Development of Manual for Enhanced Service Life of ABC Projects

QUARTERLY REPORT

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A. DESCRIPTION OF RESEARCH PROJECT

The main objective in constructing bridges with the accelerated bridge construction (ABC) philosophy is to place the bridge in service rapidly and therefore minimize traffice interruption. At the same time, the design of bridges for service life is gaining more importance as limited resources demand enhancing the service life of existing and new bridges.

The main objective of this project is to develop a manual devoted to enhancing service life ABC projects. The development of the document will consider the ABC projects nationwide. The factors that impact service life will be identified and strategies will be developed to mitigate them. It will include case studies, examples, design, inspection and maintenance information. It will be flexible and accommodating to the addition of new information as it becomes available. Tools will be developed to assist the user to navigate through the information and make the document user friendly. The general framework for the document will be similar to that described in the Guide for Design of Bridges for Service Life (Azizimini et.al.).

A.1. PROBLEM STATEMENT

The nationwide application of ABC in bridge design and construction is at its early stages. Nevertheless, a few ABC projects are decades old, and the number of ABC projects is rapidly increasing. It is essential to observe the performance of ABC projects in service, at the national level, and develop a manual that assists designers and owners in best design, construction and maintenance practices that are capable of enhancing service life of ABC bridges.

Several methods have been employed to construct ABC bridges which include lateral slides, horizontal slides, and construction with precast or prefabricated elements assembled on site.

Some of the most commonly observed problems in ABC bridges have been leaking and cracking (Culmo, 2009). Possible causes of the leakage and cracking have been identified as shrinkage, grout quality, type of details and overlay type.

Fortunately, there are some levels of uniformity in the details used for different ABC project types. This fact is partly because of the communication mechanisms that are in place now, as compared to say 50 years ago. This fact simplifies the task of developing guidelines for service life design of ABC projects.

Additionally, factors that impact service life of conventionally built bridges must also be considered. This will include corrosion and deterioration due to such factors as chloride ion intrusion. These factors may lead to revision of such details as concrete cover and concrete mixes to enhance the service life.

A.2. CONTRIBUTION TO EXPANDING USE OF ABC IN PRACTICE

Current service life challenges with many of the bridges that in the national inventory could have been avoided if designers were provided with clear guidelines for service life design considerations. Development of a document devoted and focused on service life design of ABC projects will be valuable to designers and owners and is anticipated to help enhance service life of ABC projects. As the various factors are identified that reduce or impact service life, strategies to mitigate them will also be developed. These strategies will then result in a variety of design options. The optimum design option can then be selected based on life cycle analysis.

A.3. RESEARCH APPROACH AND METHODS

The main steps in conducting this research are summarized as follows:

1- Studying the ABC project data base and discussing with those knowledgeable about ABC projects,
2- Identify the different and dominant categories of ABC projects in service.
3- For each category, select representative bridges, located in different climates and traffic conditions and inspect them by site visits. Coordinate the inspection activities with the agency responsible for the bridge and acquire their assistance during the inspection.
4- Using the general frame work listed in the Guide for Design of Bridges for Service Life (main product of SHRP2 R19A), develop a manual that is focused on ABC projects
5- Develop examples and tools for making the document user friendly
6- Develop the document so that it can be expanded in the future, as new knowledge, experiences, and systems become available.

A.4. DESCRIPTION OF TASKS TO BE COMPLETED IN RESEARCH PROJECT

Following are description of tasks as described in the proposal and their current status.

Task 1 - Literature review

Through various resources within ABC-UTC, research team is familiar with existing ABC systems and projects. Nevertheless, a formal literature search is underway to identify different ABC project types, typical details, and documented problems and failures.

One common ABC system includes fabricating various elements offsite, transporting them to the site, and assembling the various pre-fabricated units on-site. The pre-fabricated elements can be deck modules, pile caps, abutments, approach slabs and intermediate bents.

Many ABC bridges are built by constructing deck modules off site. As they are assembled and set into place, a closure pour is installed to connect the adjacent modules. This in turn, results in a serviceability concern at the interface of the pour and the joint. Shrinkage and cracking can occur at the joint, as the deck concrete and pour concrete will have differing properties. Early identification of distress or damage at these locations can significantly reduce life cycle costs and maintain safety.

Integral bridge abutments have also been constructed on ABC bridges. Inclusion of integral abutments eliminates bearings and expansion joints, which reduce maintenance costs and improve service life. A literature review has been initiated to identify issues associated with integral abutments that will need additional study. At this time, Integral abutments have been limited to relatively short span bridges with small skew angles. Two potential areas for additional research include:

1. Expanding the knowledge of integral bridge behavior into bridges with longer spans, curved or highly skewed alignments.
2. Looking for design alternatives/methodologies for the soil/structure interface at the integral abutments. This behavior is not well understood, and the soil deformation resulting from the cyclical bridge movements results in either a gap or heaving between the structure and the soil backfill that requires on-going maintenance.

The research team is familiar with the available literature, as much of it has been studied and evaluated for the development of SHRP Reports 19A and 19B. Additional effort will be carried out to further achieve the Task 1 objectives. The following discussion presents partial results of the literature review, including a basic discussion of some of various corrosion factors that impact Service Life Design.

Service Life Design Considerations

The Design Guide for Bridges for Service Life (Ref 1) defines service life as "...the time duration during which the bridge element, component, subsystem, or system provides the desired level of performance or functionality, with any required level of repair and/or maintenance." The current AASHTO LRFD Bridge Design Specifications (2012) are based on a 75 year life span. Target design lives of 100 years or more are desired.

Limitations to the service life of bridges result from either obsolescence or deficiency. Obsolescence factors include capacity, safety, clearance, span layout and increases in live loads. Typically, these factors are evaluated during the planning phases. Factors that are classified as deficiencies include load induced, natural hazards, man-made hazards, production defects and operational defects. Designers can address many of these factors and increase the target service life of the bridge accordingly.

Bridges for Service Life beyond 100 Years: Service Limit State Design (Ref 2) approaches the design process with Service Limit State (SLS) design procedures, as opposed to Ultimate Limit State (ULS) design procedures. By properly identifying the bridge elements and subsystems that can be designed with SLS methods, and properly calibrating the models, increases in the effective service life of bridges can be attained.

Developing Criteria for Performance Based Concrete Specifications

Ref 22, shows the difference between prescriptive specifications and performance based specifications. Performance based specifications are shown to be applicable for durable mix designs. Such specifications can require a coulomb resistance as opposed to a chloride content, thus measuring a performance of the concrete. Additional literature reviews will disclose other instances of performance based specifications and decisions regarding applicability can then be made.

Individual bridge elements will need to be evaluated with regard to service life considerations. The fault tree analyses presented in Ref. 1 provides an effective framework to conduct these evaluations. Ref. 2 provided results of a survey sent out to determine the service life issues. Not surprisingly, the most numerous responses included expansion joints, steel coatings, concrete cracking and corrosion. Note that these concerns are not independent of each other.

Ref. 29, "Bridges for Service Life Beyond 100 Years: Innovative Systems, Subsystems, and Components" presented a more comprehensive survey. In this report, service life issues were grouped into 9 categories:

- Concrete durability;
- Bridge decks;
- Substructure;
- Bearings;
- Expansion joints, joints, and jointless bridges;
- Fatigue and fracture;
- Structural steel corrosion protection;
- Steel bridge systems; and
- Concrete bridge systems.

Corrosion and corrosion induced damage are the largest single factor in reducing the effective service life of bridges. In looking at the groupings above, each item, with the exception of fatigue and fracture directly correlates to corrosion, as either a primary concern, or a related secondary concern.

Corrosion Cost and Preventive Strategies

Ref. 3 states that in 2001, the direct annual cost of deteriorating highway bridges was $ 8.3 Billion, and it would take $ 3.8 Billion to replace the structurally deficient bridges over the next 10 years. This report addressed several other infrastructure items that are impacted by corrosion and corrosion related deterioration, but highway bridges were the largest single item identified. This indicates that in order to increase service life, reduction of corrosion damage will be an effective place to begin.

Research related to corrosion has been extensive. References 4-8 are just a few examples of the available research, and indicate studies into various mitigation measures, including epoxy coated rebar, chloride removal methods, addition of admixtures and inhibitors into the concrete mix, and methods to identify and monitor corrosion and/or corrosion induced damage.

Ref 20 discussed corrosion of pre-tensioned reinforcement in pre-cast concrete elements in New Zealand. This study presented several of the same conclusions seen in other studies. However, it should be noted that the Transit New Zealand Bridge Manual (TNZ 2003) is based on a 100 year design working life in normal circumstances. One of the conclusions is that the orientation of the bridge can impact the amount of corrosion that eventually develops. Reviewing the TNZ Bridge Manual shows 100 year design guidelines that are in current practice.

Ref. 29, with its surveys, indicated that corrosion resisting strategies for concrete decks and elements are most often specified as adding concrete cover or placing epoxy coated rebar. Ref. 19, NCHRP Synthesis 33: Concrete Bridge Deck Performance, discusses several items that can increase concrete durability, including curing practices and its relation to cracking; concrete mix temperatures and cover requirements. This study states, “The most important construction practices to achieve a low-permeability, un-cracked bridge deck with adequate freeze-thaw resistance is to initiate wet curing of the concrete immediately after finishing any portion of the concrete surface and maintaining wet curing for a minimum of 7 days.”

Ref. 23, Durability of Concrete, states “In order to maximize the probability that concrete in a given application will be durable, it is necessary to deal not only with the direct but also with the indirect factors that can influence the ability of concrete to successfully resist a deteriorative environment.” Some of the listed factors that have a direct effect on durability include air content, sound aggregates, non-reactive aggregate, pozzolan, slag, low permeability, high abrasion-resistant coarse aggregate, and sufficient cover. This was reinforced by the study presented in ref. 26.

A number of models to predict service life have been proposed and developed. Bridge Deck Service Life Prediction and Costs, (Ref 14) attempted to develop an effective model to estimate service life of bridge decks with probabilistic methods. While this particular model was not effective, the methods presented in references 15 and 16 claimed to have some success in predicting deterioration rates and choosing cost effective corrosion remedial measures. Results of a methodology presented in ref 16 are shown below, comparing the condition rating of the bridge to the age.

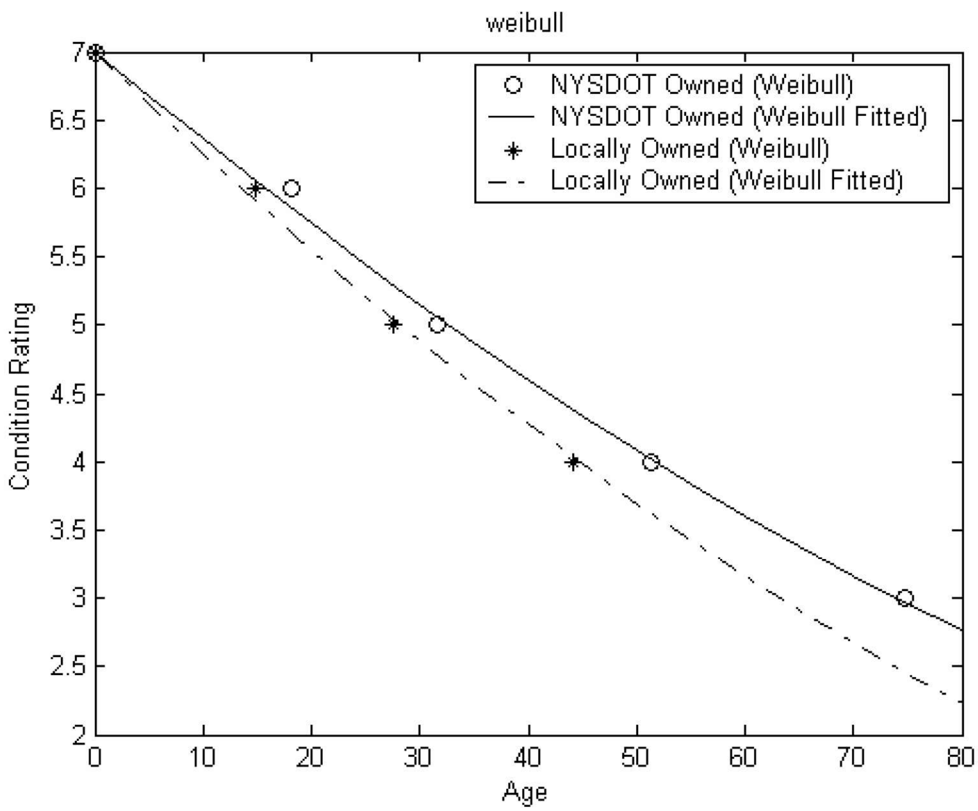

Fig. 1. Taken from Ref. 16, showing the degradation of the condition rating with age.

These are just some examples, as there are many other methodologies proposed in available literature. Ref 21 discusses risk management models applied in Florida. These models include natural hazards as well as advanced deterioration and fatigue.

Joints or connection details are a potential vulnerable area that can allow ingress of water and chloride ions. Ref 17 and Ref 28 present studies on the durability of joints and connections of various elements, and conclude that some configurations are more durable, leak resistant and corrosion resistant than other details. Additional literature reviews will likely identify successful details that can be presented in the guide specifications. Some connection details are completed with high performance concrete, such as in Ref. 18, 24 and 27.

Management and Inspection

The role of bridge management and bridge inspections is another important aspect to increasing or maintaining the effective service life of bridges. Refs 12 and 13 point this out. Early identification and remediation of corrosion or items such as concrete cracking that can lead to corrosion can extend effective service life. Planned maintenance and inspection should be built into the design process of the bridge.

Task 2 - National Survey

A short survey through AASHTO will be conducted to identify the ABC projects that are in service. Coordination made with other ongoing projects and possibly combine them in order to reduce time that different agencies have to spend on answering survey questions. While this survey has not yet been initiated, State DOT's are aware of the data base and many have submitted data to the data base.

Task 3 - Categorizing the available ABC project types

The identified ABC projects that are open to traffic was divided into several categories. The number of categories decided based on results of tasks 1 and 2. This task is ongoing as the research progresses. One potential category includes methods to install an entire bridge with a single operation, such as lateral slides or other transport methods. Another category includes construction of pre-fabricated elements which are then assembled on site. These categories may be sub-divided. Subdivisons will likely include pre-cast deck modules, pre-cast substructure elements and various abutment construction methods. Other categories will likely be identified as research continues.

Task 4 - Site Visits and Documenting Service Life performance of Select ABC projects

Under this task, site visits have been and will be conducted to inspect a select number of bridges within each category identified under task 3. Visual inspection, together with review of available design and maintenance documents, carried out to identify and document the service life performance of bridges. Attempts will be made to identify the possible causes of any observed service life issues.

As noted above under Task 1 Literature Review, closure pours have been identified as having potential service life issues. The literature review has also identified a number of typically specified details.

One of the non-destructive test methods that can provide a better understanding of the behavior and performance of closure pours is Impulse Response (IR) testing. This method is becoming a tool to assist in evaluation of structures, including bridges. IR tests will assist in clarifying the factors that reduce the effectiveness of closure pour, which in turn leads to developing strategies to mitigate these factors. The service life of ABC bridges can be increased with this understanding and by developing details that could provide better service life performances.

IR testing has been used to identify high mobility (low-stiffness) areas associated with damage such as honeycombs, voids and cracks in concrete structures. The method can be used for a quick and detailed evaluation of structural conditions.

A test program was developed to investigate IR signatures on existing ABC bridge structures and laboratory test specimens.

Site visits and a non-destructive testing program have been carried out at two bridge sites to date, and has been reported on previously (Ref 33). Field IR testing has been completed on 2 bridges. A second set of field testing is envisioned, to obtain IR testing on one or more of the MASS 14 bridges. These bridges have a closure pour detail that is about 3 feet wide with similar strength concrete as the adjacent deck sections. As discussed below, this closure pour detail was modeled in one of the laboratory test specimens.

The second phase of the study includes construction of test specimens at the Structures Lab at FIU. Three (3) specimens have been constructed, each 15 feet long. The bridge girders are spaced 6 feet apart, and are WF 30 x 99 steel sections. Nelson studs are welded to the top flange. The girders are set on top of concrete jersey traffic barricades, and rest on elastomeric pads.

Each of the 3 specimens was constructed with a different closure pour detail. These include the 2 details discussed above, and the third will have a closure pour about 3 feet wide. This third detail is modeled after closure pour details implemented in the MASS 14 projects. The test specimens are complete. IR testing of the specimens has commenced.

Fig. 2. Laboratory test specimens under construction, showing the girders and Nelson studs.

Closure pour details for the test specimens include:

- An 8-inch wide, with hairpin shaped reinforcing bars forming overlapping loops in the closure pour. Longitudinal bars will then extend through the loops. The pour will consist of ultra-high performance concrete. (UHPC). This is similar to the detail in Bridge B.

- A 12-inch wide pour reinforced with headed rebar extending into the closure pour. The concrete strength will match the concrete in the adjacent deck section. This is similar to the detail in Bridge A.

- A 3-foot wide closure pour with standard overlapped reinforcing bars. The concrete strength will match the concrete in the adjacent deck section. This is similar to the closure pour detail constructed in the MASS 14 projects in Massachusetts.

Construction of the lab specimens included simulated cracks, de-bonding and missing (or corroded) reinforcing steel. The following features were included in each section.

- a short section with a transverse discontinuity;
- a discontinuity at the joint between the closure pour and the adjacent deck; and,
- a short section where the reinforcing steel is not continued through the joint between the deck and the closure pour.

The locations of these manufactured discontinuities are shown schematically below.

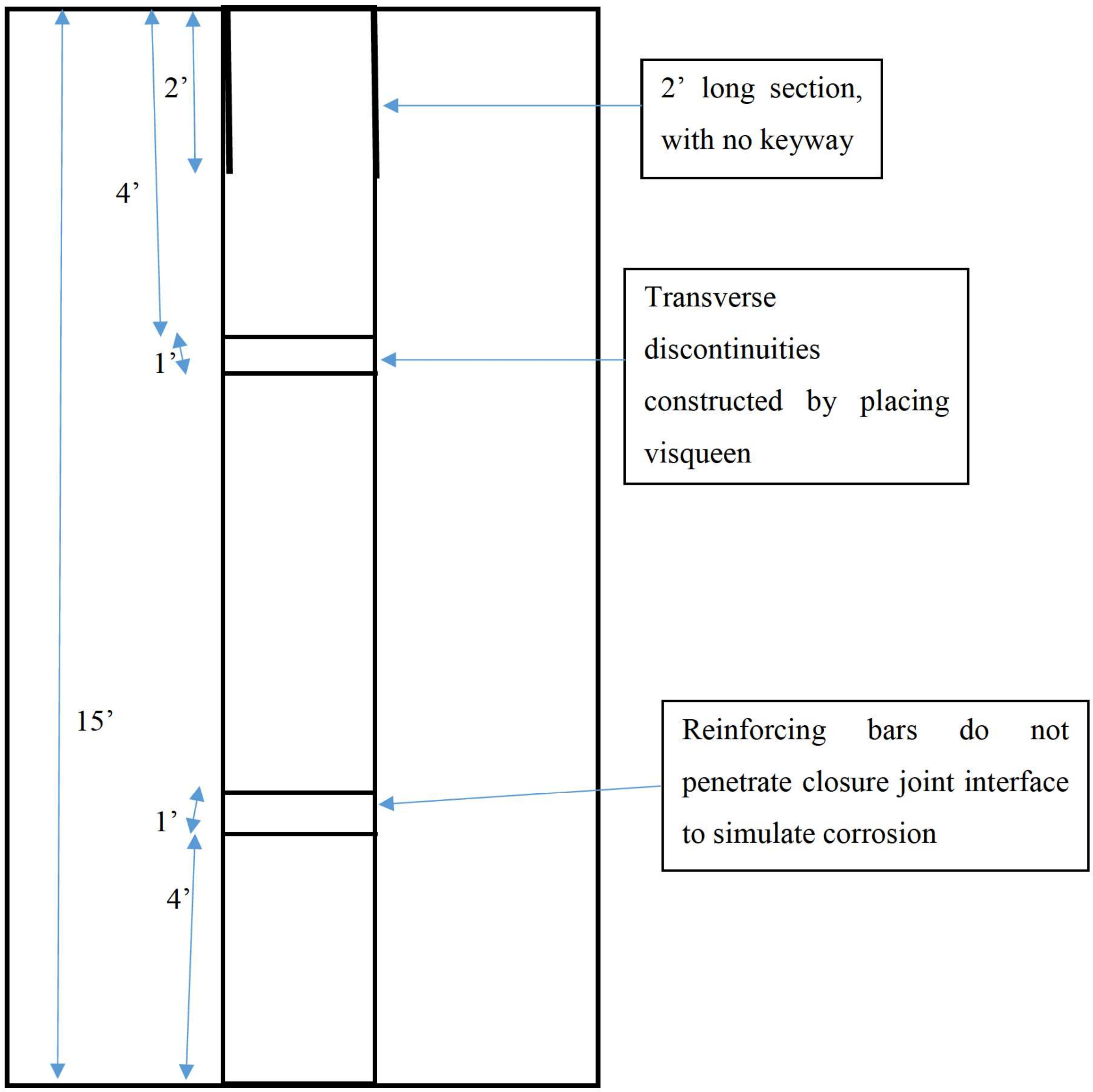

Fig. 3. Schematic of Laboratory Test Specimens

Fig. 4. Showing the Mass 14 closure detail under construction.

Fig. 5. Showing construction of the headed bar closure pour detail, modeled after Bridge A.

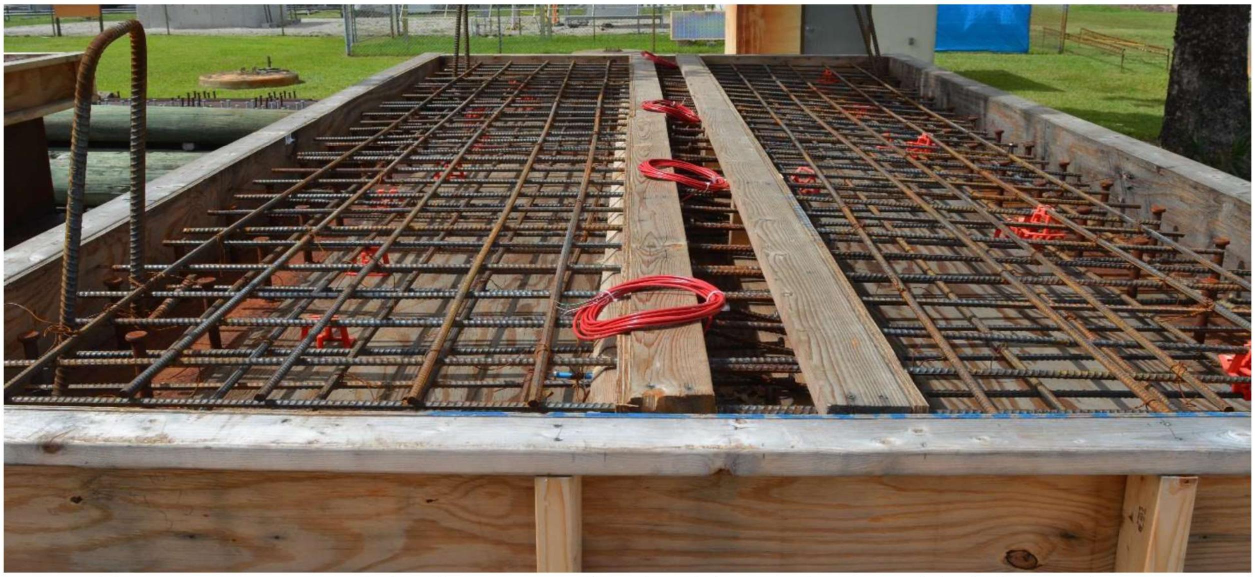

Fig. 6. Showing construction of the closure pour detail with hairpin bars, modeled after Bridge B.

Fig 7. Showing headed bar detail. Note that forms have not been completely removed.

Fig. 8. Mass 14 detail, note bars are not extending through joint.

Fig. 9. Hairpin detail, note lack of keyway on this end.

Fig. 10. Hairpin detail, note the keyway is present on this end.

Impulse Response Testing on Laboratory Specimens

This study was performed as one phase of an overall program to investigate both in-place bridge structures and test specimens constructed in the laboratory. This study presents the initial results from IR testing on laboratory constructed test specimens. As discussed above the three laboratory specimens were constructed with three distinct closure pour details. Specimen 1 follows the Mass 14 details, specimen 2 uses headed reinforcing bars and UHPC, and specimen 3 has hairpin reinforcing steel and UHPC in the closure strip.

Specimen 1

Specimen 1 represents the closure joint detail that was constructed for the ABC bridges built as a part of the Mass 14 project. The test specimen included longitudinal closure joints that are 36 inches wide, and are located between previously cast concrete supported on the wide flange beams. Reinforcing steel consists of straight bars within the closure joint.

The IR test locations were laid out with transverse section lines perpendicular to the center line. The section lines were located about 1.5 feet apart. The initial test points were laid out with one over each beam, one at each side of the closure pour, and 1 at centerline.

The measured mobility values are shown graphically in a 3-D representation on figures 11. Figure 12 shows a 2-dimensional plot of the measured values for the section shown longitudinally. The test values were normalized to the average of the mobility values measured at the steel beam.

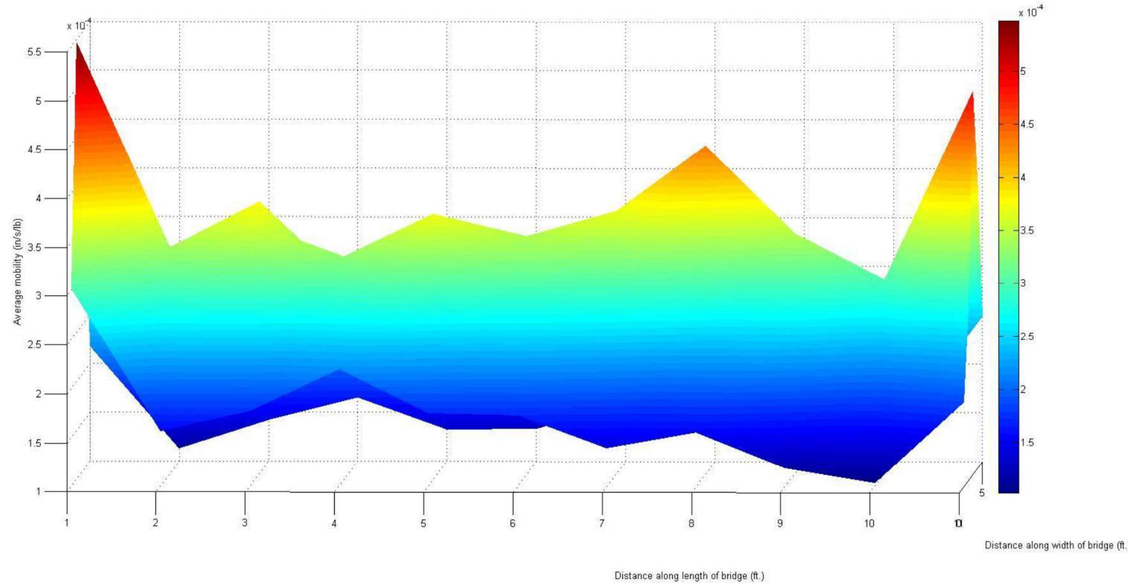

Fig 11. 3-D Mobility Plot, Mass 14 detail.

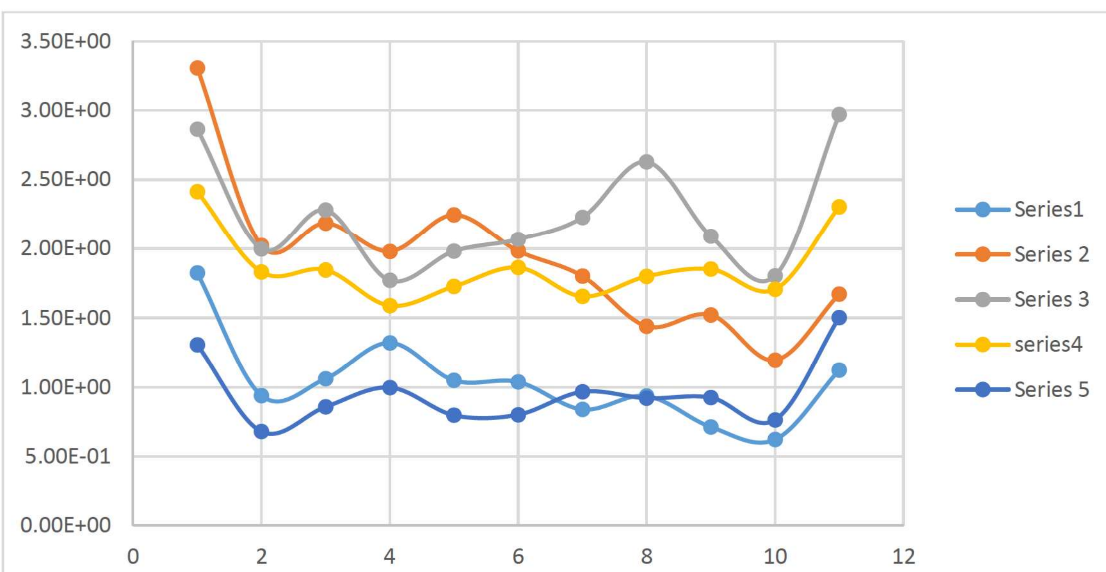

Fig 12. 2-D Normalized Mobility Plot, Mass 14 detail.

Several items can be noted in the initial review of the data obtained in this first round of testing. Note that the 2 lines across the bottom of the plot represent the test values obtained at the steel beam (series 1 and 5). The other 3 lines include the centerline (gray, series 3), and the closure joints (yellow and orange, series 2 and 4).

First, the edge effects are obvious, at each end. This is shown by the rise of the mobility values at each end of the plot at rows 1 and 11. The increase in mobility is easily attributed to the edge, as there is no bridge beyond the end of the testing. The rise in row 8 along the centerline shows the manufactured discontinuity. The high point is located between the 2 manufactured joints, and is expected to be higher, as the concrete is discontinuous across the manufactured joints made by casting the concrete against visqueen.

In the vicinity of row 10, the joint detail was changed from a keyway type joint to a straight sided joint. Based on this initial data, there does not seem to be a significant change in mobility related to the type of joint incorporated into the closure pour. The small rise in the mobility seen in the closure joint at row 5 in series 2 corresponds to the approximate location where the reinforcing steel was not carried through the joint. While a higher mobility was expected, the keyway joint in this location may provide stiffness, moderating the effect of the lack of reinforcement at this location.

Specimen 2

Specimen 2 represents the same detail as Bridge A, previously tested and reported on. Bridge A is a 2 lane, 2 span bridge carrying local traffic over an Interstate Highway. It was constructed in 2006 with ABC techniques. The test specimen included longitudinal closure joints that are 12 inches wide, and are located between previously cast concrete supported on the wide flange beams. Reinforcing steel consists of headed rebar within the closure joint.

The IR test locations were laid out with transverse section lines perpendicular to the center line. The section lines were located about 1.5 feet apart. As with Specimen 1, the initial test points were laid out with one over each beam, one at each side of the closure pour, and 1 at centerline. Additional points were located between the beam and closure joints.

The measured mobility values are shown graphically in a 3-D representation on figures 13, Figure 14 shows a 2-dimensional plot of the measured values for the section shown longitudinally. The test values were normalized to the average of the mobility values measured at the steel beam.

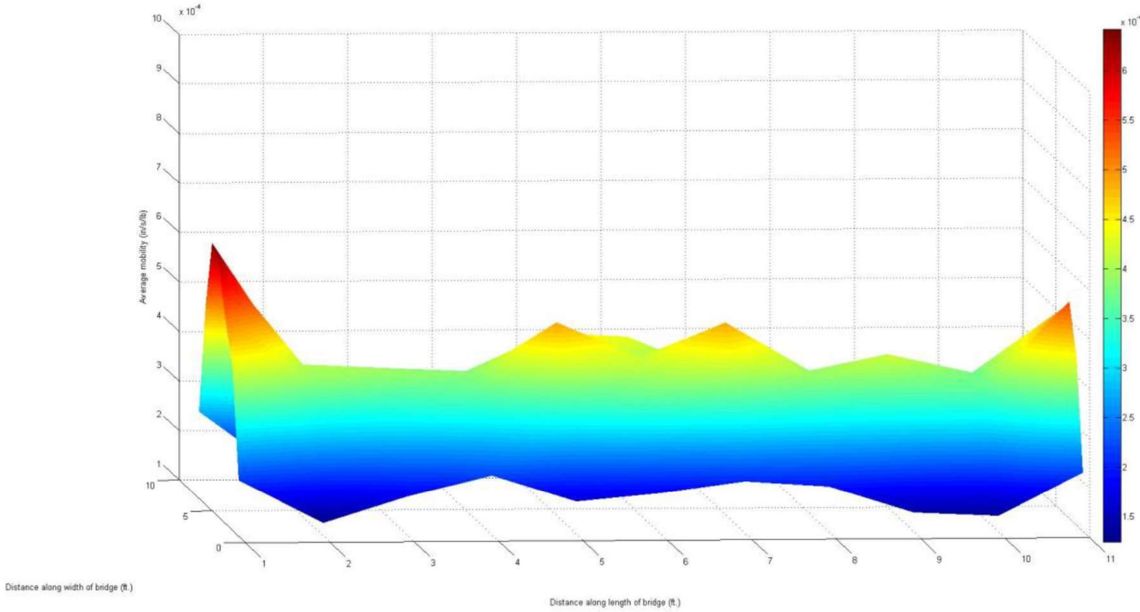

Fig. 13.. 3-D Mobility plot, Specimen 2

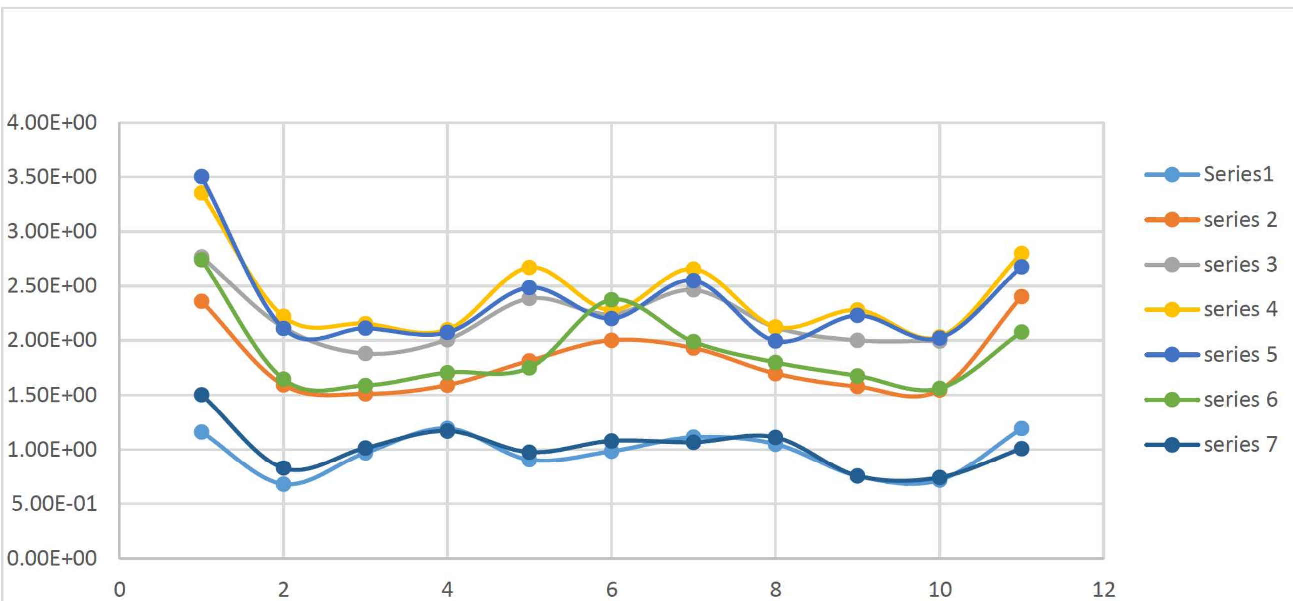

Fig. 14. 2-D Mobility Plot, Specimen 2.

Again, several items are observed in the initial review of the data obtained in this first round of testing. Note that the 2 lines across the bottom of the plot represent the test values obtained at the steel beam (series 1 and 7). The other 3 lines include the centerline (yellow, series 4), and the closure joints (gray and blue, series 3 and 5). The 2 lines (green and orange, series 6 and 2) between the beams and the closure joint lines represent the lines between the beams and the closure pour.

The edge effects are obvious at each end, as expected. This is shown by the rise of the mobility values at each end of the plot again at rows 1 and 11. The increase in mobility is easily attributed to the edge, as there is no bridge beyond the end of the testing. The rise in row 9 for the centerline (series 4) shows the manufactured discontinuity. In this plot, it is not as pronounced as in specimen 1, likely due to the narrower width of the closure pour and shorter extent of the manufactured discontinuity. The high point is located between the 2 manufactured joints, and is expected to be higher, as the concrete is discontinuous across the visqueen joints.

In the vicinity of row 10, the joint detail was changed from a keyway type joint to a straight sided joint. Based on this initial data, there does not seem to be a significant change in mobility related to the type of joint incorporated into the closure pour, as with specimen 1. The variations in mobility at rows 5, 6 and 7for series 3,4 and 5 correspond to the approximate location where the reinforcing steel was not carried through the joint. While a higher mobility was expected, the keyway joint in this location may provide stiffness, moderating the effect of the lack of reinforcement at this location.

Specimen 3

Specimen 3 represents the same detail as Bridge B, previously tested and reported on. Bridge B is a rural 2 lane, 1 span bridge carrying local traffic over a small creek. It was constructed in 2014 with ABC techniques. The test specimen included longitudinal closure joints that are 8 inches wide, and are located between previously cast concrete supported on the wide flange beams. Reinforcing steel consists of hairpin bars with longitudinal bars threaded within the "hairpins", inside the closure joint.

The IR test locations were laid out with transverse section lines perpendicular to the center line. The section lines were located about 1.5 feet apart. As with Specimen 2, the initial test points were laid out with one over each beam, one at each side of the closure pour, and 1 at centerline. Additional points were located between the beam and closure joints.

The measured mobility values are shown graphically in a 3-D representation on figures 15. Figure 16 shows a 2-dimensional plot of the measured values for the section shown longitudinally. The test values were normalized to the average of the mobility values measured at the steel beam.

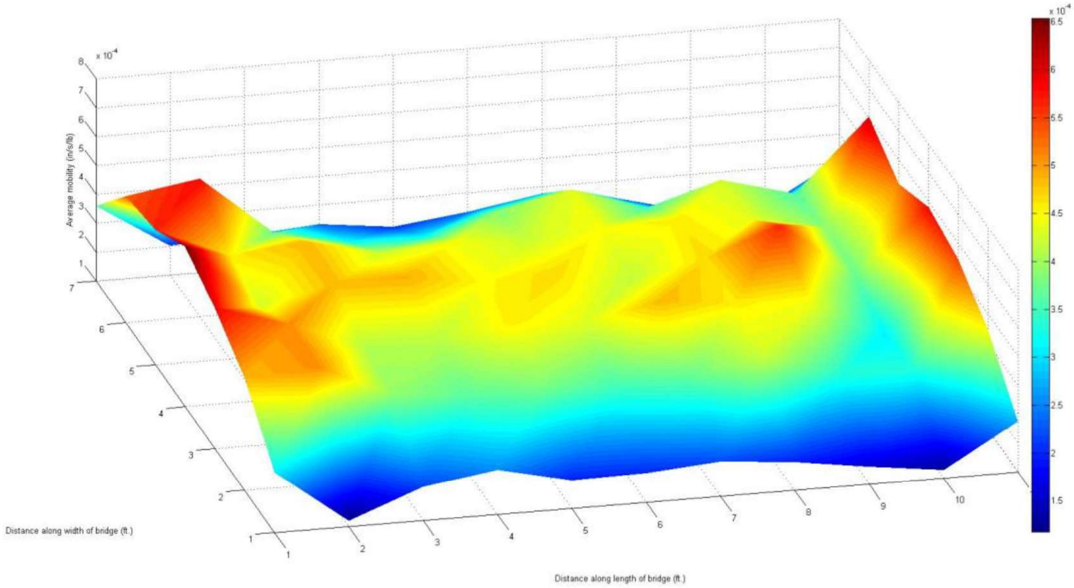

Fig. 15. 3-D Mobility plot, Specimen 3.

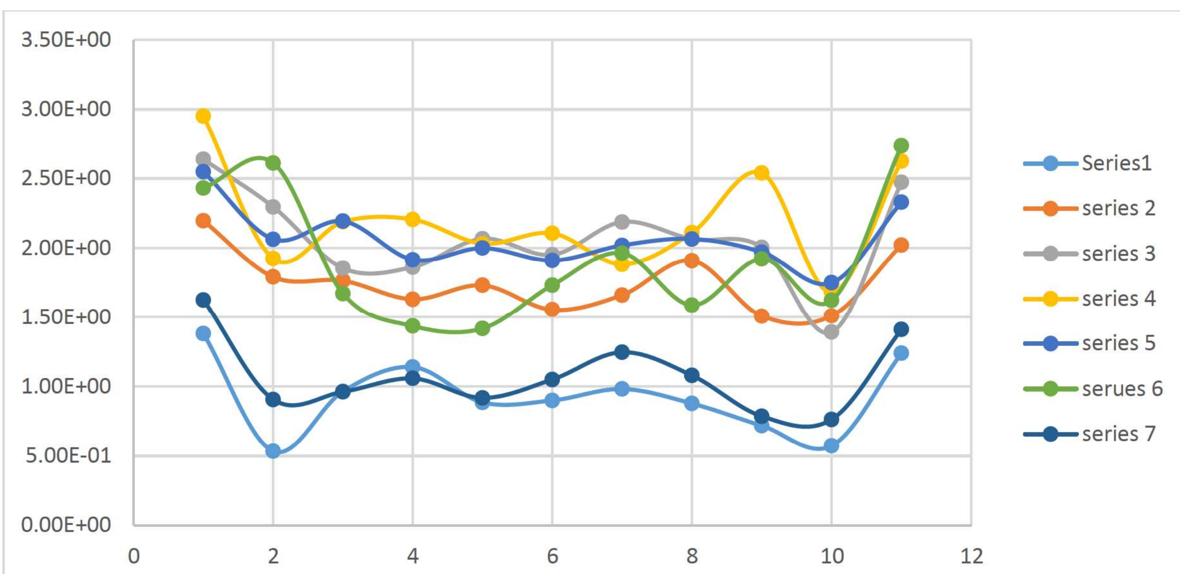

Fig 16. 2-D Mobility Plot, Specimen 3, normalized.

The initial review of the data obtained in this first round of testing shows several similarities to the other 2 specimens. Note the 2 lines across the bottom of the plot represent the test values obtained at the steel beam (series 1 and 7). The other 3 lines include the centerline (yellow, series 4), and the closure joints (gray and blue, series 3 and 5). The 2 lines (green and orange, series 2 and 6) between the beams and the closure joint lines represent the lines between the beams and the closure pour.

The edge effects are obvious at each end, as expected. This is shown by the rise of the mobility values at each end of the plot. The increase in mobility is easily attributed to the edge, as there is no bridge beyond the end of the testing. The rise in row 9 at the centerline (series 4) shows the manufactured discontinuity. In this plot, it is not as pronounced as in specimen 1, likely due to the narrower width of the closure pour and shorter extent of the manufactured discontinuity. The high point is located between the 2 manufactured joints, and is expected to be higher, as the concrete is discontinuous across the visqueen joints.

In the vicinity of row 10, the joint detail was changed from a keyway type joint to a straight sided joint. Based on this initial data, there is a reduction in mobility at about this location. More study is needed to better ascertain the phenomena involved here, as expectations were for the straight sided joint to have a higher mobility than the keyway joint. The scatter in values of mobility seems to be greater than was seen for the other 2 specimens, and may be related to the relatively high concentration of steel in the closure joint combined with the higher strength of the UHPC concrete.

Additional Testing

The test results presented above represent just the first phase of IR testing on the 3 laboratory specimens. Evaluation of these results presented above will need to be supplemented. Additional IR tests with finer test grids can be performed to better fine tune the process and to look at some of the data variations seen in this initial testing. However, it can be seen from just the initial data obtained both from the field and laboratory specimens, that IR testing can be a tool to help in identifying and locating potential areas of concern in bridge decks, as the manufactured discontinuity was observed in all 3 specimens.

As has been shown previously, the field results of the IR testing show promise, as the mobility values reflect expectations. It was expected that mobility values will increase with distance from supporting girders and bents. As testing with the laboratory specimens continues, IR testing may be able to identify issues such as cracking, de-bonding, and loss of reinforcing steel due to corrosion. IR testing is known to be able to assist in defining limits of delamination of concrete slabs.

Developing IR signatures for a variety of closure pours and manufactured discontinuities will also provide insight for IR testing to become a common structural condition evaluation tool. This evaluation will provide insight to the behavior of closure pours.

Evaluation of the IR testing results will be incorporated into the Guide. Services life recommendations resulting from the IR test results will also be included.

Task 5 - Development of framework for service life design

Closure pours are just one of the details identified that can reduce service life. Another design concept that is gaining acceptance is integral abutment bridges. While the elimination of bearings and expansion joints will increase service life and reduce maintenance costs, the integral abutment will introduce other service life impacts. Another phase of development of the manual will study integral abutments and associated service life concerns.

The steps to develop a customized manual for the design of bridges for service life is outlined in the SHRP 2 R19A report. Identification of the factors that can reduce service life for a given bridge system is integral to the manual development. Mitigation of these factors is then developed. These strategies the lead to multiple solutions.

As development of the manual continues, customized fault trees have been developed that take the reader through identification of service life factors. Once the factors have been developed, then mitigation strategies can be developed and applied to multiple design solutions. The optimal solution is then selected through life cycle cost analysis.

The fault tree is a systematic method to identify the factors that can affect service life of a particular bridge element, component, or subsystem. A general, yet comprehensive fault tree is presented in Appendix A. The fault tree methodology begins with identification of major factors that can reduce service life. The process begins with the selection of a major bridge system such as the deck, superstructure or substructure. Each system consists of subsystems, which in turn are made up of the various elements. This is shown below.

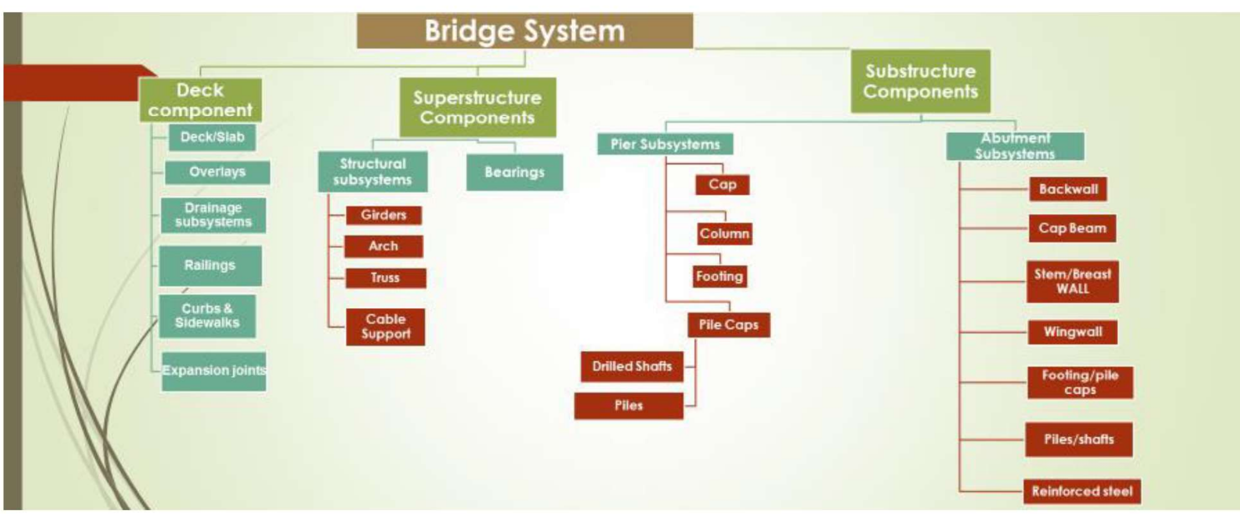

Fig. 17. Bridge System and Components

eductions in service life can be caused by obsolescence or deficiency. Obsolescence factors include capacity, geometry and other types of factors in which current traffic patterns have changed to point that the bridge is no longer functioning as needed. These issues should be addressed in planning stages of the bridge during the design phase, and are beyond the scope of this study. This study will focus on service life issues related to deficiency. These can be subdivided into additional sub categories, including

1) load-induced,

2) Hazards (natural or man-made), and;

3) Defects resulting from production or operation.

These sub categories then need to be applied to each system, again as shown below.

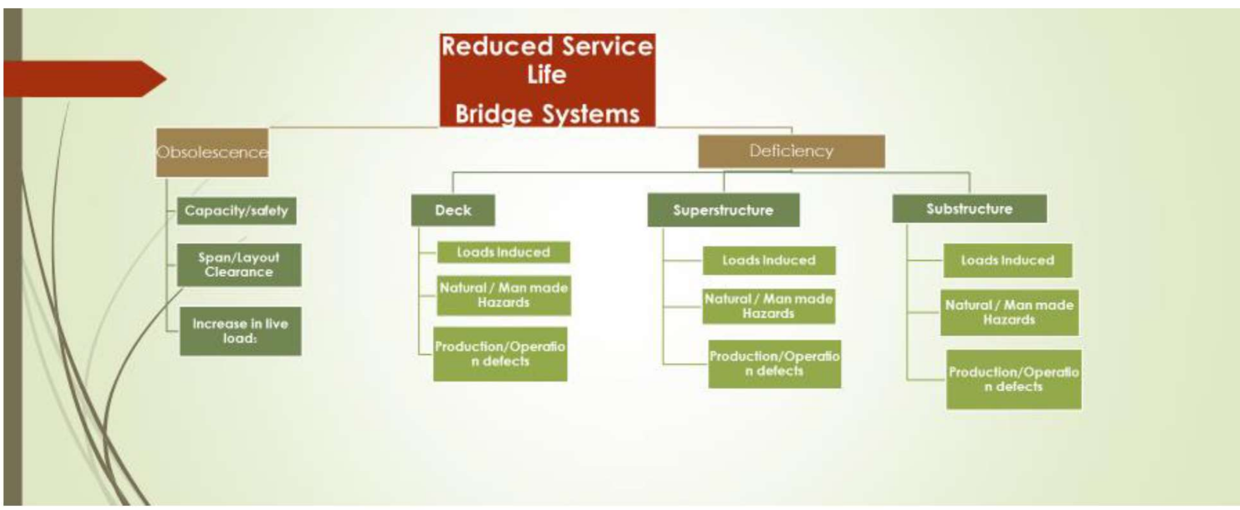

Fig. 18. Initial branches of Fault Tree.

As the user progresses through the fault tree, the tree becomes more and more detailed and specific. This allows the user to then identify which elements should be addressed to enhance the service life of the bridge to meet the operational goals. As the specific items are identified, deficiency tables can be consulted to aid in selecting options that can enhance the service life. Detailed tables are under development, but will be similar to those presented in The Guide.

As an example, the user may progress through the fault tree, and determine that deterioration related to chloride ion diffusion into the deck will shorten the service life to less than desired. Options that may be available can include designing the deck with more concrete cover, designing a less permeable concrete mix, or providing a more aggressive maintenance schedule to address the deterioration as it occurs. Once an item is identified that results in reduced service life, it can be addressed.

Task 6 - Development of Tools to navigate through the document

One of the primary objectives of this study is to have a "user-friendly" system to navigate through the process of designing bridges for service life. As the user progresses through the fault trees to identify the items that impact the service life of the bridge, changes to the design of various elements will likely be made. A basic flow chart has been developed to guide the user through this process. As the fault trees and deficiency tables continue to be developed, the flow chart can also be revised. The flow chart is presented in Appendix B.

Task 7 - Technology Transfer

Technology transfer will be accomplished by sharing the information with State DOTs; placing deliverables on the ABC-UTC web site; announcing the deliverables and their capabilities during ABC-UTC webinars; and presenting the completed and ongoing work in conferences, AASHTO meetings and workshops.

Task 8 - Final report

Results of study are being documented. Compilation of these reports will form the final report.

A.5 EXPECTED RESULTS AND SPECIFIC DELIVERABLES

The following project deliverables are envisioned as described in the tasks above.

- Final Report - Manual for Enhancing ABC Bridge Service Life
- Tools for navigating and using the manual

As the specific factors that reduce service life are identified in the above described research, the issues as well as methods to mitigate these factors will be discussed in the manual. Designers can then devise strategies and systems incorporating these methods to develop various alternative designs. The optimum design alternative can then be selected by analyzing the life cycle cost of the systems.

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