REPAIR OF IMPACT-DAMAGED PRESTRESSED CONCRETE BRIDGE GIRDERS WITH CARBON FIBER REINFORCED POLYMERS

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ABSTRACT

With the continued deterioration of infrastructure and the increase in structurally deficient structures, the need for viable structural repair strategies is apparent. In this paper, repair methods are presented for three prototype prestressed concrete bridge girder types (adjacent boxes, spread boxes and AASHTO-type I-girders) having four different levels of damage. Twenty prototype repair designs are presented using 5 variants of CFRP-based repair systems. It is the authors' contention that each structural repair scenario should be assessed independently to determine which repair approach is best suited to the unique conditions of a specific project. Nonetheless, a detailed matrix of issues to be considered when selecting a repair methodology is presented.

KEYWORDS

CFRP, prestressed concrete beams, flexural strengthening, repair, impact damage.

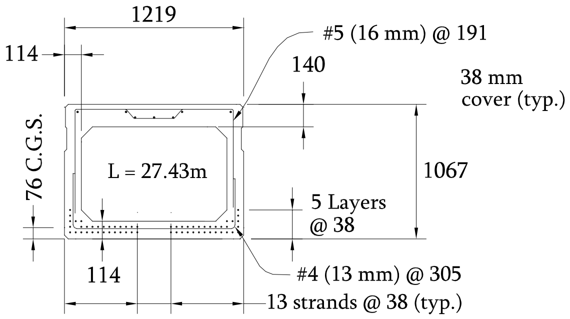
INTRODUCTION

Prestressed concrete bridges are exhibiting signs of deterioration and distress. Recent catastrophic collapses (Harries 2009) have led to re-evaluation of the condition of many prestressed structures resulting in postings and in some case emergency decommissioning of structures. It is posited that with more education and familiarity with field applications of appropriate repair technology, the more often repair actions will be selected over bridge replacement, ultimately conserving resources. Very often if a girder cannot be repaired using superficial methods (such as painting or patching techniques) it is replaced. Although there are many research and case studies addressing repair of prestressed bridge girders, there is little comprehensive guidance available. NCHRP Project 12-21 (Shanafelt and Horn 1980 and 1985), ultimately completed in 1985, remains the most comprehensive US study to address the evaluation and repair of prestressed bridge members. Few studies address the two primary sources of deterioration of prestressed bridge girders: corrosion and vehicle impact – and significantly the combination of these effects which has been demonstrated as being critical (Harries 2009). Additionally, extant studies do not address newer methods of retrofit including those using FRP and prestressed FRP materials. In this study, the following systems were considered: preformed carbon fiber reinforced polymer (CFRP) strips, CFRP fabric, near-surface mounted (NSM) CFRP, prestressed CFRP (P-CFRP) and post-tensioned CFRP (PT-CFRP). P-CFRP and PT-CFRP differ in the manner by which the prestress force is transmitted to the substrate concrete. P-CFRP systems are drawn into tension independent of the structure and bonded to the soffit while under stress; the prestress is transferred to the concrete substrate via the bonding adhesive. PT-CFRP use the member being repaired to provide the reaction for tensioning of the CFRP material. The prestress is then 'locked off' at the stressing anchorage. The PT-CFRP may additionally bonded to the concrete substrate to mitigate prestress losses associated with creep of the anchorage. Although not reported here, the present study also considered common non-FRP repair systems including strand splicing and external steel post-tensioning.

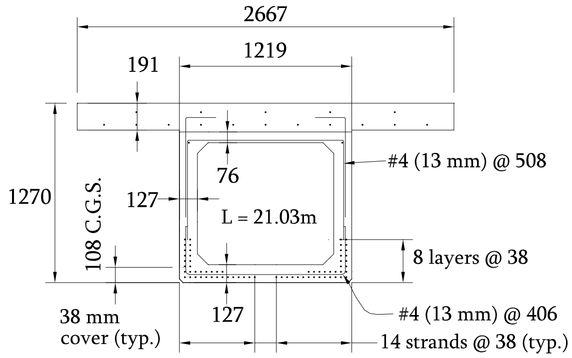
PROTOTYPE GIRDERS AND MODELED DAMAGE

Three prototype girders were considered: an adjacent box (AB), a spread box (SB) and an AASHTO-type I-girders (IB). Each prototype was based on existing damaged bridges found in Southwestern Pennsylvania. All prototypes were designed and built in the late 1960's; thus the details are typical of a large inventory of aging bridges found in the Northeastern United States. The AB prototype is based on the Lake View Drive Bridge that collapsed in December 2005 under only its own dead load (Harries 2009). Details of each prototype may be found in Kasan (2009); basic dimensions and strand arrangement are provided in Figure 1.

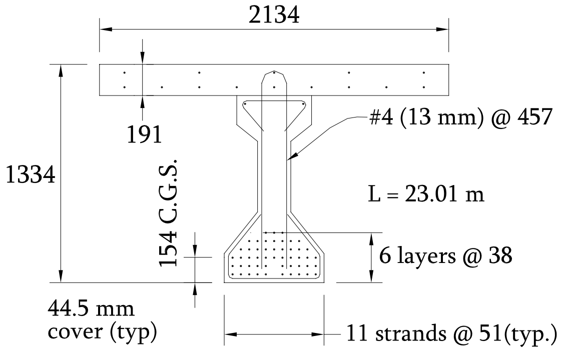
It is assumed that the most significant damage to prestressed bridge girders is related to vehicle impact. Such damage may affect the capacity of the girder or, at the very least, serve as an initiating site for further degradation and corrosion. To model this damage, it is appropriate to remove strands beginning at the exterior web-soffit corner and move inward across the soffit of the girder. Even if truck impact is not the source of damage, removing strands in this manner represents a worst-case scenario since it results in an eccentric girder section cross section (Harries 2006). In the analyses presented, strands were removed from the lower three strand layers only. The three-digit identification of each prototype indicates the number of strands ***removed*** from the lower, second and third layers, respectively. Thus, IB 6-2-1 indicates 6 strands removed from the lower, 2 from the second and 1 from the third layer, for a total of 9 strands removed from the I- girder section. In all cases the strands were removed from the exterior face working inward. Table 2 lists all damage scenarios considered. In Table 2, the residual capacity of the damaged girders is given along with the nominal capacity of the undamaged girder. The objective of all presented repairs is to restore the undamaged girder capacity. As will be discussed, this objective is not achievable with all repair methods, particularly as the girder damage becomes more severe.



(a) Adjacent box girder cross section



(b) Spread box girder cross section



(c) AASHTO I-girder cross section

Figure 1. Prototype girder cross sections details
(C.G.S. = center of gravity of strands)

REPAIR DESIGNS

The NCHRP Project 12-21 reports (Shanafelt and Horn 1980 and 1985) are considered seminal and identify the state-of-the-art and state-of-practice as of their 1985 publication. A significant amount of work has been performed using this study as the primary reference. Although conventional repair methods were considered in the present study, the focus was on methods developed since 1985. Specifically, the present study focuses on the use of externally bonded post-tensioned and non post-tensioned CFRP repair systems. Typical CFRP material and geometric properties used in the designs presented in this study are given in Table 1. All P-CFRP and PT-CFRP repairs use the preformed CFRP strips.

Table 1. Manufacturer reported CFRP material and geometric properties.

Property	CFRP strips	CFRP fabric
Material type	unidirectional preformed CFRP strip	unidirectional CFRP fabric
Tensile strength, f_{fu}	2800 MPa	720 MPa
Young's Modulus, E_f	160,000 MPa	65,000 MPa
Rupture strain, ε_{fu}	0.0170	0.010
Material thickness	1.2 mm	1.016 mm
Size/packaging	100 or 50 mm strips	635 mm x 15.24 m rolls
Application	strip, NSM, P-CFRP and PT-CFRP	fabric

For the repair design and subsequent analysis of the girders some assumptions and simplifications have been made to permit generalized representative designs to be prepared. It is noted that in practice, every scenario is different and all designs must consider local conditions and circumstances. Assumptions and simplifications used in this study include: 1) all girders are modeled as interior girders and thus load and stiffening effects from the barrier wall are neglected; and 2) the torsional moment introduced as a result of the unsymmetric damaged cross section is neglected. Harries (2006) has shown that the effect of this torsional moment is negligible for interior girders (although it can be significant for exterior girders having composite barrier walls).

All repairs were designed using the methodology described in ACI 440.2R-08 (ACI 2008) which employs conventional Whitney stress block factors. Subsequent analyses of the repaired sections were carried out using the commercially available fiber sections analysis program *XTRACT* (Chadwell and Imbsen 2002). The sections analysis design methodology for FRP repair systems is based on strain compatibility and does not consider beam curvature. In modeling the repair designs for the FRP systems, for convenience the ***target*** repair capacity was determined based on the moment capacity of the undamaged girder at a curvature, φ = 0.0059 rad/m. For externally bonded CFRP applications, the FRP strain expected to cause debonding, ε_{fd}, typically represents the design limit state; this value is presented in Table 2. In all cases presented the ultimate capacity of the repaired girder was determined to be controlled by the CFRP debonding limit state. The maximum capacity of the ***repaired*** girder, and the curvature at which this is achieved, determined from the *XTRACT* fiber section analysis, is presented in Table 2. While the ultimate curvature varies considerably, all reported values continue to represent a reasonable degree of ductility (Kasan 2009).

NSM repair geometry (required slot size and spacing) is prescribed by ACI 440.2R-08 (ACI 2008); thus for a given soffit width, an optimal strip size can be determined so as to maximize the area of NSM reinforcement provided. For the IB repairs utilizing NSM, strip size was optimized and each slot was considered to contain two 22 mm CFRP strips.

For the P-CFRP repairs, it is important to consider the achievable prestressing and post-tensioning forces. Experiments have shown that a sustained prestress force of 30% of the ultimate strain capacity of the CFRP strip is achievable with a P-CFRP system (ElHacha *et al*. 2003); thus this value is added to the ACI 440.2R-08 calculation of debonding strain for P-CFRP designs. Similarly, the force sustained in a PT-CFRP system was based upon experience and taken as 50% of the ultimate strain capacity of the CFRP strip.

DISCUSSION

Repair methods must be selected on a project-by-project basis. It is not feasible to standardize repair method selection based on damage level due to the variability between structures, the unique nature of damage to a particular girder, and the original girder's design or stress requirements. Despite this, the following discussions are offered as a basis for repair method selection.

Table 2. Summary of repair details and capacities.

undamaged girder strand details	**Damage**	**CFRP**		**Capacity (kN-m)**			**Repaired curvature** (1/m)	ε_{fd}
		Detail	A_f (mm^2)	Damage	Target	Repair		
Adjacent box girder 60 – 9 mm 1760 MPa strands	4-0-0	6 – 50 mm strips	360	4610	4940	5000	0.0075	0.0066
	8-2-1	17 – 50 mm strips	1020	4040	4940	4960	0.0075	0.0066
	8-2-1	8 – 50 mm P-CFRP	480	4040	4940	5240	0.0098	0.0109
	8-2-1	6 – 50 mm PT-CFRP	360	4040	4940	4920	0.0071	0.0138
Spread box girder 68 – 9 mm 1760 MPa strands	4-0-0	6 – 50 mm strips	360	6300	6710	6700	0.0059	0.0059
	8-2-1	18 – 50 mm strips	1080	5600	6710	7040	0.0059	0.0059
	8-2-1	9 – 50 mm P-CFRP	540	5600	6710	6640	0.0051	0.0102
	8-2-1	6 – 50 mm PT-CFRP	360	5600	6710	6510	0.0051	0.0131
AASHTO I-girder 50 – 11 mm 1760 MPa strands	4-0-0	fabric	520	6130	6700	6710	0.0087	0.0100
	6-2-1	fabric	2220	5440	6700	6470	0.0051	0.0058
	10-2-1	fabric	2220	4870	6700	5910	0.0051	0.0058
	4-0-0	8 – 22 mm NSM	211	6130	6700	6860	0.0102	0.0119
	6-2-1	22 – 22 mm NSM	580	5440	6700	7260	0.0102	0.0119
	10-2-1	22 – 22 mm NSM	580	4870	6700	6400	0.0102	0.0119
	4-0-0	2 – 50 mm P-CFRP	120	6130	6700	6340	0.0051	0.0102
	6-2-1	9 – 50 mm P-CFRP	540	5440	6700	6560	0.0051	0.0102
	10-2-1	11 – 50 mm P-CFRP	660	4870	6700	6250	0.0051	0.0102
	4-0-0	3 – 50 mm PT-CFRP	180	6130	6700	6570	0.0051	0.0131
	6-2-1	8 – 50 mm PT-CFRP	480	5440	6700	6710	0.0051	0.0131
	10-2-1	12 – 50 mm PT-CFRP	720	4870	6700	6650	0.0051	0.0131

Repair Technique Applicability

The repair method chosen is a function of the original girder's design considerations such as soffit stress, girder shape, strand spacing or layout and damage, amongst other factors. Additionally, the goal of the repair must be considered: if the repair must restore prestressing force, an active repair such as strand splicing, P-CFRP or PT-CFRP is required. If flexural capacity is the only consideration, this may be achieved with a passive (non-prestressed) repair. Table 3 summarizes potential repair applications and a number of selection and design considerations for each repair type. Although specific damage levels are not suggested, the limits of applicability of each repair type are suggested. Table 3 updates and revises a performance comparison matrix developed as part of NCHRP 12-21 (Shanafelt and Horn 1980). Due to the different bases for comparison (specifically the inclusion of CFRP methods), the ranking and practicality of various methods conventional methods have changed. For instance, steel jackets (Shanafelt and Horn 1980) are no longer considered practical. They are cumbersome, untested, and their design, installation and performance are all expected to be exceeded by CFRP methods.

In terms of CFRP methods, non-prestressed methods are well established in both the literature and practice. Prestressed or post-tensioned methods are presently limited to proprietary systems and have similarly limited field experience. Nonetheless, PT-CFRP holds great promise for highway bridge applications. NSM CFRP generally out performs surface-mounted CFRP, however this performance comes at a cost in terms of constructability. Additionally, NSM repairs may be more limited in their application than surface mounted methods due to slot geometry and spacing requirements.

All external methods require protection from the environment. Steel methods may use galvanizing, epoxy coating or encased (unbonded post-tensioning type) strand. CFRP itself requires little environmental protection, although adhesive systems do. Therefore, CFRP systems are often painted with a gel coat to limit moisture intrusion and protect against UV radiation.

External repair methods must also be protected from mechanical damage. Repairs that are attached to the beam soffit encroach upon the roadway clearance below. The only viable method for protecting against mechanical damage is ensuring the repair is not impacted. This therefore, should be an initial design consideration. In general, external CFRP systems are smaller and have a 'lower profile' than steel systems. NSM and strand splicing are internal repairs and have little effect on beam geometry.

Cost and aesthetic rankings given in Table 3 are quantitative assessments of the authors based on North American practice. Once again, due to the unique nature of each repair project, it is difficult to provide cost efficiency in a general sense.

Girder Shape

Girder shape plays a role in repair selection and design. For instance, IB girders have a more vertically distributed arrangement of strands resulting in a higher center of gravity of strands than AB and SB girders. As a result, strands lost from the bottom layer of strands in an IB girder have a greater proportional affect on the strand center of gravity (and thus girder capacity) when compared to the same damage for an AB or SB girder. That is, one lost strand has more of an impact on the flexural capacity in an IB girder than for an AB or SB girder. As a result, the repairs for IB girders are more substantial as compared to those for AB or SB girders having the same damage level. This can be seen in the repairs presented in this document. Furthermore, the bulb of an IB girder results in certain geometric constraints on the repair. NSM slots are limited and external CFRP requires rounding of the bottom corners in order to be extended up the side of the bulb. Extending the CFRP vertically from the soffit also results in proportionally less efficient use of the CFRP (as its centroid rises).

Ductility

Using ultimate curvatures as an indicator of ductility, it can be seen that passive repair methods are more ductile than active methods. It is believed that the active utilization of the material (i.e. post-tensioning) creates a greater possibility of material yielding and thus a less ductile failure than a passive repair application. This relationship can be seen in Table 2. As a result, it is concluded that maximizing an active repair for a girder is not ideal and other solutions should be investigated. One possibility not considered here is a ‘partially prestressed’ repair where only a portion of the CFRP provided is post-tensioned.

CONCLUSIONS

Various CFRP repair types have been shown to be successful in flexural repair of prestressed concrete bridge girders. It is believed that there is no correlation between girder damage and repair method selection. Although only briefly discussed, all aspects of a CFRP repair (including material use, repair method applicability, girder shape and constructability) must be considered. It has been found that while active repairs utilize the CFRP material more efficiently, the difficulties in construction are more significant than the CFRP material savings (particularly in the case of P-CFRP repairs). PT-CFRP repairs are potential alternatives to conventional external post-tensioned steel repairs, but again are somewhat cumbersome to apply in the field.

ACKNOWLEDGMENTS

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Table 3. Repair selection criteria.

Damage Assessment Factor	**Repair Method**								
	reported in present study (Kasan 2009)					**reported by NCHRP 12-21** (Shanafelt and Horn 1980 and 1985)			
	preform CFRP strips	**CFRP fabric**	**NSM CFRP**	**P-CFRP**	**PT-CFRP**	**PT steel**	**Strand Splicing**	**Steel Jacket[2]**	**Replace Girder**
Damage that may be repaired[1]	Severe I	low Severe I	Severe I	Severe II	Severe II	Severe II	low Severe I	Severe II	Severe III
Active or Passive repair	passive	passive	passive	marginally active	active	active	active or passive	passive	n/a
Applicable beam shapes	all	all	IB, limited otherwise	all	all	all	IB, limited otherwise	IB	all
Behavior at ultimate load	excellent	excellent	excellent	excellent	excellent	excellent	excellent	uncertain	excellent
Resistance to overload	limited by bond	limited by bond	good	limited by bond	good	excellent	excellent	uncertain	excellent
Fatigue	limited by bond	limited by bond	good	limited by bond	excellent (unbonded)	excellent	poor	uncertain	excellent
Adding strength to non-damaged girders	excellent	good	excellent	excellent	excellent	excellent	n/a	excellent	n/a
Combining splice methods	possible	possible	unlikely	possible	good (unbonded)	good	excellent	excellent	n/a
Number of strands spliced	up to 25%	limited	limited by slot geometry	up to 25%	up to 25%	up to 25%	few strands	up to 25%	unlimited
Preload for repair[3]	no	no	no	no	no	no	possibly	possibly	n/a
Preload for patch[3]	possibly	no	yes	possibly	possibly	possibly	yes	no	n/a
Restore loss of concrete	patch prior to repair	patch prior to repair	patch prior to repair	patch prior to repair	patch prior to repair	patch prior to repair	excellent	patch prior to repair	n/a
Constructability	easy	easy	difficult	difficult	moderate	moderate	difficult	very difficult	difficult
Speed of repair	fast	fast	moderate	moderate	moderate	moderate	fast	slow	very slow
Environmental impact of repair process	VOCs from adhesive	VOCs from adhesive	VOCs from adhesive & concrete sawing dust	VOCs from adhesive	minimal	minimal	minimal	welding	typical erection issues
Durability	requires environmental protection	requires environmental protection	excellent	requires environmental protection	requires environmental protection	requires corrosion protection	excellent	requires corrosion protection	excellent
Cost	low	low	moderate	moderate	moderate	low	very low	moderate	high
Aesthetics	excellent	excellent	excellent	excellent	fair	fair	excellent	excellent	excellent

n/a: not applicable

[1] See Kasan (2009) for definition of Severe I, II and III.

[2] Due to their complexity and the fact that they are untested, steel jacket repairs are not recommended; CFRP repairs address all advantages of steel jackets while overcoming some of their drawbacks.

[3] Preload may be required for the repair or simply to pre-compress associated concrete patches. Jackets render the need to pre-compress the patch unnecessary.