided. Based on the chosen repair technique for each damage type, repair procedure flowcharts are created. However, these are only general recommendations merely based on the previous literature which are intended to provide the reader with the most common and most efficient methods of repair that are typically used for different bridge girder deficiencies. Identifying detailed repair procedures corresponding to different types and levels of damage to the girders depends on the specific conditions of the project, and cannot be generalized.

5.1. Selection of the repair approach

If the inspection of the bridge results in the decision for its structural repair, then, the following parameters should be considered while selecting an appropriate and efficient repair technique.

- Girder concern/Deficiency (Impact damage, corrosion, fire damage)

- Girder section type (rectangular, T-shaped)

- Repair material (CFRP, GFRP, steel, FRCM, UHPC, shotcrete)

- Repair configuration (complete wrap, U-wraps, two side bonded, EB to soffit, NSM on the soffit, NSM on the sides, continuous vs discontinuous)

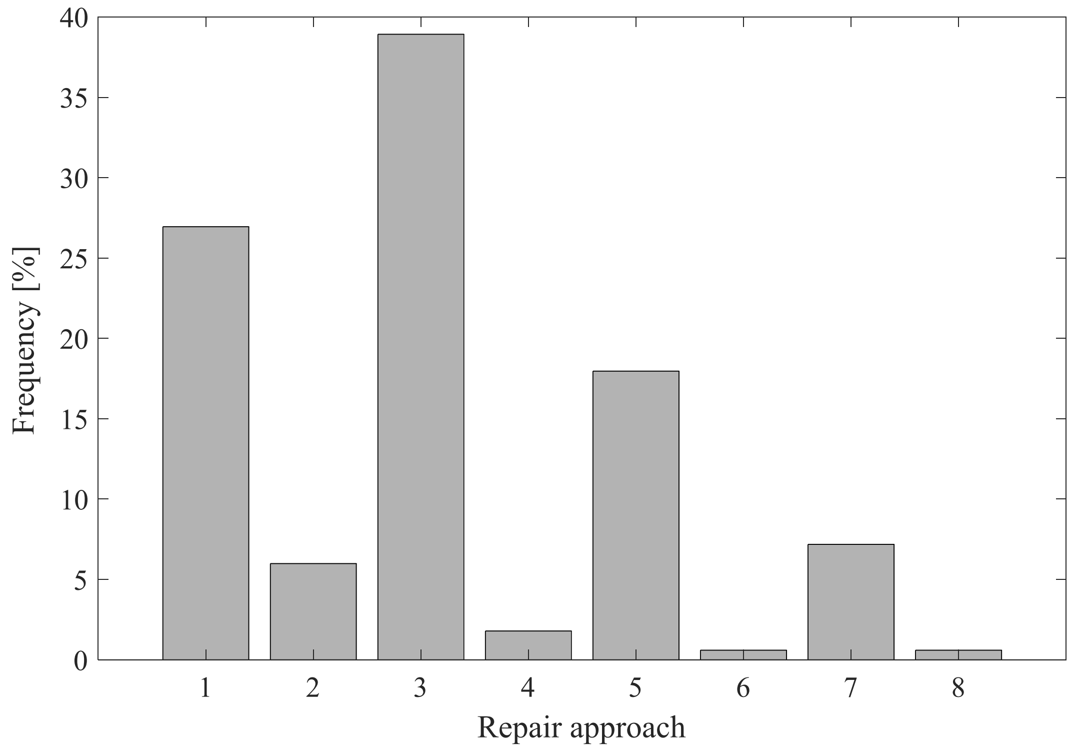
- Anchorage system (longitudinal FRP strips, fan-shaped FRP anchors, mechanical bolted anchors, prestressing anchors)

As can be seen, the first step in choosing a proper repair process is to identify the type of the damage. Common sources of damage to RC bridge girders, as mentioned above, are: (1) impact damage which can lead to severed prestressing strands and flexural or sometimes shear deficiencies. (2) corrosion which usually leads to shear deficiencies and serviceability issues, and (3) fire damage.

The second step is to find the proper repair material as well as repair configuration, and a suitable anchorage system for the specific project in hand. In this regard, from the repair case studies gathered in the previous sections corresponding to each girder deficiency, the utilized repair approaches including the information on the repair material, configuration, and the anchorage system, if any, are summarized in the following sections for impact damaged girders, corroded girders, and fire damaged girders respectively.

5.1.1. Impact damage

Bridge girders experiencing impact damage are usually subjected to: (1) concrete crushing, (2) prestressed strand and/or steel reinforcement being exposed which makes them more susceptible to further damage and corrosion, and (3) prestressed strand loss. Harries et al., [257] indicated that when 25% of the strands in a girder no longer contribute to its capacity, girder replacement is a more appropriate solution. Otherwise, for the purpose of the repair of the section and restoring its capacity, the severed prestressing strands are usually spliced together, and the shape of the section is restored by concrete or mortar. Cracks, if any, are filled with proper available material such as epoxy. Surface preparation using appropriate methods mentioned in section 4.2 is implemented, ready for the main repair material to be applied. Figure 5-1 shows different repair approaches for impact damage that were reported in the previous sections along with their frequency of usage in percentage.



Repair approach:

1) EB FRP sheets on the soffit + EB FRP U-wraps or complete wraps [29, 33, 35, 48-51, 59, 63, 72, 82, 87, 124, 126, 131, 132, 134, 136, 139, 141, 147, 158, 165, 167-169, 171, 176, 177, 179, 180, 182, 187-190, 198, 201, 204, 210, 212, 213, 215, 226, 232]

2) EB continuous FRP U-wraps [18, 33, 36, 47, 60, 134, 157, 166, 223, 227]

3) EB FRP soffit plates or strips [35, 41, 43, 44, 62, 63, 67, 79, 81, 85, 87, 124, 131, 140, 142, 145, 148, 150, 153, 159, 163, 164, 172-174, 177, 178, 183-186, 191, 194-197, 199, 200, 202, 203, 206, 208-210, 214, 216, 218, 221, 224-226, 228-231, 233-238, 240, 241, 243, 251]

4) EB FRP plates on the girder soffit and sides with or wo EB FRP U-wraps [28, 29, 193]

5) NSM FRP strips or rods + w/wo EB transverse CFRP sheets [17, 56, 57, 70, 84, 142, 144, 146, 151, 154-156, 158, 160-162, 175, 180, 181, 185, 189, 190, 192, 196, 197, 206, 207, 212, 217, 221]

6) Embedded longitudinal and transverse GFRP bars [3]

7) EB hybrid composites (FRCM, CRP, UHPFRC, etc.) on the soffit or wrapped around the girder bulb [18, 20, 27, 58, 60, 61, 64, 143, 149, 157, 185, 242]

8) EB steel plates on the girder soffit [235]

Figure 5-1. Frequency of the techniques in the gathered literature for the repair of the impact damaged girders

As can be seen in Figure 5-1, the most utilized repair method for impact damaged girders is FRP plates or strips externally bonded to the girder soffit. These results for the repair procedure of RC bridge girders damaged by vehicle impact are reflected hereinafter.

It can also be seen that externally bonded (EB) techniques, with or without transverse wraps, have been used more frequently compared to the near surface mounted (NSM) technique. The reason for this, in addition to the relatively easier implementation of the EB methods as well as lower costs, can be their ability to act as additional sacrificial reinforcement, preventing damage due to the future potential impacts. However, upon the availability of the equipment, as well as experts for the design and the implementation of the NSM technique, it could be a more suitable approach compared to the EB methods. This is because the NSM technique, in general, can lead to a higher increase in the girder capacity due to the enhancement in the bond behavior which enables the girder to take advantage of the full capacity of the repair material, making it a suitable method for collapse prevention. Also, the corrosion resistance of the repair material is better compared to the EB techniques due to the placement of the repair material inside of grooves in the cover concrete. Additionally, the NSM technique, usually uses less repair material, which as mentioned before, upon the availability of the required equipment and experts, makes this a more economical approach both for the initial costs and for the long term costs.

The most common anchorage system according to the literature is transverse U-wraps evenly spaced along the entire length of the girder or at parts where it was necessary. The U-wraps enhance the bond behavior of the FRP sheet attached to the tension side of the girder as a means of flexural strengthening. They also help in reducing crack propagation in the concrete section. While continuous CFRP U-wraps are also commonplace for the repair of the impact damaged girders, Graeff [72] showed that the performance of the continuous U-wraps, in the absence of shear deficiencies, is not enhanced over evenly spaced discontinuous U-wraps. In the situations where shear strengthening of the section is also required, continuous FRP U-wraps or discontinuous wraps on required regions of the girders (such as shear spans) with appropriate spacing might be used.

The most commonly used material for the repair of the impact damaged girders seen in the literature is CFRP in the form of sheets and strips. However, as mentioned before, the choice of the repair approach, including the repair material and repair adhesive, highly depends on the specific project requirements and available resources. Figure 5-1 shows that the use of hybrid composites has also been quite frequent for the flexural repair of the girders. This can be beneficial due to the enhanced properties of such materials compared to ordinary FRP, including improved ductility.

The four most common repair approaches shown in Figure 5-1 are further investigated in the literature to find out their frequency of use during five-year increments starting in year 1991 and ending with year 2019. The results are illustrated in Figure 5-2.

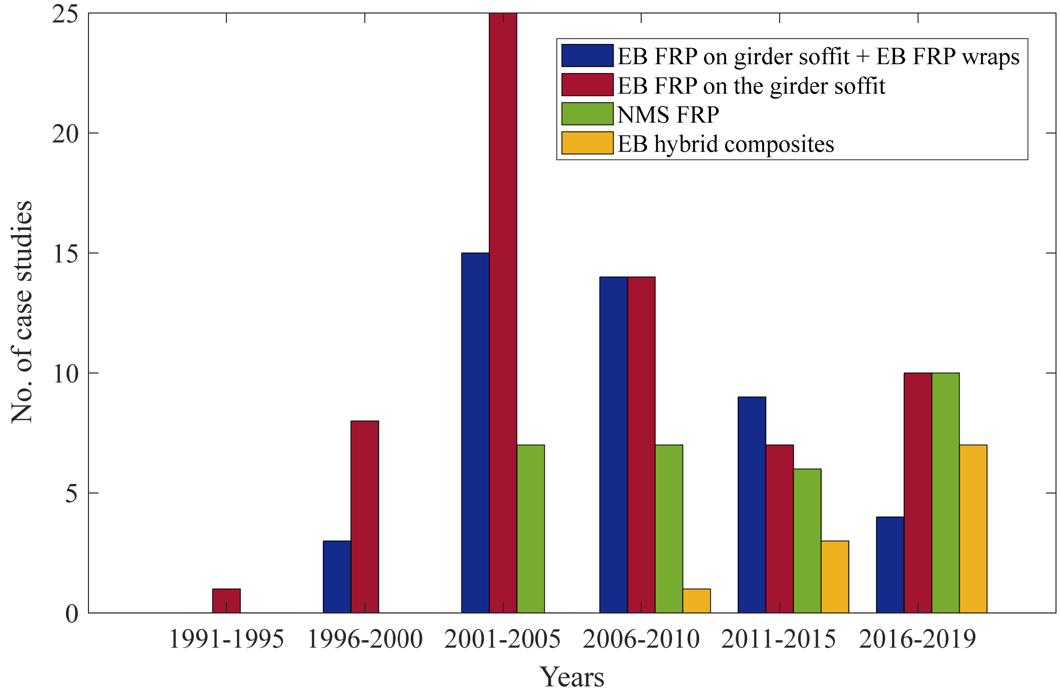


Figure 5-2. Number of case studies of the most common bridge girder repair approaches in flexure in 5-year increments

As can be seen in Figure 5-2, the 2001-2005 year increment was the peak period in the study of flexural repair methods for concrete bridge girders. It can also be seen that the FRP soffit bonding, with or without FRP wraps, is the most well-researched method of repair for flexure with the peak in years 2001-2005. It can also be inferred from Figure 5-2 that the NSM FRP method and the EB hybrid composites are the two emerging methods ever since 2005. It is evident that in spite of the advantages that these two methods might have, their use will most likely involve more uncertainties compared to the well-studied FRP soffit bonding methods.

The recommended repair process based on the most commonly used repair approach in the literature, is shown in Figure 5-3, depending on whether or not shear strengthening is needed for the damaged girder. This will be longitudinal laminates EB to the girder soffit in conjunction with evenly spaced U-wraps as anchorage, where shear strengthening is not needed, or in conjunction with properly spaced U-wraps where shear strengthening is required. If the project conditions allow, NSM mounted rods on the girder soffit might also be used. As for the repair material, although the most popular repair material was found to be CFRP, the choice of the material depends highly to the specific project conditions.

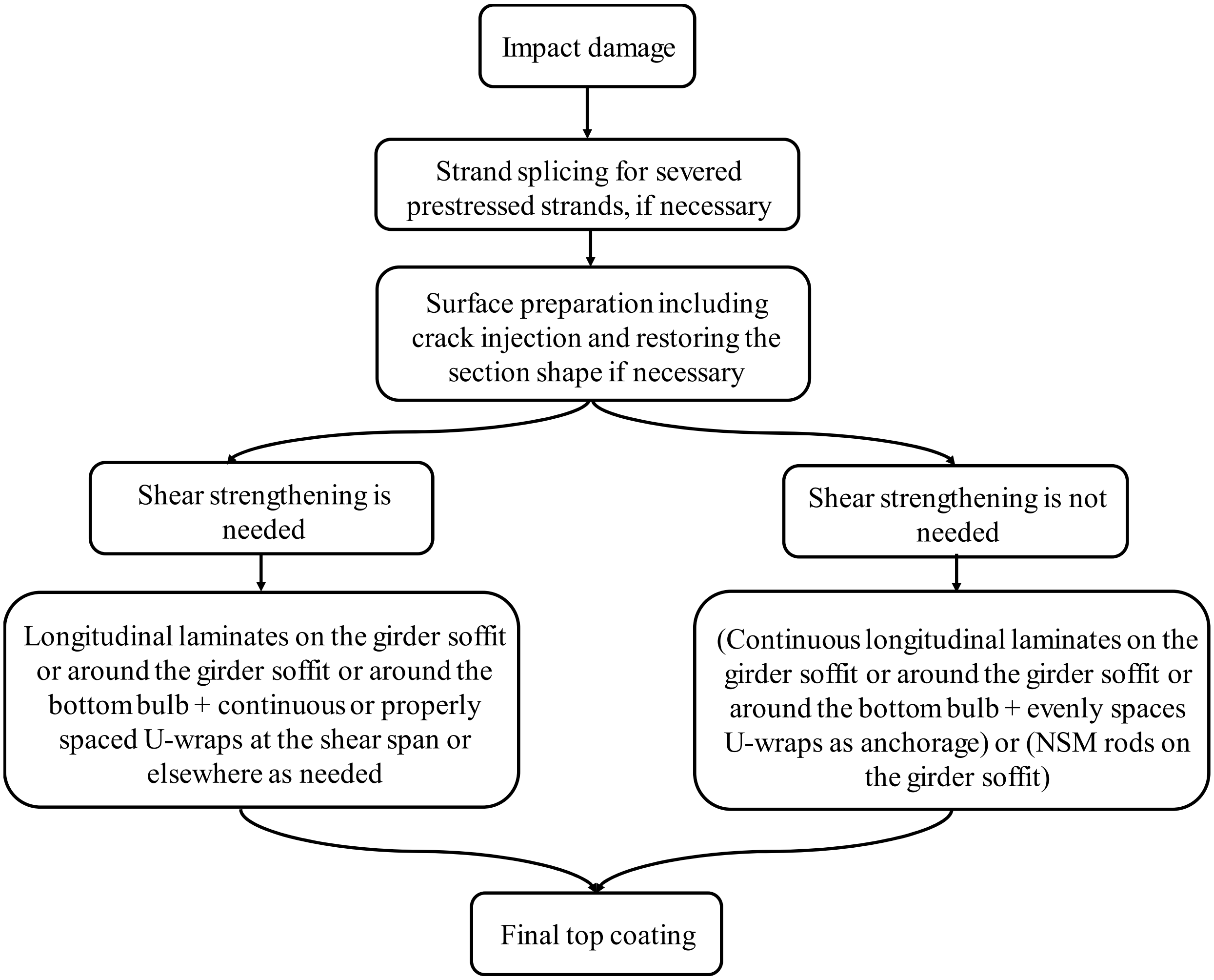


Figure 5-3. Repair procedure for bridge girders with impact damage

5.1.2. Shear cracking

Cracking of the concrete, is mainly caused by corrosion, especially at the girder ends that are subjected to high shear demands, exposed to water contaminated with chlorides and deicing salts used on the bridge which expose them to the girder end regions through deck joint leakage. Corrosion can cause delamination of the cover concrete and exposure of the shear reinforcement, hence the shear deficiency. Another cause of cracking can be the impact load of the over-height vehicles, or over-loading the bridge. Another cause of cracking in the RC girders can be insufficient shear reinforcement.

Cracking of the concrete can lead to debonding of the steel reinforcement and the prestressing strands, hence affecting the shear or flexural capacity of the girder. In this case, the cracks are structurally significant, and use of an appropriate repair approach is necessary. Cracks can also expose the girder to severe environmental conditions such as chloride contaminated waters coming from the deck joints or the brackish water coming from the see waves. As mentioned before, this can cause delamination and spalling of the concrete cover leading to corrosion of the shear reinforcement. Corrosion changes the steel properties and reduces the area of the reinforcement, thus causing shear deficiency of the girder. This situation also requires implementation of an appropriate repair approach. At less intense levels, cracking can affect the serviceability and durability of the girders which might be treated using an appropriate method such as coatings, sealers, overlays, electrochemical methods, corrosion inhibitors, admixtures, patching, reinforcing steel protection, and membranes. Protective coatings, most of which contain an epoxy resin system, as well as penetrating or surface sealers are the most popular repair approaches for such low intensity damage levels. This section deals with repair techniques used for girders with shear deficiency due to cracking and corrosion.

Shear repair of cracked and corroded RC girders usually involves proper treatment of the steel reinforcement, restoring the shape of the section using mortar or concrete which can include corrosion inhibitor, injection of the cracks with proper material such as epoxy, and finally, surface preparation and the application of the main repair material. To look deeper into the last stage of the shear repair procedure (i.e. implementation technique of the main repair material), different repair techniques used in the presented literature in the previous chapters for shear strengthening of cracked and corroded girders are summarized and illustrated in Figure 5-4.

The most utilized repair material seen in the literature, similar to the flexural repair techniques used for impact damaged girders, is the CFRP material.

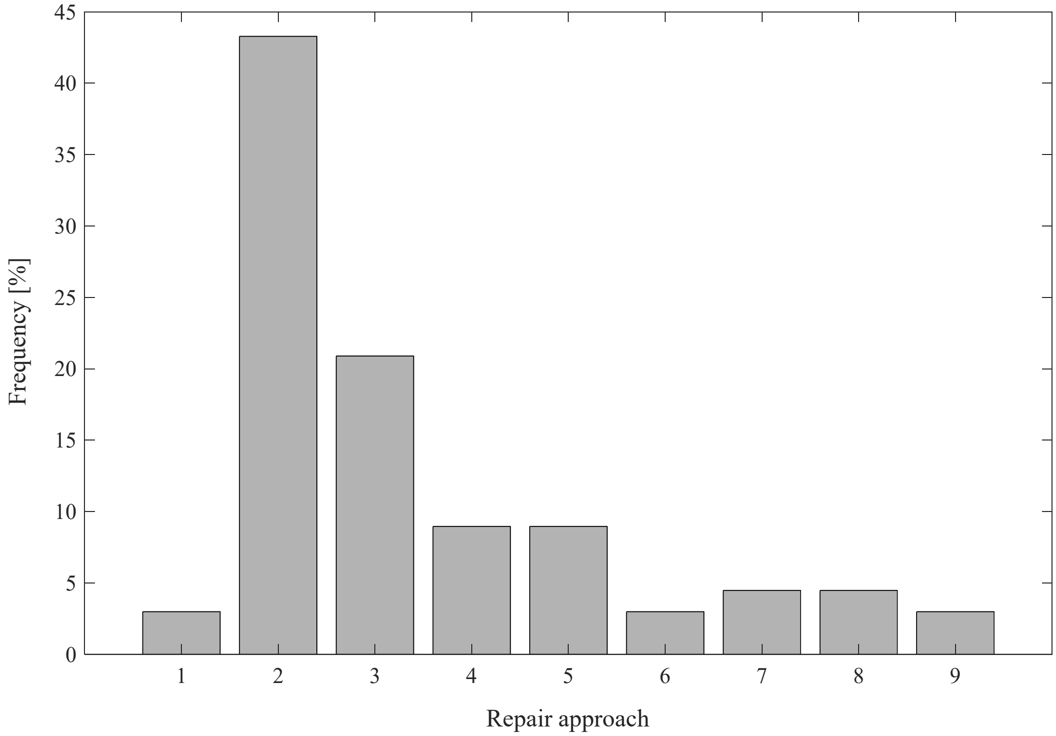
The most utilized repair method, as can be seen in Figure 5-4, is FRP U-wraps. While discontinuous U-wraps (installed vertically or obliquely) are the most common approach, continuous U-wraps have also been used quite extensively. However, Mofidi and Chaallal [100] indicated that there is no need for using additional material for continuous U-wraps or side-bonded sheets since the discontinuous wraps have shown to be more effective in increasing the shear capacity of the girders. However, they result in higher deflections [100]. The use of discontinuous wraps also provides a better condition for future visual inspection of the repair performance.

Width, thickness, spacing, and inclination of the FRP strips are other design parameters that are likely to affect the performance of the repair. In this regard, Mofidi and Chaallal [100] and Qapo et al., [8] indicated that wider strips or higher width-to-spacing ratios contribute more to the shear capacity. Increasing the thickness was also shown to enhance the shear capacity Qapo et al., [8]. Kang and Ary [102] reported an increase in strength and ductility when spacing of the FRP strips was less than half the effective depth of the PC beams, while larger spacings hardly improved the behavior. As for the inclination of the strips, while the inclined repair schemes are expected to be more effective, the labor for their installation is also expected to be more. Eventually, the repair material orientation should be specified based on the specific project requirements and the tradeoff between the labor and the efficiency of the repair.

Complete FRP wraps are also another approach for shear strengthening of girders which show the best bond behavior. However, presence of the bridge deck on the girders makes it impractical to use such repair approach. This is also illustrated in Figure 5-4 which shows that full section FRP wraps have only been used in one application among all the case studies presented in this report. In order to make the implementation of the method possible, holes were drilled into the girder flange to pass through the CFRP strips. FRP U-wraps, as a more convenient method, can have improved bond performance if used with an appropriate and labor friendly anchorage system. The failure mode of FRP U-wraps reported has been reported to be debonding in the majority of the literature. An effective anchorage system allows the externally bonded FRP reinforcements to continue carrying load, even after debonding occurs and thereby increase the shear contribution provided by the FRP sheets. Figure 5-5 shows different types of anchorage systems found in the literature that can be used in conjunction with a shear repair technique: (1) longitudinal FRP strips, (2) FRP-based fan-shaped anchors (can be used alone or in conjunction with the longitudinal FRP strips) (3) Continuous or discontinuous mechanical anchorage (simple or sandwiched) (4) Other anchorage systems involving drilling or cutting out grooves in the section such as in-slab bonding. As can be seen in Figure 5-5, although the longitudinal FRP strips are the most common utilized approach, in general, there is not a significant difference between the frequencies of the methods. Accordingly, it can be inferred that there does not exist a single dominant anchorage system that can be applied to the majority of shear repair projects. Additional horizontal FRP strips are very easy to install and require the least amount of labor among all anchorage systems. However, according to Bae and Belarbi [93] and Belarbi et al., [95], different levels of effectiveness have been observed from them in various studies. The mechanical anchorage systems have shown good performance in some cases. However, according to TexasDOT [256], they can cause damage to the FRP material. This is where the fan-shaped FRP-based anchors can be useful. A short overview of each of these methods is explained in section 4.3 through different example applications. Other anchorage systems involving drilling or cutting out grooves in the section such as in-slab bonding have also been proposed in the literature. However, the authors believe that, in case of spending money and labor work into complex installation on site such as cutting grooves, the NSM techniques can provide a more efficient way of repair compared to an EB method with a complex anchor.

Although the NSM methods require more labor for their implementation: (1) they usually result in less material use. (2) They also have better bond behavior in general, which usually leads to higher capacity increase as a result of full utilization of the FRP material. (3) The quality of the concrete inside the groove is typically superior to the surface concrete, which adds to the efficiency of the repair. Also, surface preparation is minimized. (4) Lastly, they exhibit better resistance to corrosion, hence the improved serviceability. These Four reasons might offset the additional initial cost that the NSM technique has compared to the EB methods. It should be noted that in shear repair applications, the repair procedure is usually implemented on the web of the girder. Therefore, most likely, there will be no need for above head groove cutting or other highly inconvenient practices. Also, the grooving is obtained with a single saw cut without any concrete chipping. Therefore, instead of using complex, labor intensive, and expensive anchorage systems in conjunction with the EB U-wraps that seem to be the common shear strengthening approach at the time, NSM methods can be used for an improved structural performance and higher long term economy.

Eventually, it seems that the EB FRP U-wraps with longitudinal FRP strips as the anchorage system is the most common and well-researched technique for shear repair of RC bridge girders, which can usually increase the shear capacity of the girders at least by 25 percent. In case more increase in the shear capacity is needed, use of fan-shaped FR-based anchors in conjunction with the longitudinal strips seems to be a promising approach that has gained popularity in the last few years. Depending on the conditions of the project in hand, if the human and monetary resources for the implementation of the NSM technique are available and its long term efficiency based on calculations similar to what is suggested in section 5.3 is proven to be superior to the EB method, use of a NSM mounted method is also recommended. These conclusions are reflected in the repair procedure chart shown in Figure 5-6.



Repair approach:

1) Discontinuous complete wrap with FRP strips [87, 126]

2) Discontinuous FRP U-wraps w or wo anchorage, vertical or oblique [8, 10, 12, 16, 32, 34, 39, 48, 55, 71, 92, 93, 95, 98, 100, 102, 104, 107-110, 114, 118, 119, 122, 123, 129, 130, 133]

3) Continuous FRP U-wraps w or wo anchorage [6, 23, 34, 89, 94, 100, 101, 106, 116, 120, 127, 131, 132, 134]

4) FRP side bonding [10, 42, 99, 111, 117, 132]

5) NSM FRP laminates, bars, or strips on the web, vertical or oblique [55, 96, 97, 113, 114, 124]

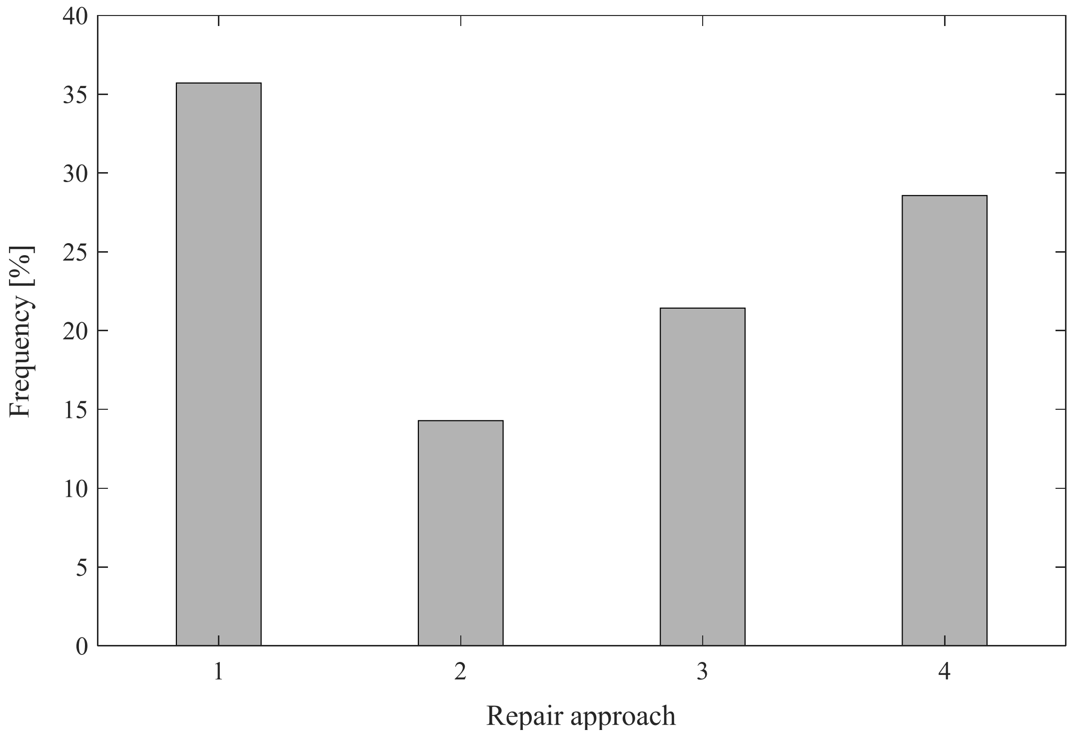
6) EB hybrid composites (FRCM, TRM, etc.), Aluminum, or steel [4, 16]

7) EB or NSM Aluminum alloys or steel plates [7, 23, 128]

8) Embedment methods with FRP based material or steel etc. [80, 101, 105]

9) Shotcreting [26, 103]

Figure 5-4. Frequency of the techniques in the gathered literature for the repair of the cracked girders needing shear repair



1) Longitudinal FRP strips epoxied to the girder surface [55, 71, 93, 95, 109, 110]

2) Fan-shaped FRP based anchors (alone or with longitudinal FRP strips) [16, 256]

3) Continuous or discontinuous mechanical anchorage (simple or sandwiched) [71, 93, 95]

4) Other anchorage systems involving drilling or cutting out grooves in the section [6, 92, 98, 110]

Figure 5-5. Frequency of the usage of different anchorage systems in the literature

Using the discussions provided above, a repair procedure for shear deficient bridge girders is proposed and is illustrated in Figure 5-6 as a repair flowchart.

5.1.3. Fire hazard

Fire hazard for bridges is caused by crashing vehicles, burning of fuels in the vicinity of the bridges, arson, and wildfire. Fire damage is rare, but occurs occasionally when the resulting elevated temperature is high enough to damage the concrete cover. It can lead to up to 70% decrease in the compressive strength with further increase of the temperature. The heat may also result in cracking, delamination, and spalling from the expansion of aggregates and steel reinforcement.

Fire hazard is a relatively recent research topic, but is gaining popularity due to the substantial increase of petrochemical transport along the nation's vast highway network and high number of bridge collapses caused by fire which bring up extreme economic impact.

High temperatures resulting from fire hazard can adversely affect the performance of the epoxy resins. Therefore, in case FRP based repair methods using epoxy resin materials are used in a bridge, ACI 440 recommends ignoring the capacity contribution of FRP. This is the major issue in the utilization of the most common materials (i.e. FRP-based material) in the repair of bridge structures. Solution to this problem is the use of cement-based adhesives instead of epoxy or application of cement based fire proofing to the FRP layers. The later was used by Beneberu and Yazdani [253] in a research study, while the former was used by Yang et al., [33] in form of shotcrete repair of a bridge in Texas after intensive fire damage.

The summary of the discussion in this section is provided in Figure 5-7.

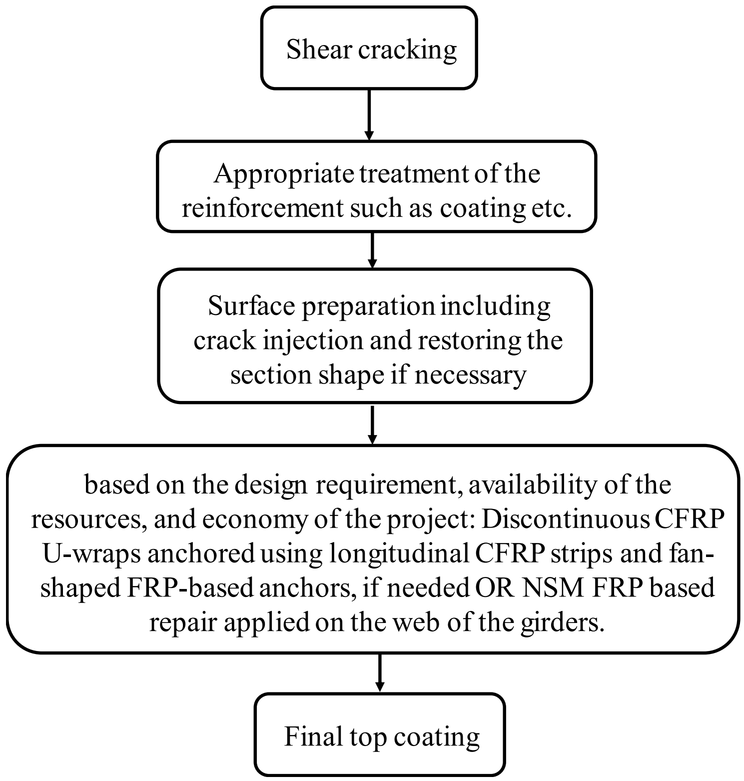


Figure 5-6. Repair procedure for bridge girders with shear cracks

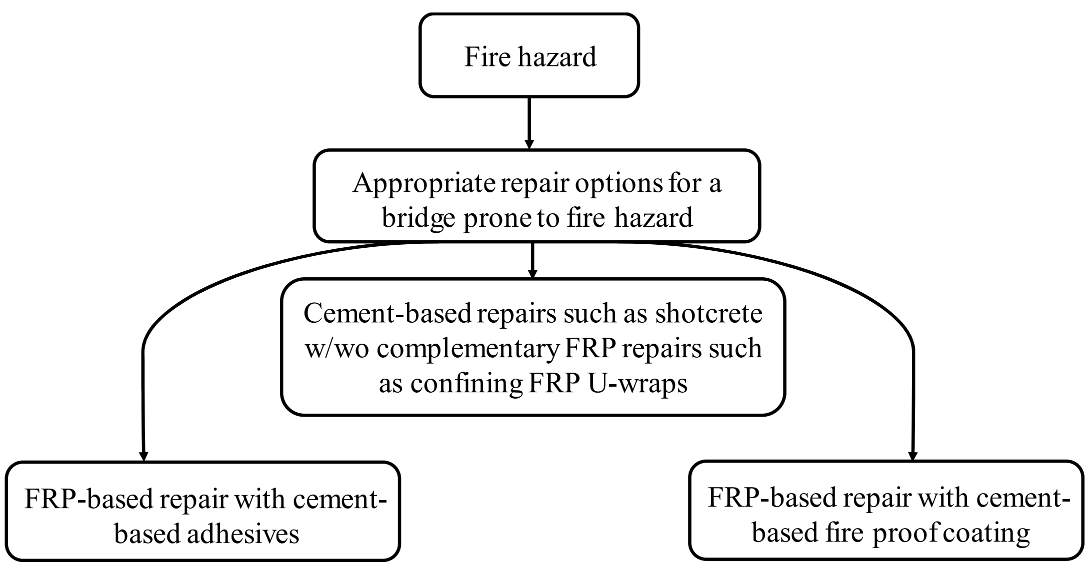


Figure 5-7. Appropriate repair approaches for bridges prone to fire hazard

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