FULL-SCALE FLEXURAL AND FATIGUE TESTING OF LATERALLY DAMAGED AASHTO TYPE II BRIDGE GIRDERS REPAIRED USING NONPRESTRESSED CFRP FABRIC LAMINATES

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ABSTRACT

This study presents a selected portion of a detailed experimental program performed to investigate the proper and most efficient configuration to apply carbon fiber reinforcing polymers (CFRP) to repair laterally damaged prestressed concrete (PSC) bridge girders. The flexural behavior of eight, 40-feet long, full-scaled AASHTO type II prestressed concrete (PSC) girders is reported. The simulated vehicle collision impact damage was induced by saw cutting the girders' lower concrete corner and slicing through three of the pre-stressing strands. Then, to repair the damaged area, epoxy injections and other concrete repair materials and methods were used. Multiple layers of CFRP (both longitudinal strips on girder soffit and U-wrapping) were applied to each girder to constitute the structural repair. The eight PSC girders were then tested in both flexure and fatigue until failure using either a four point or three point loading setup respectfully. All tests were performed at the Florida Department of Transportation (FDOT) structures research lab. The Analysis of the results provided solid evidence for conclusions to the most efficient level of CFRP strengthening, the behavioral aspects of the configuration to avoid CFRP debonding, and other information that is useful for properly repairing laterally damaged bridge girders.

Keywords: CFRP, Repair, Full-scale, AASHTO, Collision, Damaged

INTRODUCTION

Carbon Fiber reinforced Polymer (CFRP) has been used to repair laterally damaged prestressed concrete (PSC) bridge girders caused by over-height vehicles' lateral collision. Limited research was conducted on the assessment of impact damage and few studies were reported on the performance of CFRP repaired girders under fatigue loading. To develop appropriate design guidelines for bridge applications, an understanding of the factors affecting the fatigue performance of strengthened beams is required.

There is a need to explore the CFRP innovative technique to restore the ultimate strength capacity of damaged girder and withstand the repetitive service fatigue loadings. Several researchers addressed the use of FRP in repir[1-17]. CFRP has proven to be a more desirable solution providing a rapidly applicable repair method that restores the girder capacity while maintaining the original configuration and overhead clearance of the structure.

It is worth noting that the damage caused by over-height vehicle collisions can be too severe for superficial repairs. Yet, for less severe impacts, classifications for degrees of damage and applicable repair methods were presented in Kasan, 2009[6] and were updated in NCHRP Project 12-21. These classifications include acceptable damage for the use of non-prestressed CFRP laminates for repair and restoration. In addition, several field studies have demonstrated that impacted PSC bridge girders can be repaired using FRP materials after large losses of concrete cross-section and the rupture of a small number of prestressing strands[17-20]. However, research conducted in a laboratory setting to describe the overall behavior of impact damaged PSC girders is sparse and the documents present mixed results. Di Ludovico et al. 2005, Green et al. 2004, and Klaiber et al. 1999 reported issues with premature debonding failures due to either inadequate transverse CFRP anchors or development lengths[1].

The test results of this study demonstrated that CFRP repair is capable of restoring the damaged girder's ultimate strength and stiffness to that of the undamaged girder.

EXPERIMENTAL STUDY

The experimental testing presented in this paper investigated the behavior and analysis of eight full scaled AASHTO type II PSC girders with imposed simulated lateral damage and CFRP repair applications. Three of the eight girders were tested under fatigue loading, while the remaining five were subjected to static testing. This paper only reports the fatigue test data of the full scale girders.

The full scale AASHTO type II PSC girders had an imposed simulated damage and applied CFRP laminates. The repaired girders varied in both CFRP configurations and levels of strengthening. The PSC girders were tested under fatigue loading (3 point loading) for 2 million cycles of 2 Hz. Then, they were tested in flexure until failure under a four point loading arrangement. Load measurements, deflection measurements, and strain measurements were recorded for all girders during their testing. Similarly, the modes of failure and observed behaviors were also documented during testing, all of which are discussed with the results and analysis.

TEST SPECIMENS

MATERIALS

The CFRP product decided upon for the research was a unidirectional carbon fiber fabric. It was used in conjunction with the saturant provided, which is an epoxy designed by the manufacturer specifically for the CFRP product. A unidirectional fiber was desired for the research because of its affordability and efficiency. The specific unidirectional fiber product chosen was selected based on the properties and outcomes reported in previous research documents[13-28]. All of the design values provided for the reinforcement properties of the materials used in the test specimens are listed in Tables 1 and 2.

Table 1. Properties of CFRP materials utilized in repair methods

CFRP Material Properties	Tensile Strength	Tensile Modulus	Ultimate Elongation	Density	Weight per Sq yd.	Nominal Thickness
Typical Dry Fiber Properties	550 ksi 3.79 GPa	33.4×10^6 psi 230 GPa	1.70%	0.063 lbs/in^3 1.74 g/cm^3	19oz. 644 g/m^2	N/A
*Composite Gross Laminate Properties	121 ksi 834 MPa	11.9×10^6 psi 82 GPa	0.85%	N/A	N/A	0.04 in. 1.0 mm
*Gross laminate design properties based on ACI 440 suggested guidelines will vary slightly						

Table 2. Properties of prestressing steel used in the test specimens

Steel reinforcements	Dia.	Bar Area	grade	Young's Modulus	Weight	Yield Strength	Ultimate Strength
PS strand	0.4375 in 11.1 mm	0.115 in^2 96.9 mm^2	270	27.5×10^6 psi	0.367 lbs/ft	243,000 psi 1676 MPa	270,000 psi 1862 MPa

DESIGN OF FULL SCALE GIRDERS

For the full scale AASHTO Type II girders, the overall length was 40 ft and the deck was 8 inches, as shown Figure 1. The lateral damage simulation was achieved by saw cutting through the concrete at the bottom flange of each girder and slicing through one of the prestressing strands. A schematic of this procedure and a picture of the resulting cut are shown in Figure 2. To repair the cut, the opening left from the saw was first roughened up using chisel tools to help improve the bonding area. The surface of the concrete exposed by the cut was then thoroughly cleaned with a water jet and pressurized air. The cleaned opening was filled with a high strength cementitous repair mortar and a high pressure epoxy injection procedure was performed after the mortar set. The procedure resulted in a near perfect repaired concrete cross-section.

Fig. 1: Full scale AASHTO Type II girders

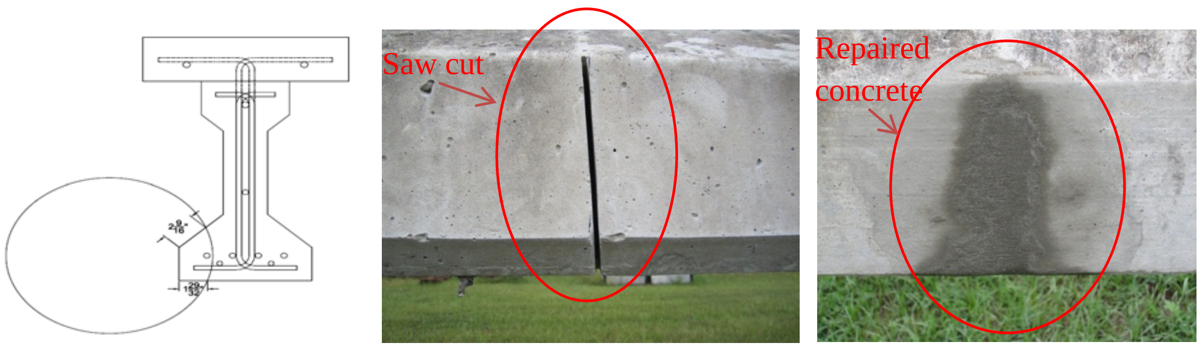

Fig. 2: (a) Girder cross section, (b) Saw cutting to simulate damage, (c) Concrete repair

CFRP CONFIGURATIONS

Multiple CFRP configurations and strengthening levels were used to repair the full scale AASHTO Type II girders. The transverse U-wrappings were twelve inches wide and extended to the top of the web of the each girder. Another longitudinal CFRP Strip was bonded to tie all the top ends of the U-wraps. Figures 3 & 4 show the CFRP configurations for the full-scaled AASHTO type II girders tested in static flexure.

In figure 3, the remaining girders PSC 1, 2, and 3 had both simulated impact damage imposed on them and 2, 3, and 4 layers of CFRP, respectively, at the same spacing. For the fatigue girders PSC 1, 2, and 3, the spacing between U-wrappings was set at a distance of thirty-two inches. In Figure 4, girder (PSC-4) is a control girder that represents a damaged and unrepaired specimen. Girder (PSC-5 and 6) are damaged girders that were repaired with 2 layers of CFRP after the concrete repair. Girder PSC-7 was a damaged girder that was repaired with 3 layers of CFRP after the concrete repair. Girder (PSC-8) was another control girder with no cut and no CFRP repair.

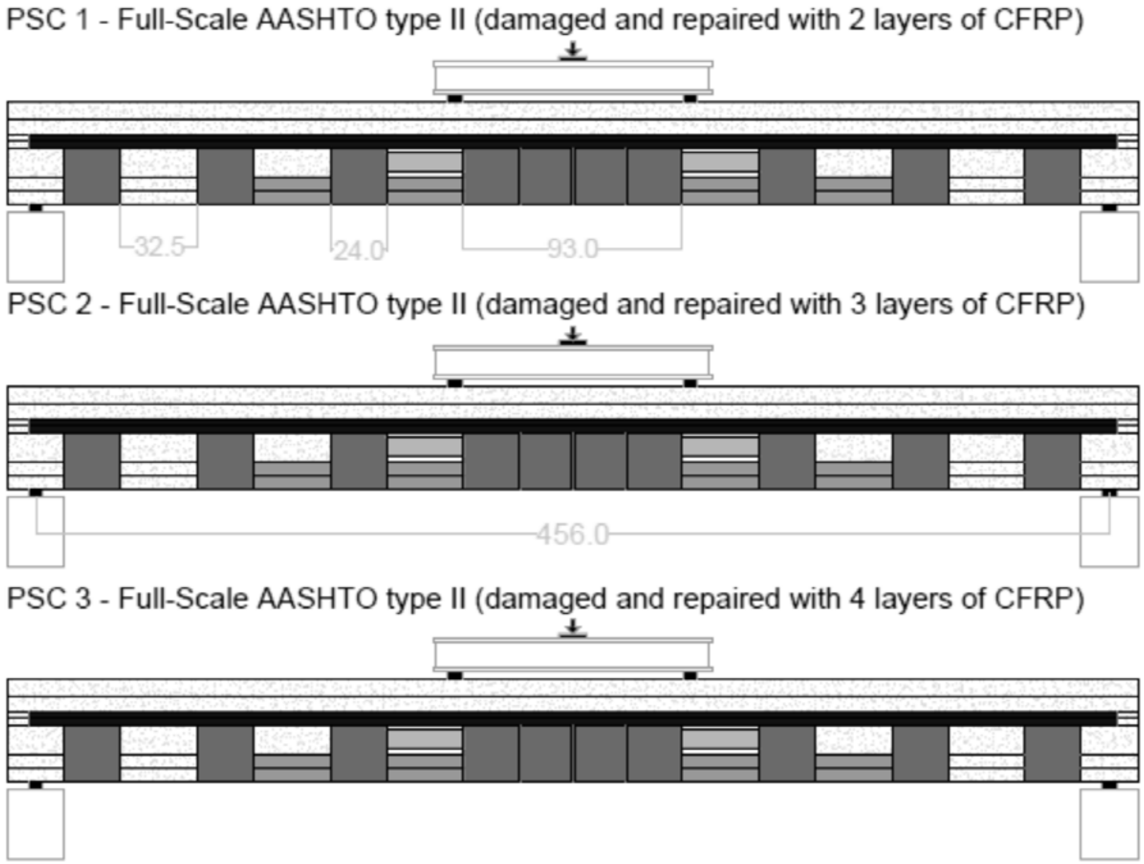

Figure 3: CFRP repair configuration for full-scale AASHTO type II girders dynamically tested

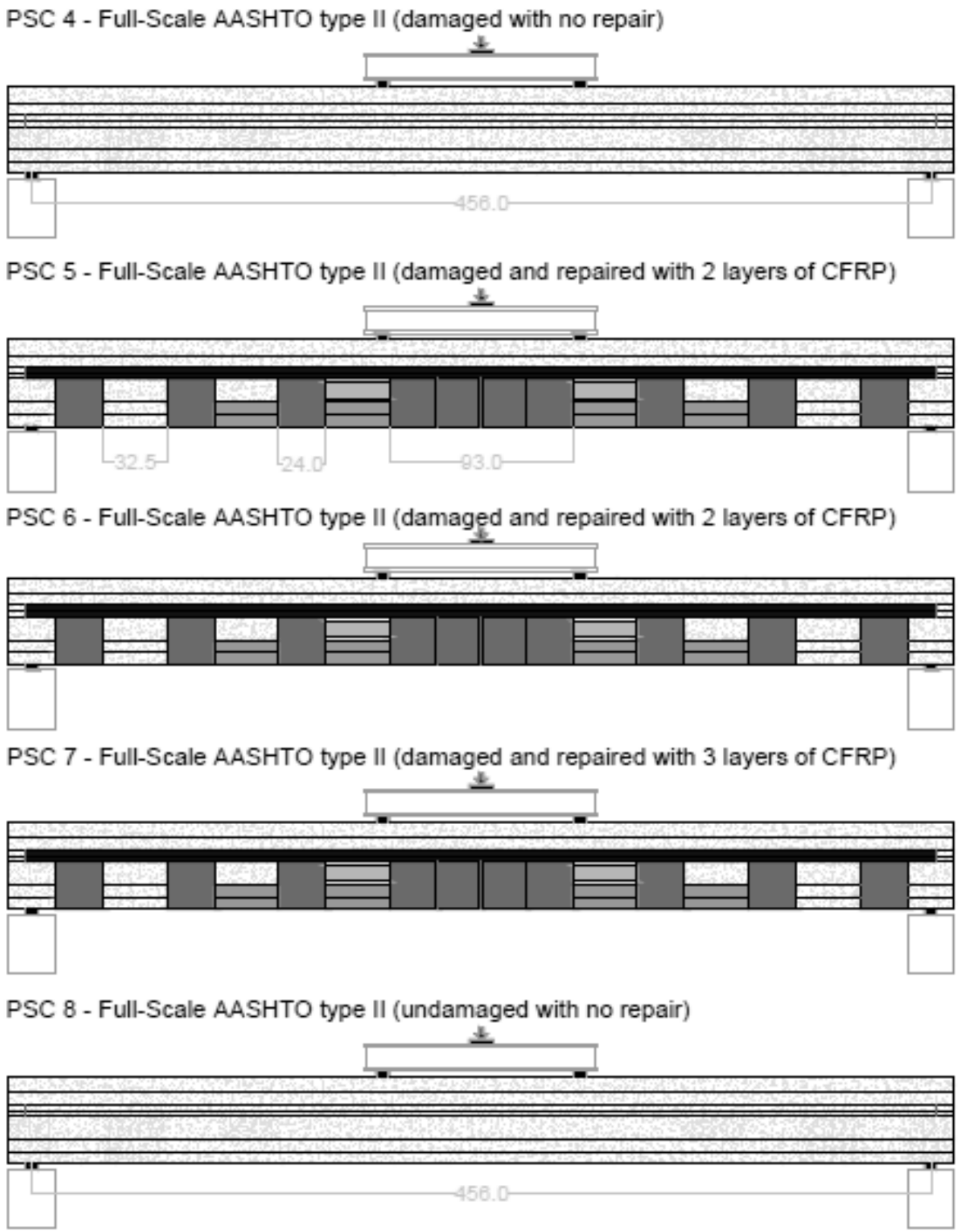

Figure 4: CFRP repair configurations for full-scale AASHTO type II girders statically tested

TEST SETUP & INSTRUMENTATION

The full scale PSC AASHTO type II girders were tested in flexure under four point loading using an 800 kip load actuator at the FDOT structures research lab. The 40-ft long PSC girders spanned 38 feet between the centerlines of the bearing pads which rested on stationary supports. The girder loading was applied using a steel spreader beam resting on another set of two pads. Figure 5 shows one of the tested girders just prior to loading. .

Figure 5: Full scaled girder test setup and testing

Measurements were recorded through the set-up of many gage devices, as shown in figure 6 and figure 7. Load and deflection measurements were recorded by the actuator. Also, the girders were instrumented with six LVDT (linear variable differential transformer) deflection gages and up to twelve strain gages (30 mm long- 120 ohm). Two LVDT deflection gages were positioned at center span on each side of the girder, two LVDTs were placed at girder top surface above the support areas, and the remaining two LVDTs were placed at quarter points of the girder span. On each girder, four of the strain gages were placed along the height of the cross-section at mid-span and the remaining strain gages were distributed along the flexural tension side at various locations depending on the CFRP configuration.

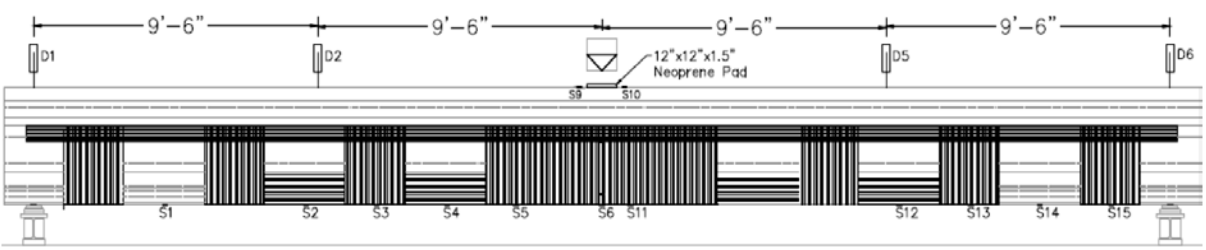

Figure 6: Fatigue loading setup arrangement for full-scaled AASHTO PSC girders

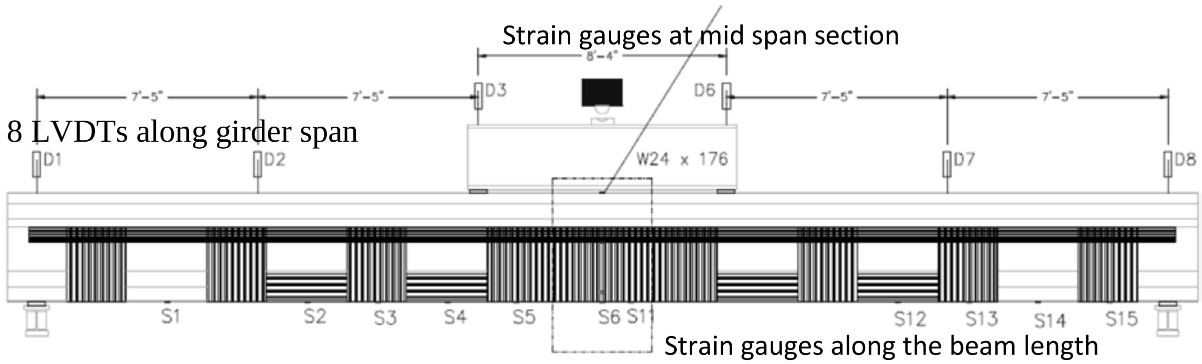

Figure 7: Static loading setup arrangement and gage placement locations for full-scaled AASHTO PSC girders

TESTING RESULTS & ANALYSIS

When repairing laterally damaged girders having a loss of concrete and ruptured prestressing strands, longitudinal CFRP laminate applied to the girder soffit along with U-wrapping anchored with a longitudinal CFRP strip at the top ends of U-wrappings proved to be an excellent repair option. The evenly spaced transverse U-wrappings provided a very efficient configuration for CFRP flexural repairs to mitigate debonding. The behavior of the U-wrapped girders was comparable to that with full wrapping. Premature failure and debonding of the U-wraps occurred when the U-wraps were not anchored with a longitudinal CFRP strip at their top ends. It is necessary to cover the damaged section with transverse and longitudinal strips to restrain the crack opening and propagation in the critical region which initiates early debonding.

For the static testing of full scale girders, the maximum loads reached, the corresponding deflections, and the increased capacity results are listed in table 3. It is shown that a comparison between the failure load of control girder PSC-1 (damaged and un-strengthened with CFRP) and repaired girders with 2 and 3 layers of CFRP shows that CFRP repair enhanced the flexural capacity by a range of 23% to 28% compared to control damaged girder PSC-4 with less strands. Also, for repaired girders with 2 and 3 layers of CFRP, increases in the flexural capacity were reported to range from 10 % to 16% compared to control undamaged girder PSC-8. That means that the repair not only restored the flexural capacity of the damaged PSC girder but also exceeded the capacity of the undamaged girder.

The CFRP configuration, repair preparation, and failure modes are presented in figures 8 to 11.

Figure 8: CFRP pattern

Figure 9: Repair preparation

Figure 10: failure shape mode of full scale PSC beam by static testing

Figure 11: failure shape mode of full scale PSC beam by static testing

Values of maximum load capacity, the corresponding deflections, and percent increases for the full-scale AASHTO type II girders are shown in Table 3.

Table 3. Max Load/Deflection Results for Full-Scale PSC Girders

Girder designation	Max Load (kips)	Corresponding deflection (in.)	% increase compared to damaged PS-4	% increase compared to undamaged PS-8
PSC-4	166.83	2.41	N/A	9.9%**
PSC-5	205.38	2.58	23.1%	10.9%
PSC-6	214.77	4.94	28.7%	16.0%
PSC-7	206.32	3.04	23.7%	11.4%
PSC-8	185.22	2.99	11.0%*	N/A

* Increase of flexural capacity of PSC-8 compared to that of PSC-4
** Loss of flexural capacity of PS-4 due to strand cutting; a percentage of its original capacity

The fatigue load cycles were applied to 3 PSC girders. The girders survived the 2 million cycles of fatigue at 2 Hz with a load range of 20 to 45 kips for PSC 1 and 2. However, PSC-3 was subjected to a higher load range of 25 to 50 kips. All the 3 beams showed no significant loss of stiffness or degradation. The beams were tested up to failure under static test as shown in the figures. They performed very well without any sign of degradation or weakness due to the fatigue loading. Load-deflection behavior under fatigue and static failure loading after fatigue for the 3 fatigue tested girders are presented in Figure 12 through Figure 20. Load-deflection behaviors of full-scale girders PSC-4 (control) and PSC-7 (one of the best performing repaired girders) under static flexure loading are presented in figure 21 and figure 22.

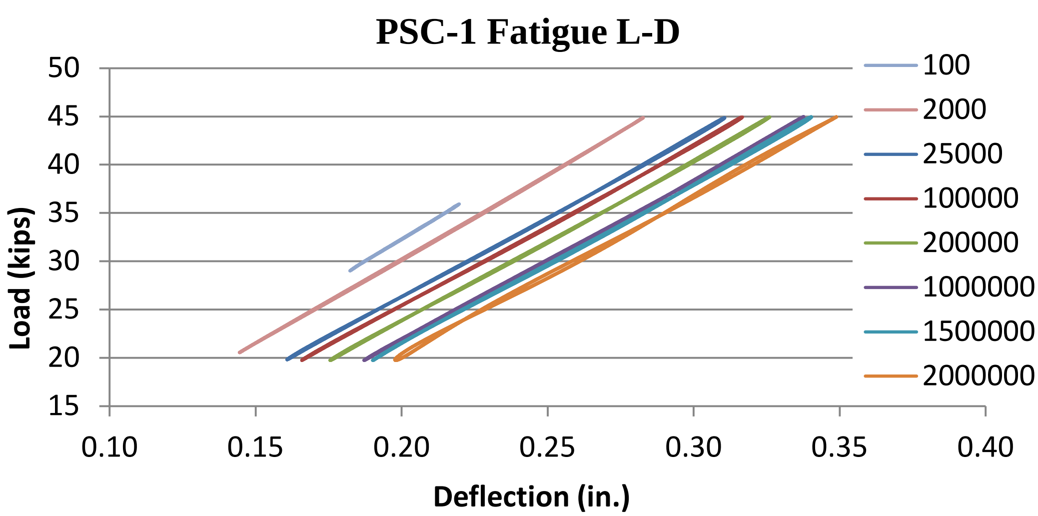

Figure 12: Fatigue Load Deflection of Full Scale Girder PSC-1

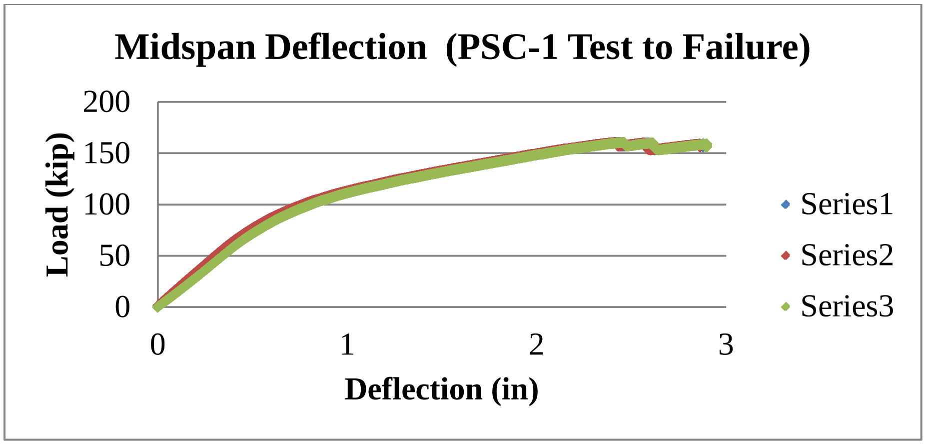

Figure 13: Load Deflection of PSC-1 at static failure after fatigue loading cycles

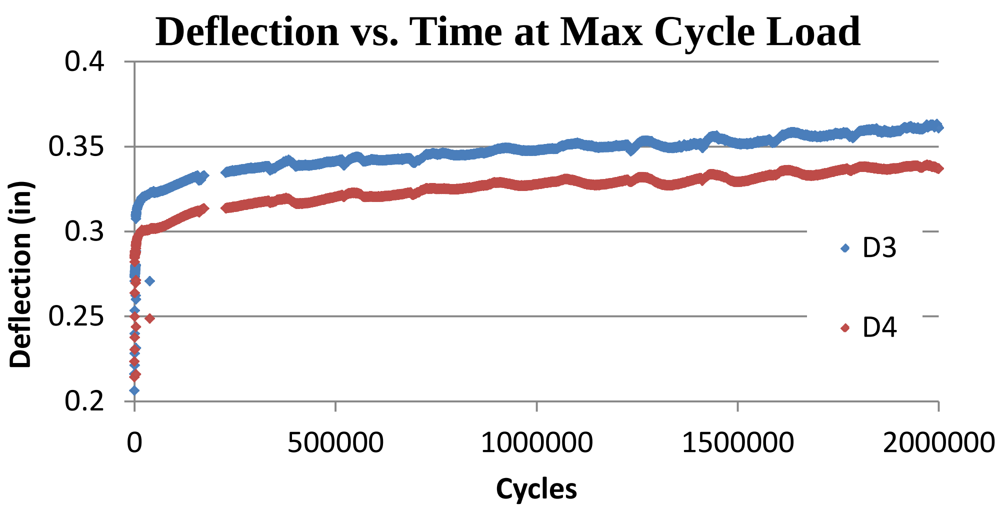

Figure 14: Deflection cycles of PSC-1 at max cycle load

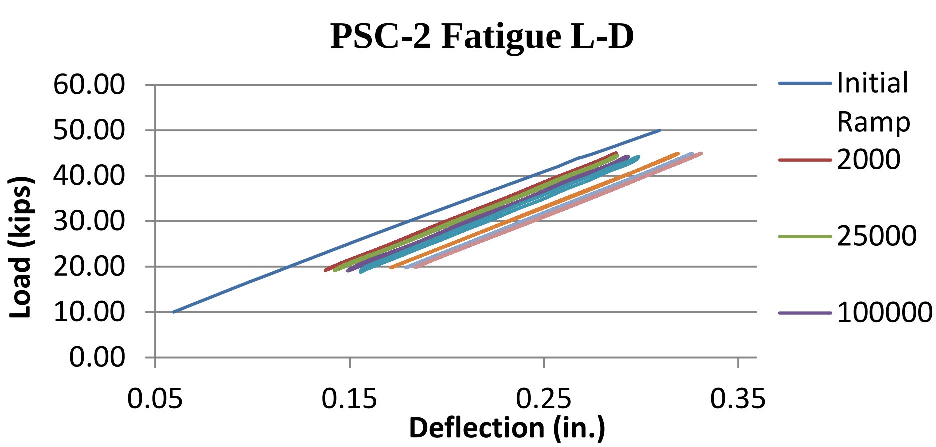

Figure 15: Fatigue Load Deflection of PSC-2

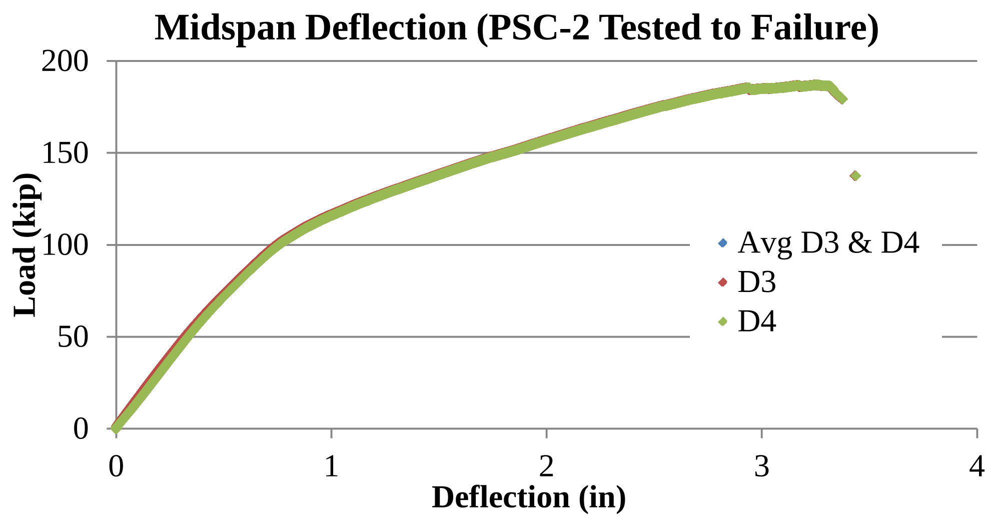

Figure 16: Load Deflection of PSC-2 at static failure after fatigue loading cycles

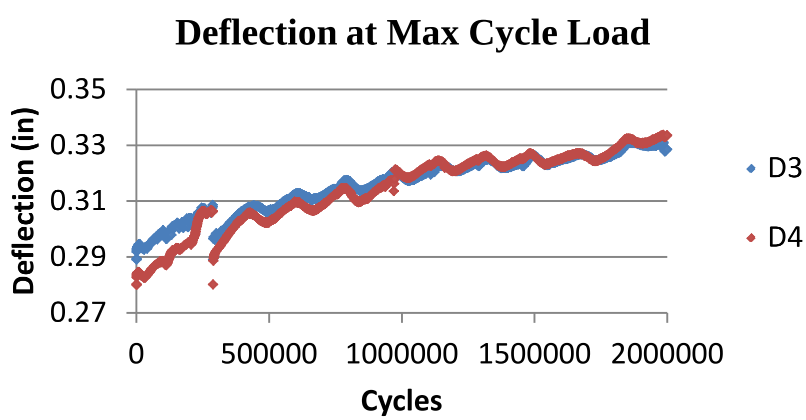

Figure 17: Deflection cycles of PSC-2 at max cycle load

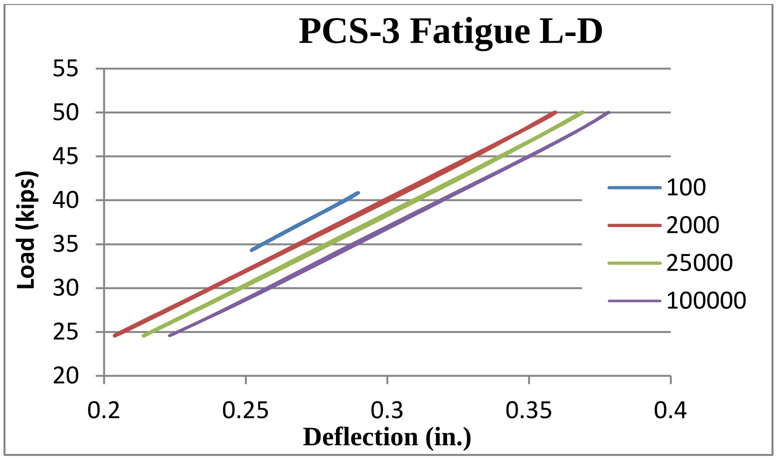

Figure 18: Fatigue Load Deflection of PSC-3

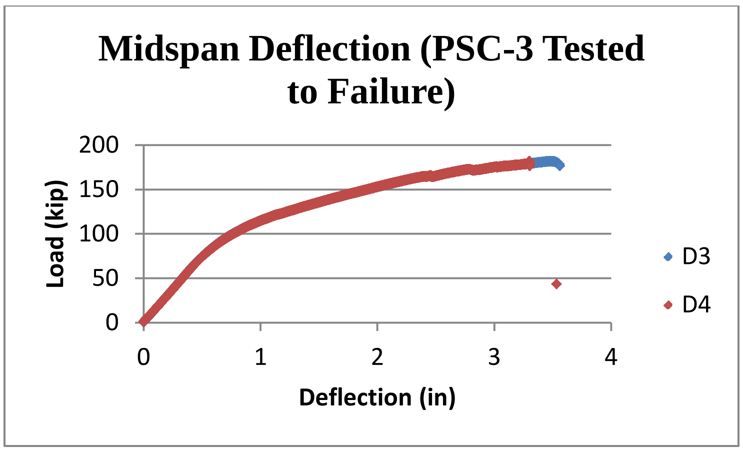

Figure 19: Load Deflection of PSC-3 at static failure after fatigue loading cycles

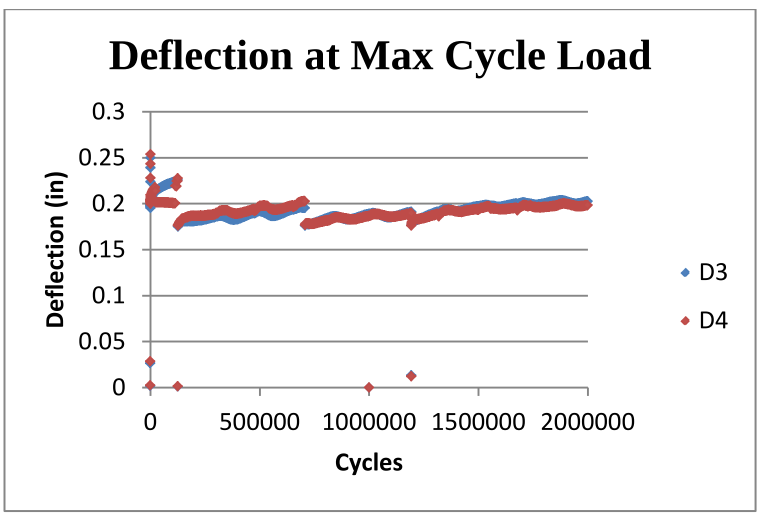

Figure 20: Deflection cycles of PSC-3 at max cycle load

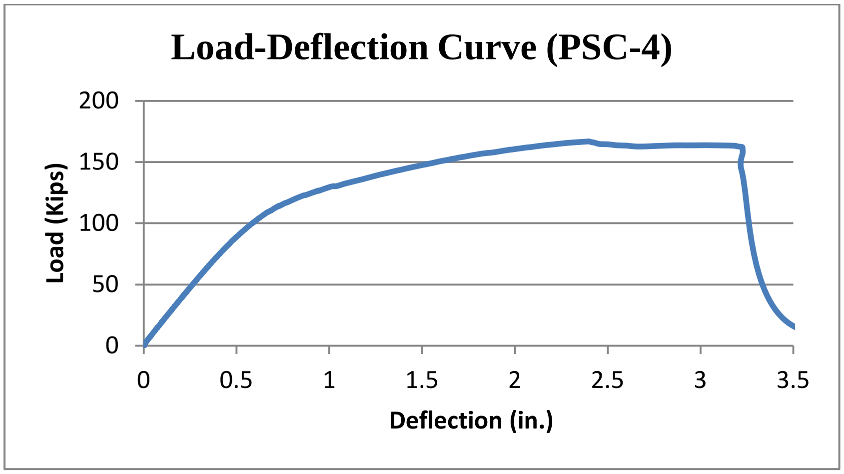

Figure 21: Load Deflection of Full Scale Girder PSC-4 (Static Flexure Loading)

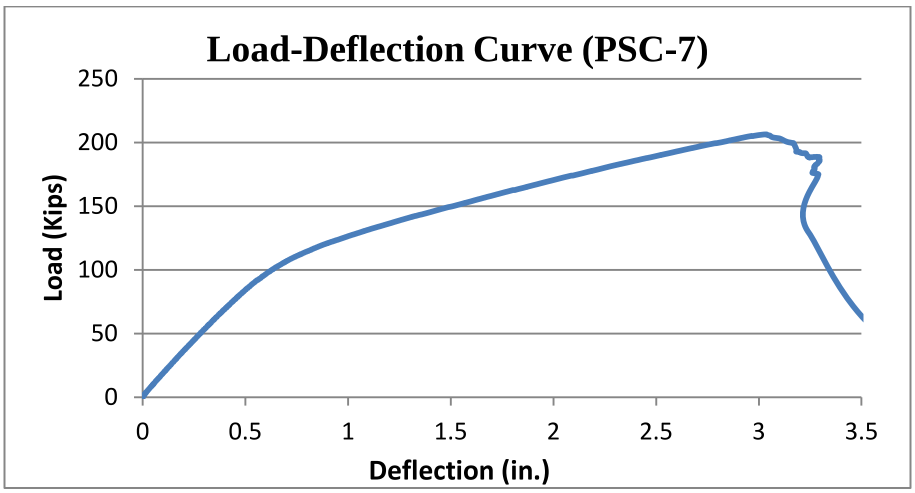

Figure 22: Load Deflection of Full Scale Girder PSC-7 Deflection (inch)

CONCLUSIONS

1. Damaged prestressed bridge girders repaired using non-prestressed fabric CFRP laminates can withstand over 2 million cycles of fatigue loading simulating service load conditions, with little degradation
2. The longitudinal CFRP strips applied to the girder soffit along with U-wrapping anchored with a longitudinal CFRP strip at the top ends proved to be an excellent repair alternative for damaged girders.
3. Evenly spaced transverse U-wrappings provide very efficient configuration for CFRP flexural enhancement repairs to mitigate debonding.
4. The original capacity of a damaged full scale bridge girder was restored and enhanced using CFRP repair applications.

5. Without consideration for shear enhancements, the optimum spacing for transverse anchoring is theorized to be between a distance of ½ to 2/3d, where d is the height of the AASHTO beam (or ½ to 1 times the height of entire composite cross-section).
6. When repairing laterally damaged girders having a loss of steel reinforcements, it is necessary to cover the damaged section with longitudinal and transverse strips to reduce the crack propagation in the critical region which initiates early debonding.
7. Proper CFRP repair design in terms of the number of CFRP longitudinal layers and U-wrapping spacing could result in obtaining significant enhancement for the capacity and desired failure modes for the repaired girders.

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