ACCELERATED BRIDGE CONSTRUCTION
UNIVERSITY TRANSPORTATION CENTER

ABC-UTC GUIDE FOR:

REPAIR OF REINFORCED AND PRESTRESSED CONCRETE BRIDGE GIRDERS

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University of Nevada Reno
Name of PI(s):
Dr. Mohamed A. Moustafa

Iowa State University
University of Nevada, Reno
FIU Civil and Environmental Engineering
Washington
The University of Oklahoma

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ABSTRACT

This guide summarizes the work activities undertaken in the study and presents the results of those activities toward development of this ABC-UTC Guide for the repair of RC bridge girders. The information is of interest to highway officials, bridge construction, safety, design, and research engineers, as well as others concerned with the available repair methods for bridge girders.

In this guide, recommendations for the repair of bridge girders with three common deficiencies, namely, shear, flexural, and fire damage are proposed 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.

ACKNOWLEDGMENTS

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1. INTRODUCTION

A majority of the United States' transportation infrastructure is over 50 years old [1]. Among the bridge structures, approximately 30% of more than 607,000 bridges and 23% of 163,000 single span concrete bridges in the country 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 [2, 3]. Main sources of damage to bridge girders are any of the following reasons or combination of them [1, 4-14]:

- Chloride attack, corrosion, and deterioration
- Fatigue damage accumulation
- Accidental damage such as overheight vehicle impact
- Upgraded loading requirements and more stringent assessment codes
- Initial design flaws, construction defects, lack of maintenance

The available options applicable to a bridge with damaged girders are "leave and monitor", "repair", or "replacement" of the girders. Harries, et al. [15] 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.

Table 1. Damage classification

Damage classification [15]				
Minor	Moderate	Severe		
		Severe I	Severe 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

Replacing bridges can cause economical loss and inconvenient vehicle traffic [16], and is usually a more expensive option compared to repair [17]. Repair costs of a prestressed I girder ranges from 35% to 69% of the cost of the superstructure replacement [18]. Additionally, it can cause environmental impacts, interruptions to service, overburdening of nearby infrastructure, and local opposition to construction [8]. 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 [19]. Accordingly, in certain projects retrofitting is the only option because of budgetary restrictions that bridge owners are facing [20]. However, assessment and strengthening of deficient bridges in the United States has been estimated as being in excess of $140 billion [8], which is still a huge amount of money. These factors make 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 [6]. 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 [1], and in order to eliminate the bridge deficient backlog by 2028 in the US, $20.5 billion would need to be invested annually.

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 techniques, there is a lack of readily available laboratory results. [25, 86]. The main objective of this study was to gather the information about different materials and methods of bridge girder repair implementation that have been used so far in practice or 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 [21].

In this guide, the final deliverables of the study, recommendations for the repair procedure for a specific girder deficiency (shear or flexural deficiencies) proposed by the authors are presented. This is meant to enable researchers, engineers, and decision makers to compare the available repair methods more conveniently to find the most efficient and accelerated repair approach for their specific projects based on the economic, environmental requirements as well as structural and construction conditions.

2. RECOMMENDATIONS FOR BRIDGE GIRDER REPAIR

The general repair procedure, disregarding the type of the damage to the girder includes: (1) inspection and monitoring; (2) choosing a repair material; (3) choosing a repair method; (4) surface preparation; (5) application of the repair material; (6) prestressing of the repair material (optional); (7) anchorage system; and (8) strand splicing (if needed).

In the following sections, based on a comprehensive literature review, each step of the repair procedure is briefly explained, followed by recommendations for the repair of two common bridge girder deficiencies, namely shear and flexural damage.

2.1. INSPECTION AND MONITORING

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 [4, 22].

2.2. CHOOSING A REPAIR METHOD

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 [23]. Common materials used for the repair of RC bridge girders are fiber reinforced composite and steel, in addition to other materials such as ultra-high performance fiber reinforced concrete (UHPFRC), Aluminum alloy, Ferrocement, and shotcrete. Details about each of these materials can be found on the full final report, uploaded to the ABC-UTC website.

2.3. CHOOSING A REPAIR MATERIAL

After the repair material is chosen, the next decision is to choose a proper way for the application of the material to the damaged girder. There are several factors affecting this decision, including: (1) whether the repair technique is commercially available (2) girder type (box girder or I-girder): 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 (3) dominant repair limit state (4) severity of the damage that it can repair (5) fatigue performance (6) whether strengthening is needed beyond undamaged capacity (7) whether the method can be combined with strand splicing (8) speed of mobilization (9) constructability (10) whether specialized labor is required (11) whether proprietary tools are required (12) whether lift equipment is required (13) how much is the closure below the bridge (14) time for typical repair (15) environmental impact of repair process (16) durability (17) The resulting change in the size of the element that is being repaired 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 (18) cost (19) aesthetics [23-25].

Methods for the application of the repair material to the damaged girder include: Externally Bonded (EB) techniques, Near Surface Mounted (NSM) techniques, and Embedded reinforcement. Details about each of these methods can be found on the full final report, uploaded to the ABC-UTC website.

2.4. SURFACE PREPARATION

Surface preparation, i.e. cleaning and roughening the surfaces of composites is a critical step in the repair process which can improve bond strength. 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 due the delamination of the concrete substrate [19, 26-30].

The required steps for surface preparation are as follows:

(1) 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 [24].

(2) Select a patching method (if needed): In case there are cracks on the girder, they should be filled with proper materials i.e. patching. 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, (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 [24, 31]. Figure 1 shows an example of a concrete girder surface after epoxy injection.

Figure 1. View of the crack filled with low viscosity epoxy [32]

(3) Surface polishing (roughening): As part of the surface preparation, the surface of the concrete is usually polished until fine aggregates are exposed [33]. This improves the bond between the main strengthening material and the concrete surface. Abrasive blasting or sand blasting is one way of surface roughening [34]. Diamond grinding is another technique utilized for this purpose [35]. It can also be done using high pressure waterjetting [36] or using a grinder. the roughening can be implemented to the aggregate level [17].

(4) 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 [33]. It is usually done using compressed air or water [37]. It can also be done using a wire brush. It is also important to make sure that the surface is dry and free from any oil, or greasy substances [38]. Sandblasting can also be used to clean the repair area [34]. Compressed air is also widely used for cleaning the concrete surface from dust and debris [28].

(5) 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. Dong, et al. [33] 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.

2.5. APPLICATION OF THE REPAIR MATERIAL

The next step after surface preparation is the application of the repair material. Depending on the repair approach being used (externally bonded (EB) technique, near surface mounted (NSM) method, or as embedded reinforcement), the repair material should be applied in different ways and configurations. The process for the application of the repair material for each method is briefly described in this section, while the repair configuration which mostly depends on type of the girder deficiency is described in section 2.9, section 2.10, and section 2.11 for shear, flexural, and fire damage deficiencies, respectively.

EB technique: 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 (see Figure 2), 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 to be cured. 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 [1, 19, 24, 39]. 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 [19]. 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 [1, 19, 24, 29, 39].

Figure 2. wet-layup approach for the application of CFRP sheets [17]

NSM technique: 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) [39]. The procedure for an example application of the NSM repair is shown in Figure 3.

Figure 3. FRP NSM repair process [39]

2.6. PRESTRESSING OF THE REPAIR MATERIAL (OPTIONAL)

To increase the efficiency of the repair, the material for both EB and NSM methods can be prestressed. Pre-stressing was first utilized for strengthening bridges in 1950s [40]. 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 [41]. 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 [42]. Some of the advantages of prestressing the repair material are: Fully utilizing the high strength of the material, improving the serviceability of RC beams, limiting the propagation of old cracks, delaying the formation of new cracks, enhancing the stiffness of the 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 [43, 44]. However, it should be noted that generally, different levels of prestressed forces will result in different failure modes. Also, 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 [19]. Figure 4 shows the prestressing setup and procedure for the implementation of the NSM technique for an RC girder.

Figure 4. Implementation procedure for the prestressd NSM technique: (a) form the groove, (b) place the anchorage device, (c) apply pre-stress, (d) inject the filler [16].

2.7. 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 strengthening plan that otherwise would not meet design code provisions, allowing the repair material to continue carrying load even after debonding occurs and thereby increasing its contribution. It can enable greater strengthening or the use of a wider range of possible configurations and material properties. Different anchorage systems has been introduced so far depending on the strengthening approach that they are used with. Some examples include: additional horizontal strips of the repair material, embedment of the repair material into the beam flange through precut grooves with adhesive bonding, various mechanical anchorage systems involving bolts and plates, and fan-shaped textile-based anchors [30, 39, 42, 45]. Figure 5 shows a schematic of the first three systems, while Figure 7 shows a real-life application of the horizontal strips which is the most common approach. Figure 6 provides an illustration of a typical fan-shaped textile-based anchor, while Figure 8 shows a real-life application of the anchors to the web-bottom flange interface of an RC girder. These anchors 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 [7].

A drawback of the use of many anchorage systems is the added cost and complexity of installation [30].

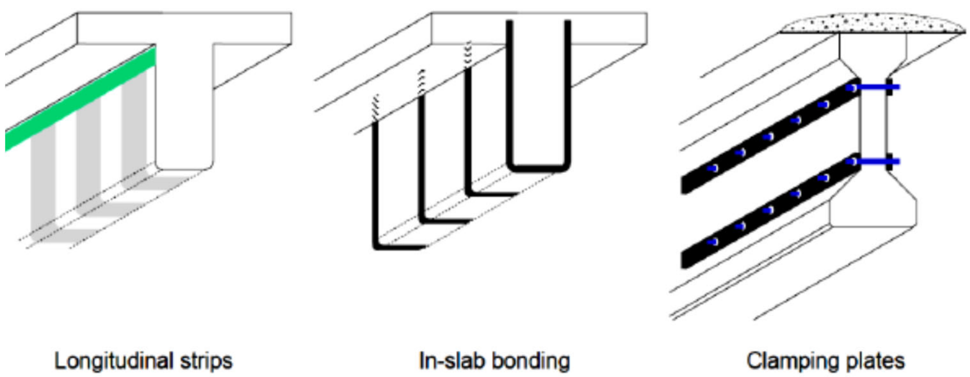

Figure 5. Schematic of the common anchorage methods

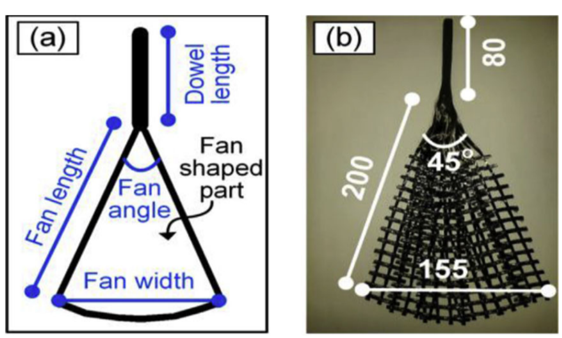

Figure 6. Fan-shaped textile-based anchors [7]

Figure 7. End anchorage system using CFRP or GFRP strips [39].

Figure 8. Plugs of CFRP anchors inserted into holes inside the concrete surface [46]

2.8. STRAND SPLICING (IF NEEDED)

When one or more prestressing strands in a prestressed girder are damaged, strand splicing can be used to do the repair. It is a fast, efficient, and cheap repair method for reconnecting damage or broken prestressing strands in order to restore the prestressing force. 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 ($0.85 fpu$), i.e. the advertised minimum strength of a strand splice. In order to increase their efficiency, the splices should be staggered (see Figure 9) and limited to splicing 15% of strands in a girder, regardless of staggering [47, 48]. It should be mentioned that commercially available splices are available for strand diameters only up to 0.5 in [19, 24, 47]. 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 [24]. However, they can be combined with an externally bonded repair method using a repair material such as FRP or FRCM [49].

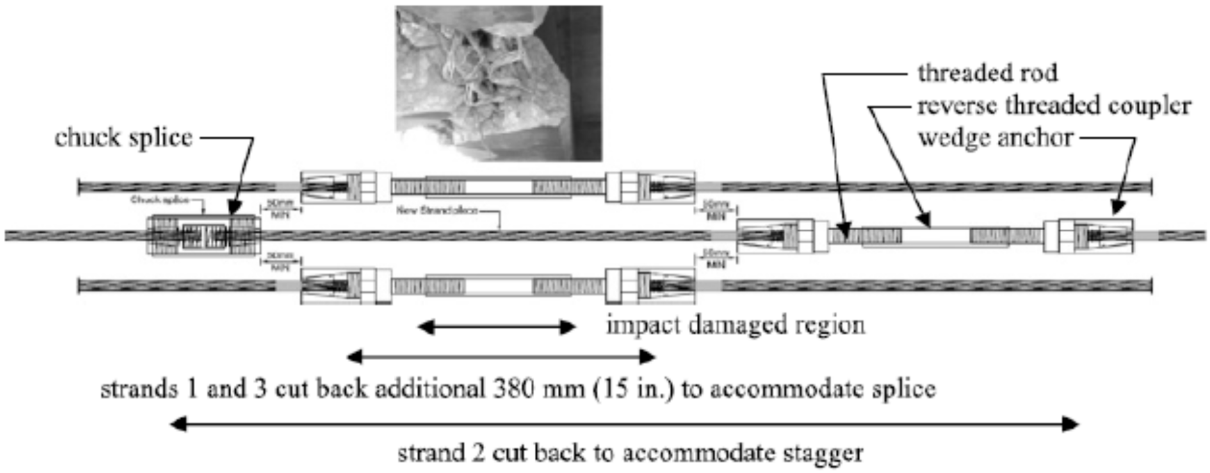

Figure 9. Staggering of the strand splices [47]

Figure 10 illustrates the procedure for strand splice repair of a RC girder.

Figure 10. 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 [19]

2.9. REPAIR FOR SHEAR

This section provides recommendations for the repair of girders with shear deficiency, which is provided based on the repair case studies found in 62 publications.

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. Higher levels of damage (i.e. structural deficiencies) require implementation of an appropriate repair approach.

Shear repair of structurally deficient 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.

For the application of the main repair material, according to the literature review study implemented in the final report of this project (available on the ABC-UTC website), the most utilized method 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 [50] 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. They usually result in higher deflections though [50]. 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 [50] and Qapo, et al. [10] 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. [10]. Kang and Ary [51] 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.

As for the anchorage system that might be used in conjunction with the main shear repair method, 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 [45] and Belarbi, et al. [25], 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 [46], they can cause damage to the FRP material. This is where the fan-shaped FRP-based anchors can be useful. 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 anchorage system. 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.

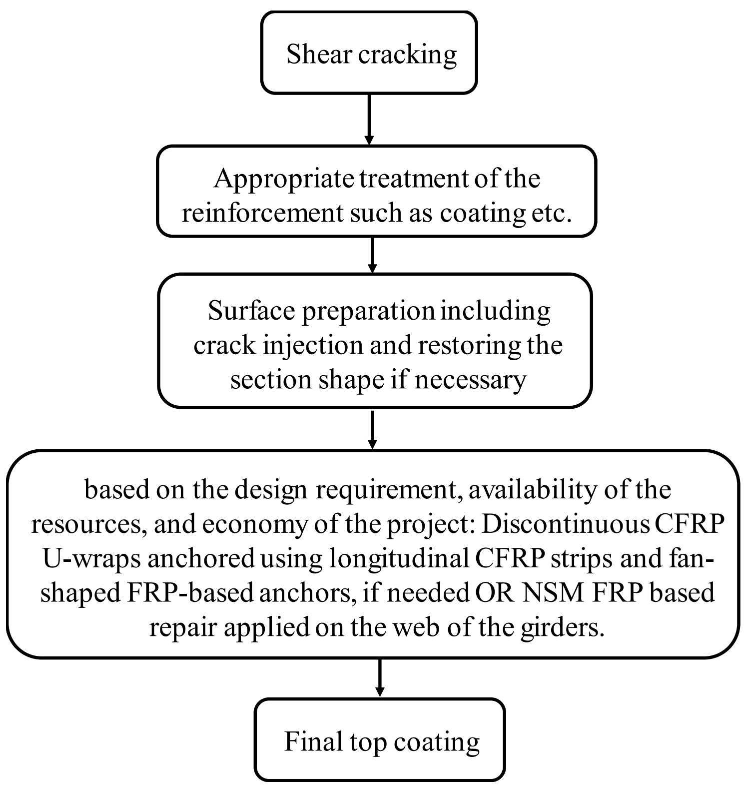

Figure 11. Repair procedure for bridge girders with shear cracks

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 is proven to be superior to the EB method (if long-term efficiency is a requirement of the project), use of a NSM method is also recommended. These conclusions are reflected in the recommended repair procedure chart shown in Figure 11.

2.10. REPAIR FOR FLEXURE

This section provides recommendations for the repair of girders with flexural deficiency, based on the repair case studies found in 151 publications.

According to the literature review study implemented in the final report of this project (available on the ABC-UTC website), the most utilized repair method for flexural deficiency of the girders is FRP plates or strips externally bonded to the girder soffit. These results are reflected in the repair flowchart recommended in Figure 12. It is also concluded in the final report 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 [22] 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. 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 recommended repair process based on the most commonly used repair approach in the literature, is shown in Figure 12, 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.

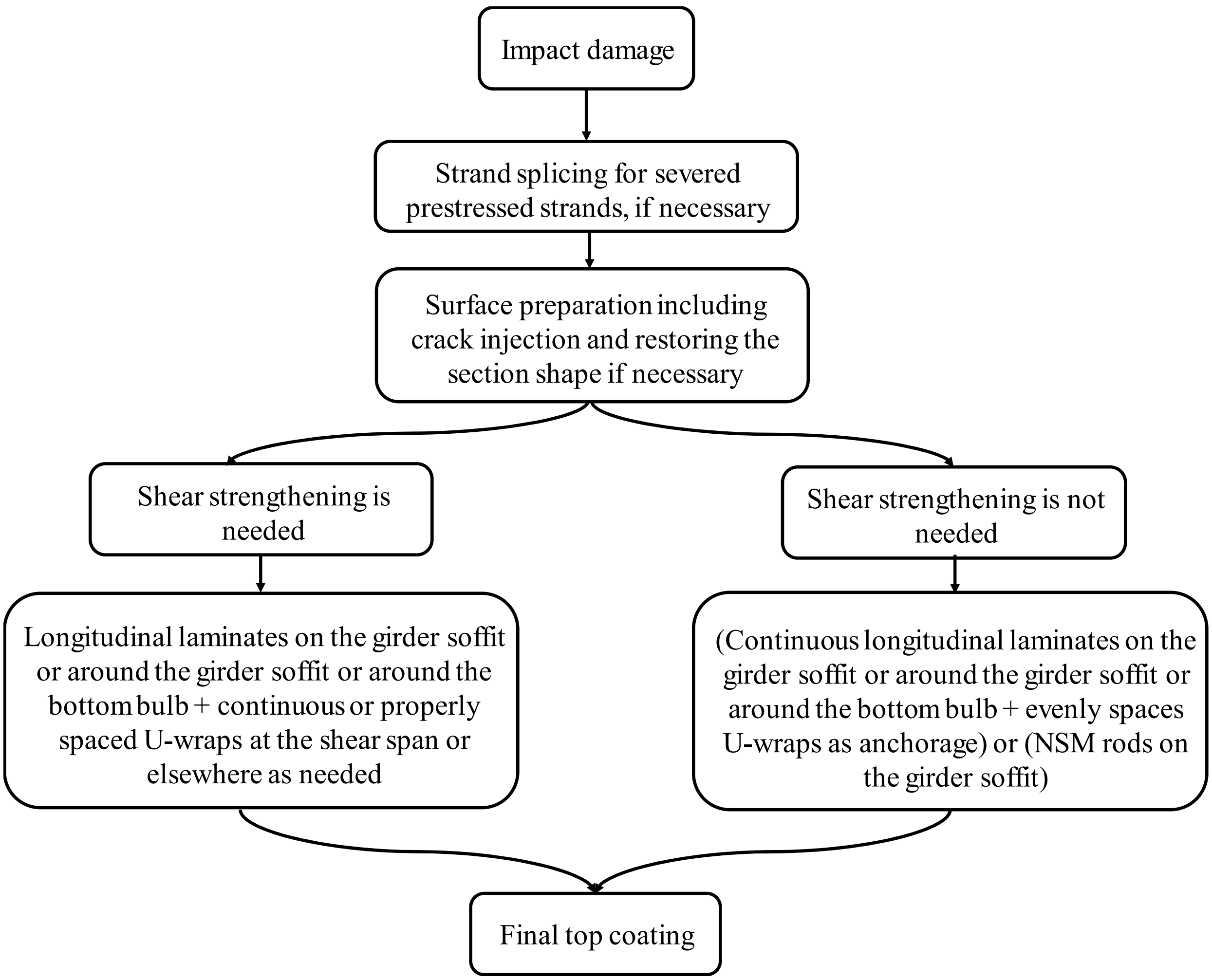

Figure 12. Repair procedure for bridge girders with impact damage

2.11. REPAIR FOR FIRE DAMAGE

Fire hazard for bridges is caused by crashing vehicles, burning of fuels in the vicinity of the bridges, arson, and wildfire. [52]. 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.

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 [29, 52, 53].

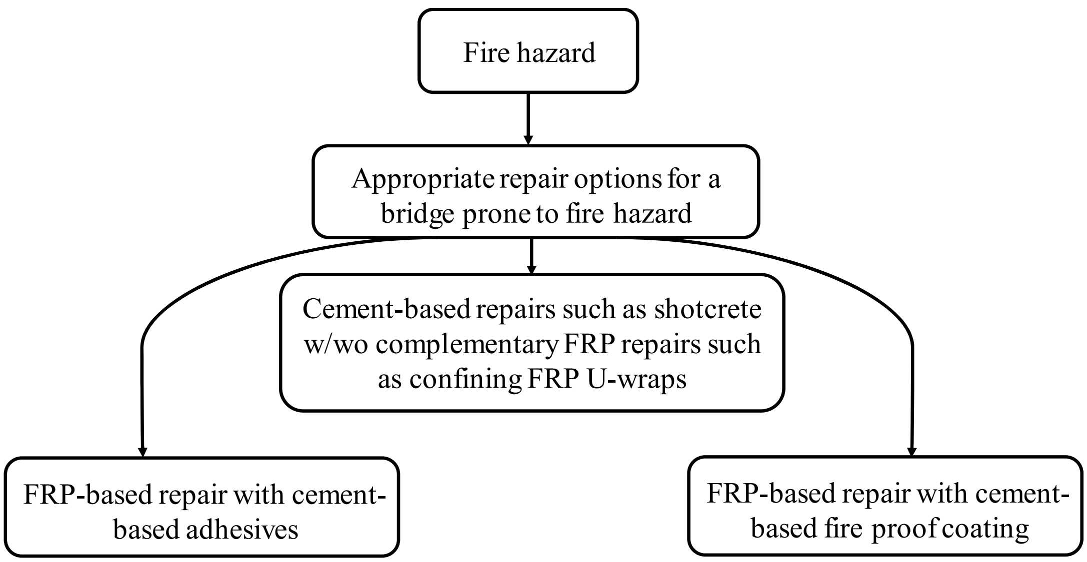

Figure 13. Appropriate repair approaches for bridges prone to fire hazard

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 [53] in a research study, while the former was used by Yang, et al. [34] in form of shotcrete repair of a bridge in Texas after intensive fire damage.

Based on the repair approaches for fire-critical bridge girders found in the literature, a repair flowchart with three possible repair scenarios is provided in Figure 13.

3. CONCLUSIONS

Bridge girder repair is an important topic due to the aging of the bridge structures in the US as well as higher cost of the girder replacement along with other disadvantages such as being time consuming and causing inconvenience. The objective of this study was to provide a comprehensive reference for researchers, engineers, and decision makers to compare different repair approaches together, and find the best method that suites their specific repair problem. The main girder deficiencies in bridge structures are shear deficiencies due to corrosion and exposure of the shear reinforcement, and flexural deficiencies due to vehicle impact damage.

Choice of a repair approach highly depends on the specific conditions of the project. However, the following methods were found to be the most common means of repair in the previous literature:

Shear repair: CFRP U-wrap (continuous or discontinuous, vertical or oblique) and NSM CFRP laminates on the web (no need for anchorage, no above head installation)

Flexural repair: EB CFRP sheets on the soffit + EB discontinuous CFRP U-wraps

Fire repair: use of cement-based adhesives instead of epoxy and/or fire proofing of the FRP layers

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