Fatigue Enhancement of Welded Details in Steel Bridges Using CFRP Overlay Elements

Benjamin N. Kaan, P.E., M.S.[1]; Fatih Alemdar, M.S.[2]; Caroline R. Bennett, Ph.D., A.M.ASCE[3]; Adolfo Matamoros, Ph.D., A.M.ASCE[4]; Ron Barrett-Gonzalez, Ph.D.[5]; and Stan Rolfe, Ph.D., P.E., Dist.M.ASCE[6]

Abstract: Carbon-fiber reinforced polymer (CFRP)-overlay elements were developed with the purpose of enhancing the fatigue performance of welded connections in steel bridge girders. Fatigue tests of seven specimens, including four CFRP-strengthened specimens and three control specimens, were performed to quantify the effect of the CFRP overlays on the fatigue crack initiation lives of the welded connections. Results showed that bonding of CFRP overlays significantly reduced the stress demand on welded connections tested at high stress ranges, leading to a large increase in fatigue crack initiation life. The level of effectiveness of the CFRP-overlay elements in extending the fatigue crack initiation lives of the tested connections was found to be affected primarily by bond strength under cyclic loading; bond strength was found to be dependent on the composition and thickness of the resin layer used to bond the CFRP to the steel. With the AASHTO fatigue design curves as a frame of reference, it was found that when an optimal bond composition was employed, reinforcing the welded connections with CFRP overlays led to a change in fatigue performance category from that consistent with Category E to runout at high stress ranges. An optimal bond composition was identified that resulted in excellent performance under fatigue loading. **DOI:** 10.1061/(ASCE)CC.1943-5614.0000249. *© 2012 American Society of Civil Engineers.*

CE Database subject headings: Fiber reinforced polymer; Steel bridges; Girder bridges; Composite materials; Fatigue; Cracking; Welding.

Author keywords: Carbon fiber-reinforced polymer; Composites; Bridges; Fatigue enhancement; Fatigue crack; Girder; Fatigue life; Cover plate; Weld.

Introduction

An emerging fatigue enhancement technique for aging steel bridges is the use of fiber-reinforced polymers (FRPs) to reduce stresses at fatigue-vulnerable welded connections. FRPs are an ideal material choice to strengthen welded connections in steel bridge construction because of their high strength and stiffness, low weight, ability to diffuse crack propagation (Meier 1992), and ability to be molded into various geometries. Attaching FRP materials as external overlay elements to steel bridge connections can provide an alternate load path that reduces stress demand at the tip of a crack or at a previously uncracked welded connection. Lower stress demand translates into both increased fatigue crack initiation and increased fatigue crack propagation life, with the increase in fatigue life being proportional to the reduction in stress range at the fatigue-vulnerable detail.

An investigation is described wherein carbon fiber-reinforced polymer (CFRP) materials were used to stiffen welded connections common in welded steel bridge girders. A significant body of research exists investigating the effect of FRP sheets bonded over cracks in plates subjected to tension (Jones and Civjan 2003; Sabelkin et al. 2006; Colombi et al. 2003a, b). However, welded connections present a stress state significantly more complex than that seen in plates. Therefore, in this study, composite overlays were bonded over welded connections of coverplate specimens with the goal of reducing peak stresses at the weld and extending the fatigue crack initiation life of the welded connection. This paper focuses on the conceptual design and the fabrication aspects of the bond between the overlay and the welded connection, which were validated through experimental testing of the CFRP-stiffened steel specimens under cyclic loading.

Background

Several studies in the literature show that CFRP materials can be used successfully to strengthen structural steel elements (Jones and Civjan 2003; Tavakkolizadeh and Saadatmanesh 2003; Deng and Lee 2007). For this strengthening technique to be effective, a key aspect is maintaining the bond between the composite materials and the steel. There are a number of studies that have investigated bond characteristics between FRP and steel under monotonic loading (Sebastian and Luke 2007; Buyukozturk et al. 2004).

[1]Project Engineer, Thornton Tomasetti, 912 Broadway, Suite 100, KS City, MO 64105.

[2]Graduate Research Assistant, Univ. of Kansas, 1530 W. 15th St., Lawrence KS 66045.

[3]Assistant Professor, Univ. of Kansas, 1530 W. 15th St., Lawrence KS 66045 (corresponding author). E-mail: crb@ku.edu, caroline.rose.bennett@gmail.com

[4]Associate Professor, Univ. of Kansas, 1530 W. 15th St., Lawrence KS 66045.

[5]Associate Professor, Univ. of Kansas, 1530 W. 15th St., Lawrence KS, 66045.

[6]A.P. Learned Professor, Univ. of Kansas, 1530 W. 15th St., Lawrence KS, 66045.

Note. This manuscript was submitted on February 24, 2011; approved on August 15, 2011; published online on August 17, 2011. Discussion period open until September 1, 2012; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Composites for Construction***, Vol. 16, No. 2, April 1, 2012. ©ASCE, ISSN 1090-0268/2012/2-138–149/$25.00.

Experimental work focusing on FRP repairs under fatigue loading has been more the purview of the aerospace industry, which has spent significant resources in developing techniques to address the recurring problem of fatigue cracks in aircraft fuselages (Sabelkin et al. 2006).

The majority of studies in the literature investigating the use of FRP materials to improve fatigue performance focus on methods for improving the fatigue crack propagation life of specimens with various types of preexisting notches, in both the aerospace and structural engineering fields (Bassetti et al. 2000a, b, c; Colombi et al. 2003a, b; Tavakkolizadeh and Saadatmanesh 2003; Jones and Civjan 2003; Nozaka et al. 2005a, b; Sabelkin et al. 2006). These studies provide several important conclusions. For example, one of the key findings in the work by Bassetti et al. (2000a, b) was that it is essential for CFRP strips being used for fatigue repair to have a strong and durable bond between the steel and composite such that adequate and reliable load sharing can be accomplished. Bassetti et al. (2000a, b) found that debonding of the composite lessened the effectiveness of the CFRP strips, which in turn accelerated the rate of crack growth and led to further debonding. Internal and external delaminations were common problems experienced in investigations examining use of composite materials applied to steel structural members (Colombi et al. 2003a, b). Often the bond material was not able to sufficiently resist shear stresses to provide continuous load sharing between the bonded materials for a significant number of load cycles. Additionally, Hertzberg (1996) found that once a crack began to form in the bond layer, it tended to propagate quickly because of the brittle behavior of most bond materials at standard testing temperatures.

Other important findings from previous studies were given careful consideration in the development of this experimental program. First, the bond layer between the steel and composite must be composed of a material that is durable, strong, and able to withstand significant levels of shear stress. Second, it was known that thickness of the bond material greatly affects the extent of load sharing between the steel and composite (Colombi et al. 2003a, b), so further testing should include investigation of multiple bond layer thicknesses. Third, an increased number of plies in the composite increased the maximum moment the detail could withstand when used as an overlay on a fatigue-vulnerable detail on the flange of a steel girder and, thus, decreased the stress demand at the critical location (Nozaka et al. 2005a, b). Fourth, use of finite element modeling as an evaluation tool helped to focus experimental work and pare down the number of variables associated with the use and testing of composite materials (Colombi et al. 2003a, b).

As noted, previous studies focused primarily on using CFRP strips to extend the fatigue crack propagation life of already cracked specimens. Studies investigating the use of composite materials to repair the type of welded connections commonly found in structural steel bridges are very scarce. One of the few studies found is that of Nakamura et al. (2009), who successfully used CFRP strips to repair specimens simulating welded web gusset joints. The application investigated in this study is significantly different from others found in the literature because it is focused primarily on increasing fatigue crack initiation life of uncracked specimens with welded connections, in which the composite overlay was used to reduce the stress demand in a region with high stress gradients caused by abrupt changes in geometry. This application is different from the use of composite sheets to repair cracked plates subjected to tension; in the former scenario, the stress field is significantly more complex than that in a plate element, inducing both tension and shear stress demands along the interface bond layer between the overlay and the steel.

Research Plan and Objective

It was quite common for bridge engineers to employ welded coverplates to reinforce steel girder flanges in regions of high moment demand as recently as 40 years ago. Although this retrofit technique is seldom used today, its common use in the past created numerous fatigue crack initiation sites, especially for welds at the ends of thick steel coverplates [>20.3 mm (0.80 in.)]. This particular type of welded connection proved to be so prone to development of fatigue cracks that AASHTO (2007) subsequently categorized it with the worst fatigue grouping, denoted as Category E′. Although the engineering community now recognizes that this type of connection is a poor performer under fatigue loading, many examples can still be found in aging, existing steel bridges.

Effective use of FRP overlays to prevent or repair fatigue damage in steel structures hinges on preventing fatigue failure of the retrofit measure itself. Failure of the type of repair discussed in this paper may occur as a result of fatigue failure within the overlay or bond failure between the overlay and substrate under cyclic loading. Previous studies by the authors have found that the type of overlay applied was not governed by fatigue strength of the overlay (Alemdar et al. 2009; Alemdar 2010; Kaan 2008a, 2008b). For this reason, this study focused on evaluating the effect of configuration parameters and fabrication techniques such as bond layer thickness, bond layer composition, and boundary conditions of the bond layer on the bond strength under cyclic loading between composite overlays and the steel substrate.

A plate–coverplate specimen [Figs. 1 and 2(a)] with fatigue-vulnerable welded connections was chosen for this study, because the goal was to evaluate the bond performance of repairs with CFRP overlays [Figs. 1(b) and 2(b)] under fatigue loading. This type of specimen was chosen because of the well-documented poor fatigue performance of the welded connections (Albrecht and Lenwari 2007), the common use of coverplates in the past, and the stress demands that the specimen imposes on the bond layer between the FRP and the substrate steel (combined effects of tension and shear).

The research was carried out in the following manner. A suite of finite element analyses were performed to identify parameters critical to the performance of the bond layer under fatigue loading. The shape of the interface bond layer was varied, and the effect on computed shear and peel stress demands was quantified. An experimental program was subsequently carried out to validate results from the analyses, and to investigate the effect of fabrication techniques on fatigue performance of the interface layer.

Analytical Investigation

Finite element analyses were performed to examine the effects of bond layer thickness and bond layer length on the effectiveness of the CFRP-overlay elements. A two-dimensional model of a 25-mm (1.0 in.)-wide segment of specimen was created to study the effects of various parameters on fatigue life. Computer simulations were performed using the finite element analysis software ABAQUS (Simulia 2011). Steel, weld, and composite materials were defined as linear elastic materials.

The components were meshed separately and joined together using interaction surfaces. The connections between the plates and the weld and between the plates and the composite overlays were modeled using tie constraints. A tie constraint is a finite element modeling technique that joins two separate surfaces to one another so that they displace together as one piece at the tie(s) location(s) (Simulia 2011). The interface between the flange and coverplate was modeled using hard contact interaction. A pressure

J. Compos. Constr. 2012.16:138-149.

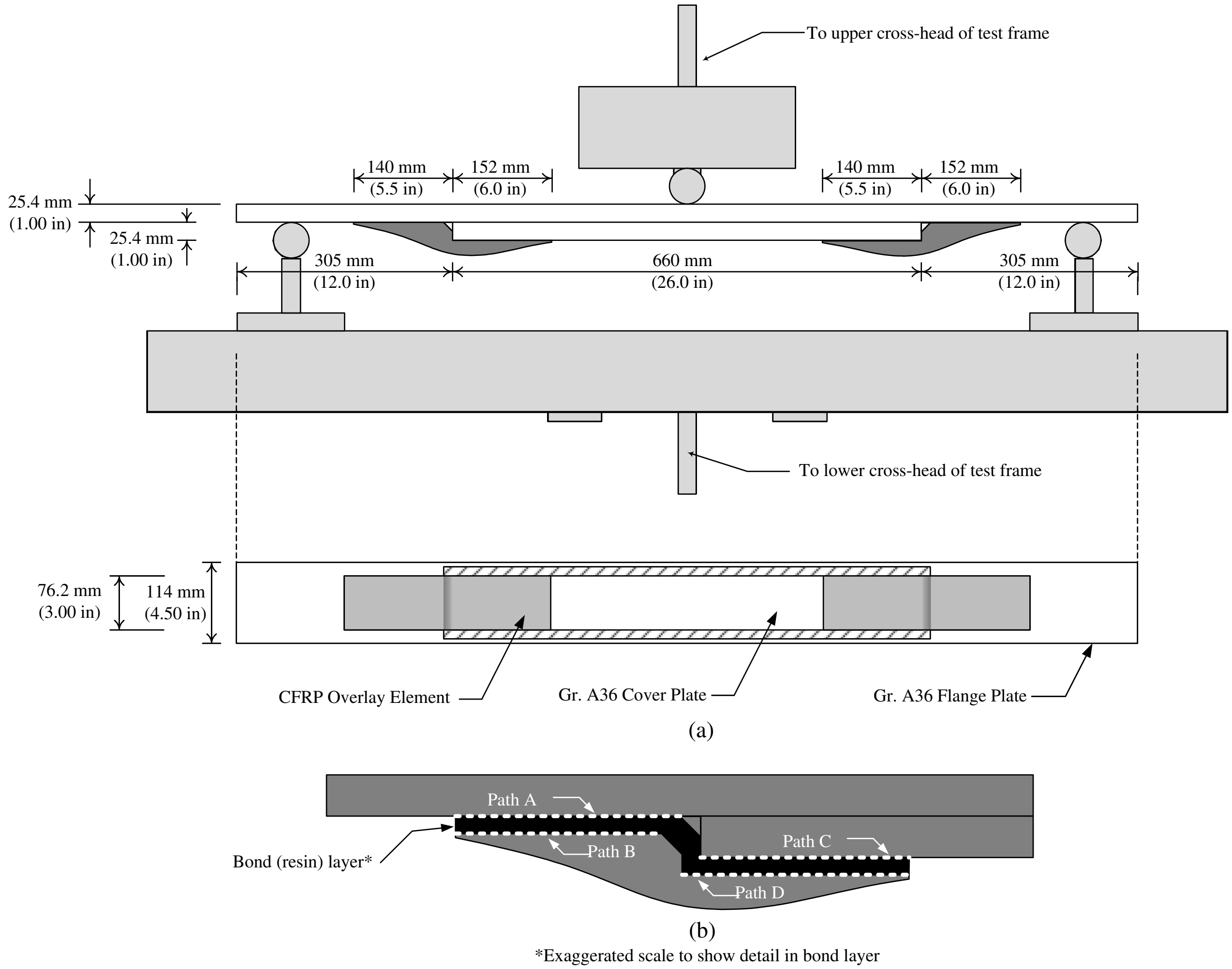

Fig. 1. (a) Schematic of three-point bending fixture with CFRP-stiffened specimen; (b) detail of CFRP–resin–steel bond interface

load was applied at the midpoint of the top plate to simulate the load acting on the specimen during testing, and an adjustment was made to the applied load to account for the difference between the width of the specimen and the width of the model. Vertical displacement was restricted at the two supports, both located 76 mm (3.0 in.) from the ends of the specimen, and horizontal displacements were restricted at one end of the model. Six different bond layer thicknesses between the steel and overlay were investigated analytically: 0.3 mm (0.01 in.), 0.8 mm (0.03 in.), 1.3 mm (0.05 in.), 1.7 mm (0.07 in.), 2.5 mm (0.10 in.), and 3.2 mm (0.13 in). Both faces of the bond layer were rigidly tied to the CFRP and the steel; therefore, flexibility exhibited by the bond layer was related to the stiffness of the resin. The modulus of elasticity for the resin material was conservatively taken as 2.8 GPa (400 ksi) within the models, because of the inherent variability in resin moduli; the value chosen for the models was taken as higher than the measured modulus [2100 MPa (303 ksi)] and the manufacturer's information [2300 MPa (330 ksi)], as a stiffer interface in the models would result in higher demands on the steel than a more flexible bond could induce. Poisson's ratio was taken as 0.2. Interface surfaces between the resin and the steel and between the resin and the composite were modeled using tie constraints. The CFRP modeled in the computer simulations was rectangular in profile, as can be seen in Fig. 3. A broader investigation by the authors considered effects of CFRP profile shape (Alemdar et al. 2009; Alemdar 2010), and found that CFRP profile shape had very little effect on the stress demands in the bond or steel substrate.

Stress demands between the steel and the interface resin layer, and between the resin layer and the composite overlay, were evaluated by extracting the shear and tensile stresses along paths in the interface between materials. Four different paths were evaluated. These paths, designated A through D, are illustrated in Figs. 1(b) and 3 for one of the finite element models that was analyzed.

One of the most important aspects of this type of repair is the effect of the overlays on stress demand at the weld, which is directly proportional to the fatigue crack initiation life of the welded connection. The finite element results (Fig. 4) showed that increasing the thickness of the resin layer resulted in a small reduction in the maximum stress demand on the steel plate at the location of the weld toe, the location of which corresponded to a point approximately 300 mm (11.8 in.) from the edge of the specimen in Fig. 4. The stresses shown in Fig. 4 were extracted from Paths A and C shown in Fig. 3, along the surface of the steel. Fig. 4 shows that in the area near the weld, computational models with greater resin layer thicknesses produced calculated stress demands higher than those noted for models with less thick resin layers, which indicates that the retrofit measure becomes less effective as the thickness of the resin layer increases.

Another important factor that affects the fatigue behavior of this type of repair, central to the focus of this study, is the stress demand along the interface between the composite and the steel. Calculated shear and tensile (peel) stresses were computed along the interfaces. The observed stress distribution and magnitudes along the interface between the steel and the resin were very similar for both

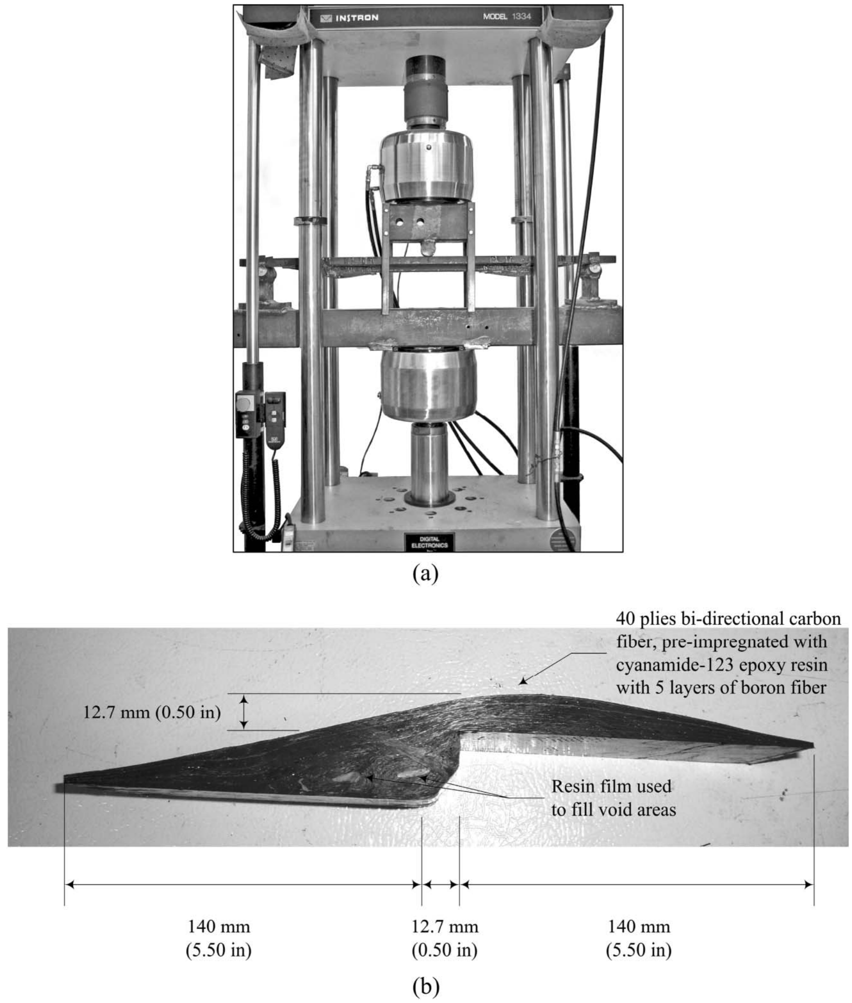

Fig. 2. (a) View of experimental test setup; (b) profile of CFRP-overlay element

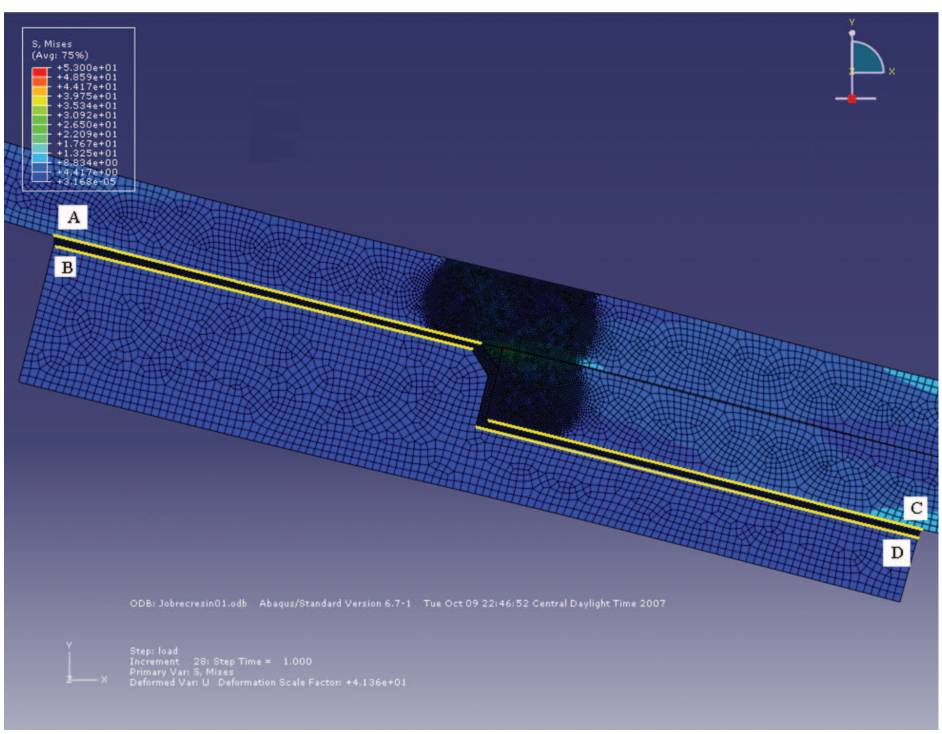

Fig. 3. (Color) Stress comparison paths on the resin layer

J. Compos. Constr. 2012.16:138-149.

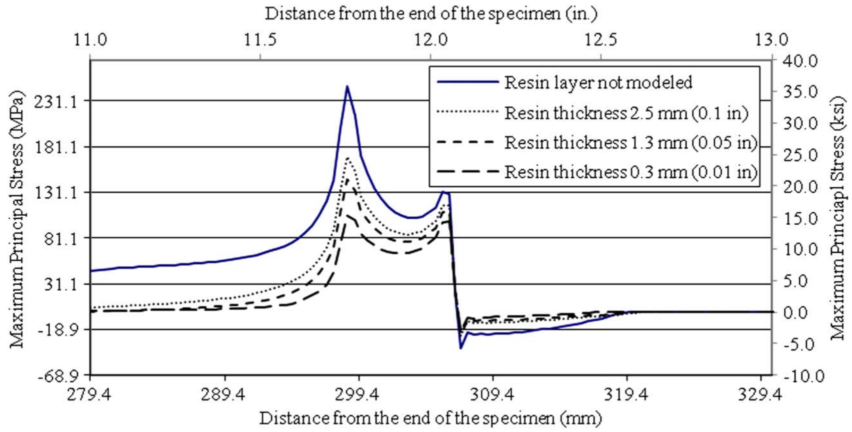

Fig. 4. Maximum principal stress on the steel plate in the area of the weld

shear and peel stresses, with peak demands located at the end of the Path corresponding to the edge of the overlay and a much smaller peak at the weld toe. The distribution of shear stress along Path A (Fig. 3) is shown in Fig. 5. It was found that in the case of the peel stresses, the peak demand at the interface between the steel and the resin (Path A) was higher than the peak stress demand at the interface between the resin and the composite (Path B); this was not unexpected, given the higher stiffness of the steel plate.

Calculated stresses along Path C were similar in nature, with peak demands occurring at the edge of the overlay and a much smaller peak occurring near the edge of the coverplate. Calculated stress demands along Path A are presented because the magnitude was higher than the stress demands along Path C, which is attributed to the greater flexural stiffness of the plate–coverplate segment (Path C), resulting in lower curvature demands in that segment of the specimen. Because the results for Paths C and D are similar in nature and lower in magnitude to the results for Paths A and B, they are not presented here; however, additional results from a broader modeling effort can be found in Alemdar (2010). Results show that the curvature of the specimen when deformed in bending induced a significant peel stress demand that is not present in composite sheet repairs of plates subjected to pure tension. Also, it should be noted that the type of specimen used in this study is likely to pose a greater peel stress demand on the interface layer than flanges of beams reinforced with coverplates, because the curvature demand in the shallow specimen used in this study is likely to be much higher than that in beams.

The distribution of the computed stresses suggests that the point along Path A (Fig. 3) corresponding to the edge of the overlay is critical in terms of fatigue performance, because at this location the interface resin layer is subjected to the highest stress demands. For this reason, it is expected that this location will be a trigger point for bond failure under fatigue loading. On the basis of this finding it was decided that one of the parameters of the experimental study should be the geometric configuration of the interface resin layer. It was hypothesized that terminating the interface resin layer directly at the edge of the overlay would be detrimental to fatigue performance because it would couple the location of a discontinuity with the maximum stress demand. For this reason, it was decided to evaluate two different configurations in the experimental phase of the study: a configuration with a resin pool extending beyond the edge of the overlay, and another without it.

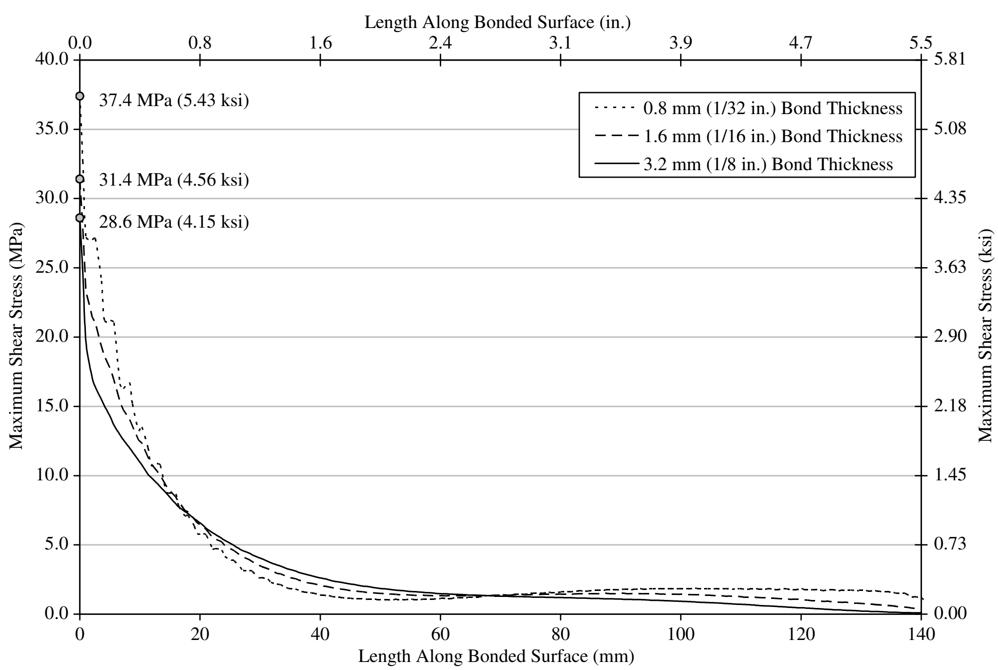

Fig. 5. Calculated shear stress along Path A in Fig. 4 for varied bond thickness

Another important consideration related to bond performance under fatigue loading is the effect of the resin layer thickness on peel and shear stresses at the interface. Although finite element analyses showed that resin layer thickness was likely to have a small effect on the fatigue life of the steel substrate, a significant effect on the interface stress demand would have an important effect on the bond strength under fatigue loading. Fig. 5 depicts the shear stress distributions along the bonded surface of the CFRP overlay found for bond thicknesses varying from 0.8 mm (1/32 in.) to 3.2 mm (1/8 in.). Fig. 5 shows that the shear stress distribution was similar for all thicknesses studied, with the greatest demand found to occur at the edge of the coverplate. The maximum shear stress demand in the bond layer decreased as the thickness of the layer increased. The trends for peel stress were similar in nature. The results also showed that stresses in the steel increased as resin layer thickness increased. As the resin layer becomes thicker, and thus more compliant, more load is transferred through the steel and less stress is resisted by the bond.

The importance of shear stress at the leading edge of the bond layer was further confirmed by experimental observation as the bond failure path propagated to the leading edge through the bond material at an angle of approximately 45°. Therefore, another hypothesis derived from finite element analyses was that increased bond thickness between the steel and CFRP elements would increase bond tenacity, while some stiffening capability would be sacrificed. A goal of the experimental testing, in light of this hypothesis, was to determine an optimal bond thickness that provided enough stiffness to the specimen to increase the life of the fatigue-vulnerable welds, while still minimizing shear stress in the bond material, thus minimizing the frequency of debonding of the CFRP-overlay elements from the steel specimens.

Experimental Program

The experimental program consisted of a series of tests of welded coverplate steel assemblies reinforced with CFRP overlays (Fig. 1) subjected to fatigue loading. Each assembly was subjected to cyclic loading until crack initiation was observed in the steel substrate or runout was achieved. Each time debonding of an overlay was observed, the overlay was removed and the weld was inspected for the presence of fatigue cracks. If fatigue cracks were not observed, the overlay was rebonded and fatigue testing resumed. CFRP-overlay elements were reused throughout tests when they suffered no visually noticeable internal degradation. As the fatigue lives of the bond layers were dependent on study variables, it was felt that using new CFRP overlays after each debond event would add little value, as each overlay would still have been subjected to a different number of fatigue cycles. Therefore, CFRP overlays were regularly inspected during fatigue testing and were replaced when internal degradation was visually observable; this occurred only once throughout the testing program. The number of cycles between the attachment of an overlay and its subsequent debonding is reported as a fatigue test of the interface bond layer, so multiple fatigue bond tests were performed on every coverplate assembly.

The test requirements used in this study were chosen because they are more stringent than real loading in a tension flange. The primary goal of this work was to test the durability of the bond between the steel and CFRP overlay. The authors have performed numerous tensile fatigue tests of cracked steel specimens with CFRP bonded over the cracked region (Alemdar 2010), none of which experienced bond failure. To better understand bond behavior and durability, and to develop a bond layer with superior fatigue performance demands, a more demanding test setup was conceived. Additionally, it was considered that this retrofit type may be used in other applications in the future, such as on a girder web or for resisting out-of-plane fatigue loading; both are common situations in which greater interaction between shear and tension would be expected.

The steel specimens to which CFRP overlays were bonded were composed of two 25.4-mm (1.0 in.)-thick plates welded together with a 7.9-mm (5/16 in.) fillet weld. Dimensions of the steel specimen are provided in Fig. 1.

CFRP-Overlay Elements

The CFRP overlays were engineered to achieve infinite fatigue life under the loading experienced in this study. The detailed process followed for the development and fabrication of the CFRP overlays is discussed elsewhere (Kaan 2008a, b). The CFRP-overlay elements were constructed by layering 40 plies of bidirectional carbon-fiber fabric preimpregnated with cyanimide-123 resin in an aluminum mold. Each layer of carbon-fiber fabric was cut to a different length such that the final profile of the stack was curvilinear. Five plies of boron fiber were included in the stack to limit out-of-plane migration of the carbon-fiber layers during the molding process, and several layers of resin film were added to eliminate voids in the CFRP-overlay profile.

A heat press was used to produce CFRP overlays with good consolidation. Heated platens of the press applied a pressure of 18.0 bar, or 1.80 MPa (260 psi), and a temperature of 177°C (350°F) to the overlay elements within the mold for 3 to 4 h until complete cross-linking of the resin was achieved. CFRP overlays produced by this method had a curvilinear profile and curvature and thicknesses that were consistent between overlays. The typical profile of a completed CFRP-overlay element is shown in Fig. 2. As discussed, it was determined in an analytical investigation (Alemdar et al. 2009; Alemdar 2010) that stress demands on the bond layer and steel substrate were very similar for rectilinear and curvilinear overlay profiles. On this basis, it appears feasible to use a simpler, rectilinear profile in similar future applications.

An important effect of the relatively large thickness of the overlays was that it significantly increased the moment of inertia of the composite-steel cross section in the vicinity of the fatigue-critical welds, increasing the flexural stiffness of the specimen and reducing deflections. The added material provided an alternate load path that lowered the stress demand at the welds. This approach was considered to be more effective than bonding composite strips to the specimens; although the approach used herein is intended to increase the fatigue crack initiation life by reducing the stress demand on the welds, the latter works essentially by slowing crack growth after cracks form at the toe of the weld. The approach implemented in this study is conceptually different from the use of composite strips evaluated previously, because the overlays were designed to reduce the stresses in an area with a very complex stress field instead of working in direct tension.

Bonding of CFRP Overlays to Steel Specimens

Because this study investigated the effect of various configuration parameters on the fatigue performance of the bond layer, all parameters unrelated to the configuration and composition of the bond layer were kept constant. All CFRP-stiffened specimens were outfitted with composite overlays manufactured using materials and processes that were as close to identical as practically possible. The same procedure was followed each time for layup, molding, and curing, and the pre-impregnated carbon-fiber fabric materials and bonding resin were from the same respective companies throughout the research and testing program.

J. Compos. Constr. 2012.16:138-149.

Bonding of the CFRP-overlay elements to the steel specimens was accomplished using Hysol (Loctite Product 9412), a commercially available high-grade resin epoxy. The surface of the steel substrate was prepared using a standard hand grinder and degreased using a mild acid solution and isopropyl alcohol. Composite overlay surfaces were roughened using 100-grit sandpaper and were also degreased using isopropyl alcohol. The resin layer was controlled for thickness and uniformity by using spacers, such as small ball-bearings and short lengths of steel rod laid on their sides. After the resin was placed, an additional benefit of the spacers was that clamping force could be applied to the CFRP overlay without displacing the resin. The Hysol layer between the CFRP overlay and the steel substrate was cured at room temperature for a minimum of 48 h before any load was applied. Four steel specimens were outfitted with CFRP-overlay elements and subsequently identified as Specimens TRI-04, TRI-05, TRI-06, and TRI-07. Specimen TRI-06 underwent extended testing, referred to as TRI-06-2.

The parameters of the testing program were: thickness of the bond layer, length of the bond layer, and composition of the bond layer. Composition of the bond layer was varied as shown in Table 1. Based on the finite element analysis results, it was hypothesized that increasing the bond layer thickness between the steel and CFRP would decrease the stiffening effect provided by the CFRP-overlay elements, as well as decrease the frequency of overlay element debonding. This hypothesis is consistent with findings by Colombi et al. (2003a, b). Specimen TRI-05 had a bond layer thickness of 1.6 mm (1/16 in.), TRI-04 and TRI-07 had bond layer thicknesses of 3.2 mm (1/8 in.), and TRI-06 had a bond layer thickness of 6.4 mm (1/4 in.).

One of the parameters of the testing program was the use of breather cloth within the bonding resin layer. The bonding resin used had a very low initial viscosity, which made the process of creating unusually thick bond layers more difficult. Specimen TRI-05 was fabricated to have 6.4-mm (1/4 in.)-thick bond layers, a dimension significantly greater than is commonly used when bonding composites to steel. Therefore, a resin captivation material made from polyester fiber breather cloth was added to the bond layers to keep the resin in place through the mechanism of capillary action. Breather cloth can be obtained in multiple materials, including nonwoven polyester and nylon. It is an excellent material for soaking up excess resin and reducing spillage and flow during some layup processes because of its high absorptive capacity, which made it ideal for use in this investigation. The polyester breather fabric used as a resin captivation layer was approximately 2.5 mm (0.1 in.) thick when uncompressed. Addition of the breather cloth was at first solely a constructability consideration to keep the bonding resin in place while wet. However, as will be discussed, improved performance of specimens that contained the fabric in the bond layer spurred the investigators to include it in subsequent tests. Three layers of the breather fabric were used when constructing 6.4-mm (1/4 in.)-thick bond layers, and two layers were used when constructing 3.2-mm (1/8 in.)-thick bond layers.

Table 1. Fatigue Testing Program and Results for CFRP-Stiffened Specimens

Specimen	Test designation	Number of cycles to bond failure	Breather cloth	Resin pool	Resin layer thickness mm (in.)
TRI 02	C0030-01	275,000	N	N	0.8 (1/32)
TRI 02	C0030-02	900,000	N	N	0.8 (1/32)
TRI 04	C0125-01	529,800	N	N	3.2 (1/8)
TRI 04	C0125-02	255,750	N	N	3.2 (1/8)
TRI 04	C0125-03	134,150	N	N	3.2 (1/8)
TRI 04	C0125-04	71,150	N	N	3.2 (1/8)
TRI 04	C0125-05	204,500	N	N	3.2 (1/8)
TRI 04	C0125-06	1,125,300[a]	N	N	3.2 (1/8)
TRI 04	CP0125-01	1,060,950[a]	N	Y	3.2 (1/8)
TRI 04	CP0125-02	722,000[a]	N	Y	3.2 (1/8)
TRI 06	CP0065-01	279,750	N	Y	1.6 (1/16)
TRI 06	CP0065-02	283,900	N	Y	1.6 (1/16)
TRI 06	CP0065-03	239,250	N	Y	1.6 (1/16)
TRI 06	CP0065-04	956,606	N	Y	1.6 (1/16)
TRI 06	CP0065-05	398,596	N	Y	1.6 (1/16)
TRI 05	CPB0250-01	1,205,315	Y	Y	6.4 (1/4)
TRI 05	CPB0250-02	1,634,756[a]	Y	Y	6.4 (1/4)
TRI 07	CPB0125-01	1,725,900[a]	Y	Y	3.2 (1/8)
TRI 07	CPB0125-02	1,725,900[a]	Y	Y	3.2 (1/8)
TRI 07	CPB0125-03	1,564,300[a]	Y	Y	3.2 (1/8)
TRI 07	CPB0125-04	1,564,300[a]	Y	Y	3.2 (1/8)

[a]Test was stopped without observing debonding.

Another parameter of the study was the geometric configuration of the resin layer. Results from finite element analyses showed that peak tensile and shear stress demands on the resin layer occurred at the edge of the overlay. The coinciding location of the highest stress demand and the abrupt termination of the interface layer was considered to be potentially detrimental to the fatigue performance of the bond layer. An alternative configuration was evaluated in which the perimeter of the resin layer was extended beyond the perimeter of the overlays through implementation of a resin pool. The resin pool was trimmed to extend approximately 25 mm (1.0 in.) beyond the ends of the CFRP-overlay element. This configuration was conceived so that high stress demands at the end of the overlay would not coincide with the termination of the interface layer and was used in the majority of the stiffened steel specimens. Use of a resin pool began with specimen TRI-04, which had a 3.2-mm (1/8 in.)-thick bond layer. The resin pool was used for part of this test, and implementation began in earnest after its beneficial effects became evident. Therefore, the first few fatigue bond tests (debonds and rebonds) on Specimen TRI-04 were performed without a resin pool. All subsequent fatigue bond tests, including all the tests performed on the remaining specimens fitted with overlays (TRI-05, TRI-06, and TRI-07), were fabricated to include a resin pool.

Material Properties

Properties of the materials used in the composite overlays and the interface layer are summarized in Table 2. Coupon tests performed in accordance with ASTM 3039D/3039M (ASTM 2000) from single-layered specimens showed that the modulus of elasticity

Table 2. Properties of Materials Used in Composite Overlays and Interface Layer

Number of layers in coupon	Number of coupons	Average modulus of elasticity GPa (ksi)	Standard deviation GPa (ksi)
1	3	85.8 (12,400)	10.0 (1,450)
3	4	75.3 (10,900)	10.9 (1,580)
5	3	61.7 (8,900)	0.3 (42.0)
9412 Hysol Resin			
Coupon thickness mm (in.)			
6.4 (0.25)	6	2.1 (303)	0.2 (25)

J. Compos. Constr. 2012.16:138-149.

of the CFRP was approximately 83 GPa (12,000 ksi). The modulus of elasticity of the Hysol resin was 2.1 GPa (300 ksi). The yield strength (F_y) of the steel was found to be 300 MPa (43 ksi), and the tensile strength (F_u) was 490 MPa (71 ksi).

Fatigue Testing Experimental Set-up

Multiple trials on the five CFRP-stiffened steel specimens (Table 1) were conducted using a three-point bending test fixture to apply fatigue loading (Fig. 1). Cyclic fatigue loads for all specimens were applied such that the minimum load was one-tenth the maximum load ($R = P_{\min}/P_{\max} = 0.1$). The maximum load applied was 17.1 kN (3.84 kip), which corresponded to a stress range at the weld toes of the transverse welds of the control specimen of 138 MPa (20.0 ksi). Cyclic loading was applied using a sinusoidal function with a constant frequency of 1.5 or 2.0 Hz. Fig. 1 is a schematic of the three-point bending fixture used in this testing. This test setup was chosen because of the stringent demands it places on the CFRP bond (tensile and peel stresses), as opposed to a pure tensile fatigue test. Load and deflection data were monitored for each loading cycle, and were saved to a spreadsheet file every 50th cycle for the duration of each test.

Testing on all stiffened specimens progressed until a crack initiated in the steel, one of the composite overlay elements experienced a bond failure, or the total number of applied fatigue cycles reached a minimum runout threshold of 1.5 million cycles. This threshold was chosen to define runout because it corresponded to expected infinite life for a Category B detail subjected to a stress range of 138 MPa (20 ksi) (AASHTO 2007). In the event that a CFRP-overlay element debonded, testing of that specimen was stopped, the CFRP-overlay element was removed, and the weld to which the composite had been bonded was inspected for the presence of a crack using a dye penetrant. If no crack was detected, then the surfaces on both the CFRP-overlay element and the steel specimen were cleaned and prepared for rebonding. This included grinding old resin residue off of the steel substrate and bringing the steel back to a shiny, roughened surface. Similarly, all resin residue was removed from the CFRP overlay by applying a small amount of heat [150°C (300°F)] and light sanding. After the composite was rebonded, testing was resumed.

Experimental Results and Discussion

A parameter that was inferred from direct test measurements was the instantaneous stiffness, or dynamic stiffness, of the specimens. Dynamic stiffness is defined herein as the change in the applied load divided by the change in deflection of the specimen for each recorded fatigue cycle

$$K_{\text{dyn}} = \Delta P/\Delta y \tag{1}$$

where ΔP = change in applied load over one fatigue cycle, and Δy = change in deflection over one fatigue cycle. A decrease in the dynamic stiffness of the specimen served as an indication of change in specimen response to load. This change was due to the initiation and propagation of a crack in the steel or the initiation and progression of a debonding failure at either of the bonded CFRP-overlay element locations. It was not difficult to differentiate between the two stiffness reduction mechanisms. Changes in stiffness resulting from crack initiation and propagation in the steel substrate occurred over multiple hundreds of thousands of cycles, whereas changes in stiffness caused by debonding occurred in fewer than 10 thousand cycles.

Fig. 6 displays average dynamic stiffness data determined for each of the four specimens tested, as well as two control specimens. The values shown are averages of the dynamic stiffness data recorded at 50-cycle intervals during testing of the specimens. For the CFRP-stiffened specimens, these dynamic stiffness data excluded load cycles in which the CFRP overlay was undergoing debonding, and are thus representative of stiffened specimen behavior. Where the suffix "−2" is seen added to the designation of a specimen, the stiffness measurement corresponds to a series of trials with an interface layer thickness different from that used in the first set of trials conducted on the specimen. The average measured dynamic stiffness for the control specimens was 4.76 kN/mm (27.2 kip/in.). Fig. 6 shows that CFRP overlays had a significant effect on the flexural stiffness of the specimens, with treated specimens having an average stiffness between 10 and 20% higher than untreated ones. In the case of specimens without breather cloth, Fig. 6 shows that increasing the thickness of the

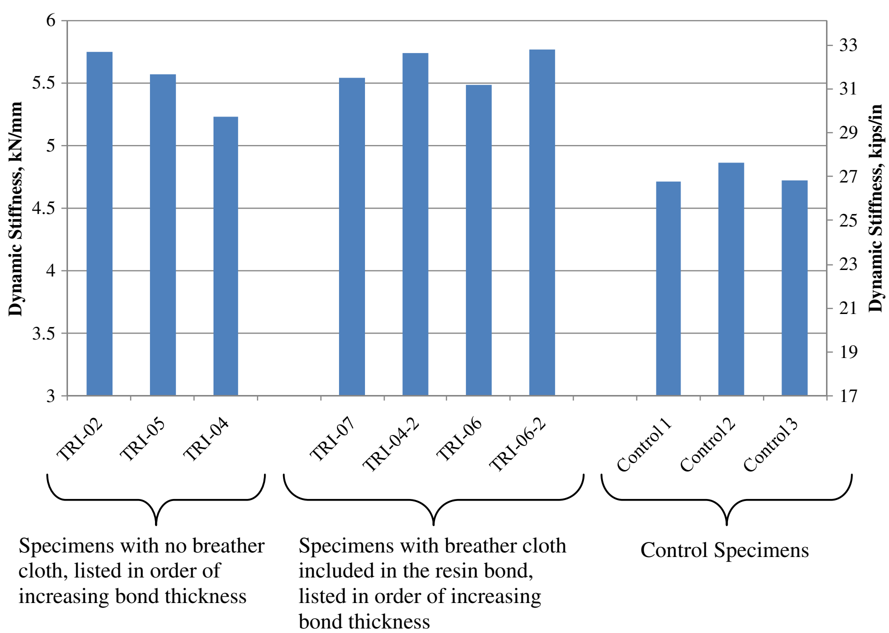

Fig. 6. Measured dynamic stiffness of specimens

resin layer has a noticeable effect on the average stiffness of the overlay, with the average dynamic stiffness varying inversely proportional to the thickness of the resin layer. For a very thin resin layer [0.8 mm (1/32 in.)], the increase in stiffness brought about by the overlays was 21%. For resin layer thicknesses of 1.6 mm (1/16 in.) and 3.2 mm (1/8 in.), the increases in dynamic stiffness were 17 and 10%, respectively. In the case of specimens with breather cloth, the trend was reversed. For resin layer thicknesses of 3.2 mm (1/8 in.) and 6.4 mm (1/4 in.), the respective increases in dynamic stiffness were 16 and 21%. The presence of resin captivation appears to have significantly increased the stiffness of the interface layer from that of the epoxy resin alone to that of a polyester fiber-reinforced polymer material (albeit one with a lower than normal fiber volume fraction). Such an increase would negate the initial hypothesis that the stiffening effect of the CFRP overlays would decrease with increasing bond thickness because the effect of the resin captivation material was not considered in the finite element analyses.

Results of fatigue testing are summarized in Table 1. Each of the four CFRP-stiffened steel specimens exhibited significantly longer fatigue lives than untreated control specimens tested in the same stress range. This effect is illustrated in Fig. 7, which shows the cumulative number of cycles on each specimen in the form of an S-N diagram with the AASHTO (2007) fatigue design curves added for reference. A control specimen tested in work reported by Vilhauer (2007) at a stress range of of 138 MPa (20.0 ksi) demonstrated a fatigue crack initiation life of 350,000 cycles. Because the specimens tested in this study experienced several bond failures, the welds were subjected to a meaningful number of cycles in an unreinforced or partially reinforced configuration. For this reason, (cp,a) the cumulative number of cycles to fatigue crack initiation observed for each specimen represents only a lower bound to the number of cycles to fatigue crack initiation if the bond is maintained throughout the entire test, and is used herein as an approximate gauge of the viability of this reinforcing technique.

Precisely determining the cumulative number of cycles at which a fatigue crack was found was a difficult task because the overlay obstructed the view of the weld. The procedure followed in this testing program to inspect the welds after debonding events or at set intervals has its limitations. For example, a fatigue crack was discovered on inspection of Specimen TRI-04 after the specimen had been subjected to 1,990,000 cycles. The same weld had previously been inspected and found to have no fatigue cracks at 1,270,000 cycles. Welds were not inspected between examinations because the CFRP-overlay element obstructed the view of the welds. There were other factors that affected the cumulative number of cycles at fatigue crack initiation shown in Fig. 7. During testing of Specimen TRI-04, it was observed that one of the CFRP-overlay elements underwent internal degradation (delamination and cracking) that led to the overlay exhibiting decreased stiffness, which could be visibly discerned. On this discovery, noted at 1,125,000 cycles, the degraded overlay was removed, and a new overlay was applied. It is hypothesized that crack initiation was influenced by the degradation of the CFRP-overlay element, but the extent of the influence could not be discerned from the data recorded. In addition, TRI-04 experienced the greatest number of debonding events of all of the CFRP-stiffened specimens, with a total of six debondments. This relatively high frequency of debonding likely coincided with TRI-04 undergoing a greater number of cycles in the unstiffened configuration than the other specimens. Given the very small size of the crack on discovery [approximately 1.6 mm (0.06 in.)], it was surmised that initiation occurred after the 1.5-million-cycle runout threshold; however, evidence to support or dispute this hypothesis was not available. Thus, the only definitive conclusion that can be made is that TRI-04 did not exhibit crack initiation until after it was subjected to 1,270,000 cycles. Although there were limitations associated with the cumulative number of cycles at fatigue crack initiation, it is indisputable that measured values were representative of a large improvement over the fatigue performance of the control specimens. Furthermore, fatigue crack initiation was not observed at all in the CFRP-stiffened specimens TRI-05, TRI-06, and TRI-07 when tested at a weld toe stress range of 138 MPa (20 ksi). This underscored the finding that although the bond was maintained between the CFRP-overlay element and the steel, the increased stiffness at the fatigue-vulnerable welded connection prevented fatigue crack initiation. In terms of the cumulative number of cycles to fatigue crack initiation, Specimens TRI-04, TRI-05, TRI-06, and TRI-07 exhibited behavior at or above the

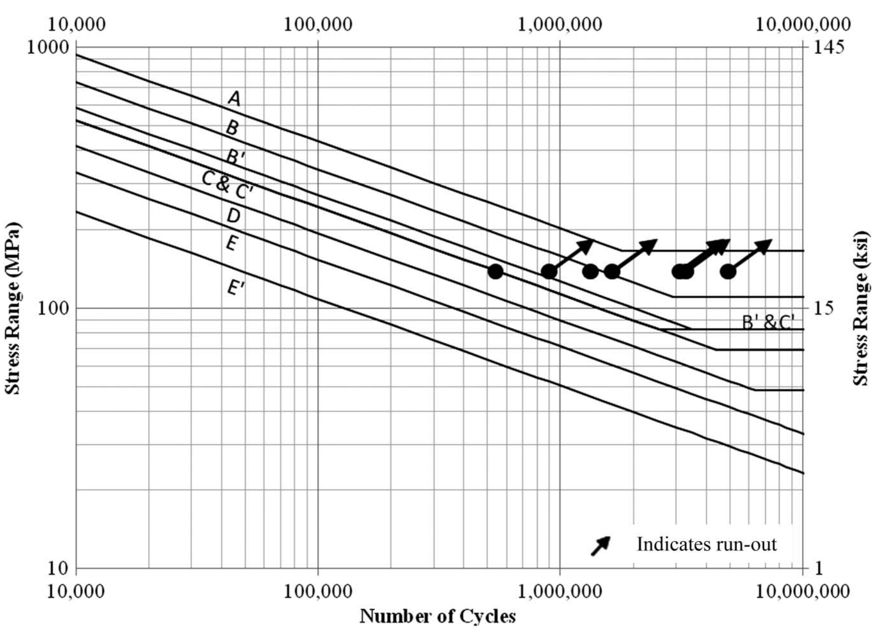

Fig. 7. S-N diagram of fatigue test results showing the cumulative number of cycles to fatigue-crack initiation for CFRP-treated specimens

J. Compos. Constr. 2012.16:138-149.

curve expected for an AASHTO Category B′ detail, and Specimens TRI-05, TRI-06, and TRI-07 exhibited behavior at or above the curve expected for an AASHTO Category B′ detail. The control specimen tested by Vilhauer (2007) exhibited behavior corresponding to AASHTO fatigue design Category D.

Effects of Bond Thickness and Composition on CFRP-Overlay Effectiveness

Results for Specimens TRI-04-2, TRI-06, TRI-06-2, and TRI-07 were especially significant, as they showed that a bond layer as thick as 6.4 mm (1/4 in.) did not reduce the effectiveness of the CFRP overlay in extending the fatigue crack initiation life of the weld, when breather fabric was incorporated into the resin bond. These results suggest that the flexibility of the bond layer, demonstrated experimentally in Fig. 6, did not have a significant effect on the stress demand at the weld toe and, consequently, was not large enough to affect the fatigue crack initiation life of the treated specimens.

The effect of the configuration of the interface resin layer on bond life is illustrated in Figs. 8 and 9. Fig. 8 shows the bond life of trials with a resin layer thickness of 3.2 mm (1/8 in.). Trials with a resin pool and breather cloth are designated CPB0125, trials with a resin pool and without breather cloth are designated CP0125, and trials with neither breather cloth nor resin pool are designated CO125. The results show that adding a resin pool resulted in a significant improvement in bond life, which confirms the hypothesis formulated on the basis of the finite element results. Although one C0125 specimen did outperform the CP0125 group by a minimal

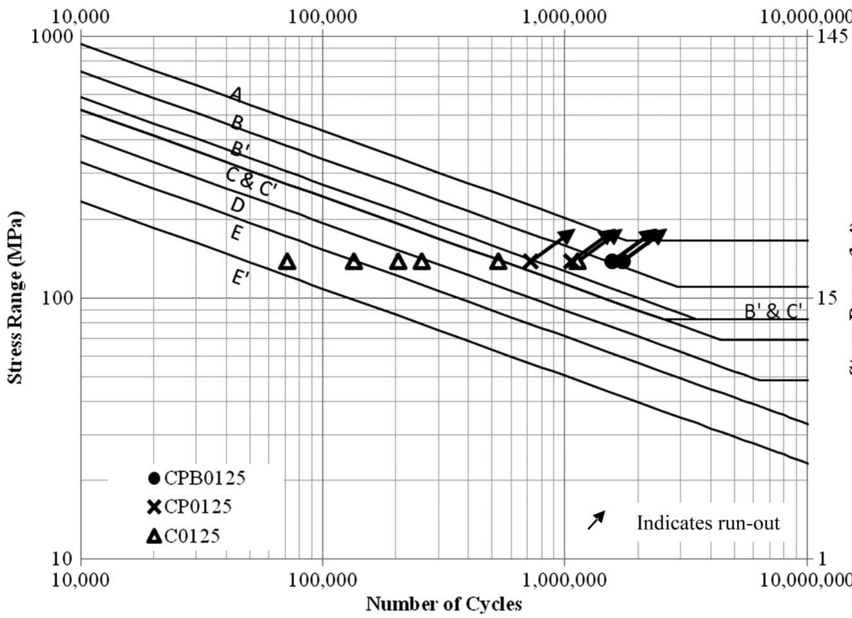

Fig. 8. S-N diagram of fatigue test results for test trials with a bond layer thickness of 3.2 mm (1/8 in.)

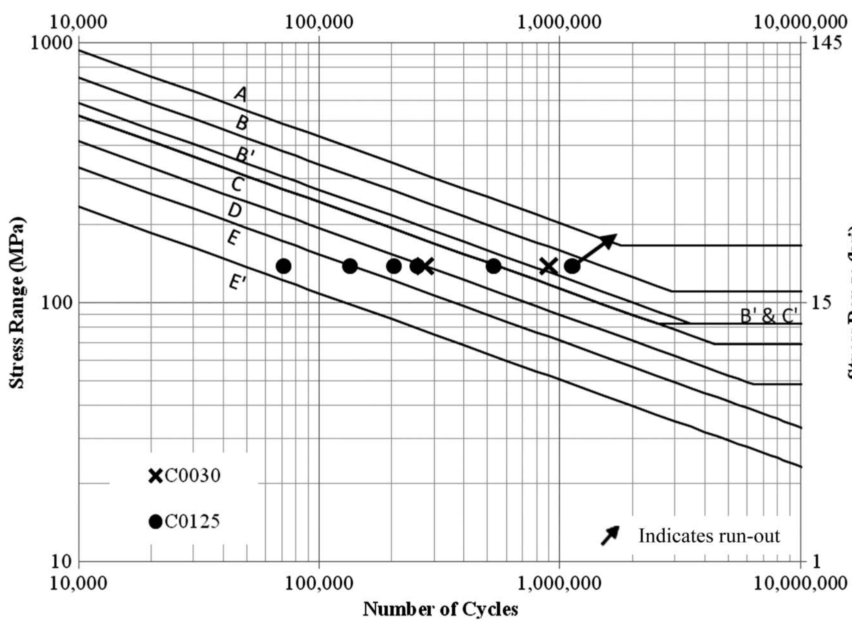

Fig. 9. S-N diagram of fatigue test results for specimens without a resin pool and without breather cloth

J. Compos. Constr. 2012.16:138-149.

amount, the average fatigue life for the C0125 specimens (386,775 cycles) was considerably less than that of the CP0125 specimens (891,475 cycles). Fig. 8 also shows that the best overall performance was obtained for trials that had both a resin pool and breather cloth.

Fig. 9 illustrates the bond life of trials with different resin layer thickness and all other configuration parameters the same (without a resin pool and without breather cloth). Trials designated C0030 had an interface layer thickness of 0.8 mm (1/32 in.), whereas trials designated C0125 had an interface layer thickness of 3.2 mm (1/8 in.). The results show a great degree of scatter with no discernible effect of layer thickness on bond life. Comparison of Figs. 8 and 9 makes clear that the presence of a resin pool and the use of breather cloth lead to a large improvement in bond life and also reduce the degree of scatter. The experimental results as a whole indicate that fabrication considerations, such as the presence of breather cloth in the resin layer or a resin pool, had a much greater effect on the bond life of the resin layer under fatigue loading than the thickness of the resin layer.

One of the most important findings of this study was the outstanding bond life of trials with breather cloth present within the resin bond tested at a nominal weld toe stress range of 138 MPa (20.0 ksi). Previous studies on the use of composites as fatigue enhancement tools have struggled to overcome the hurdle of repeated debonding events; therefore, this was an important finding.

Conclusions

Testing of steel specimens in which plate–coverplate welded connections were reinforced with CFRP-overlay elements resulted in the following conclusions:

- The bonding of CFRP-overlay elements over plate–coverplate connections increased stiffness and reduced stress demand at fatigue-vulnerable welds, improving the fatigue performance of the connections by inhibiting crack initiation.
- In specimens in which the CFRP-overlay elements debonded and were reattached, performance according to AASHTO design specifications improved from fatigue design Category E′ to Category B′ (Specimen TRI-04) and Category B (Specimens TRI-05 and TRI-06).
- The increase in fatigue crack initiation life brought about by the use of CFRP overlays was contingent on maintaining the bond between the composite overlays and the steel and on maintaining the internal integrity of the composite overlays.
- Addition of polyester fibers for the purpose of resin captivation within the interface layer led to large increases in life of the bond between the CFRP overlays and the steel, exceeding the infinite fatigue threshold of the AASHTO fatigue design curves for the stress range evaluated in the study.
- Extending the resin layer beyond the edge of the overlay by forming a resin pool led to significant improvements in bond life.

Based on observations of the tests and finite element analyses performed, it is recommended that a fibrous resin captivation layer and an extended interface layer be used during implementation of this repair technique for maintaining an adequate bond under cyclic loading. The experimental results also showed that an interface resin layer with a thickness of 6.4 mm (1/4 in.) and a resin captivation layer composed of polyester breather cloth provided the best balance of stiffness and bond tenacity for the CFRP-overlay elements studied. Results showed that use of CFRP materials to improve the fatigue performance of existing structures is a promising and viable technology.

The research reported herein was aimed at investigating factors that determine durability of the bond between CFRP and steel under a demanding fatigue test setup, as satisfactory bond performance has historically been a major hurdle to successfully using CFRP as a fatigue retrofit in steel structures. The findings and recommendations of this study are a contribution aimed at overcoming that important hurdle. Although this study was not aimed at capturing field conditions, it has removed obstacles to achieving that end. Therefore, one important aspect of future research is a thorough examination of practical matters associated with field application practices and optimizing the CFRP-overlay configuration for field implementation. Research should be performed to investigate the applicability of CFRP composite materials for fatigue enhancement of a broader range of geometries, which may guide researchers to consider the practical benefits of very thick bond layers to accommodate dimensional tolerances and different material application systems, including spray techniques. Further investigation of the effect of the fibrous resin captivation layer on the bond strength of resin epoxy, as well as effects of extending the resin pool, should also be performed.

Acknowledgments

The authors are grateful for support from the Kansas Department of Transportation (KDOT) and the University of Kansas Transportation Research Institute (KU TRI). The authors also acknowledge support provided through Pooled Fund Study TPF-5(189), which includes the participating state DOTs of Kansas, California, Iowa, Illinois, Louisiana, New Jersey, New York, Oregon, Pennsylvania, Tennessee, Washington, Wisconsin, and Wyoming, as well as the Federal Highway Administration. The authors are also grateful to Builders Steel from Kansas City, Missouri, as they contributed to this study by donating materials and fabrication assistance.

References

AASHTO. (2007). *LRFD Bridge Design Specifications*, 4th Ed., Washington, DC.

Albrecht, P., and Lenwari, A. (2007). "Fatigue-proofing cover plates." *J. Bridge Eng.*, 12(3), 275–283.

Alemdar, F., Kaan, B., Bennett, C., Matamoros, A., Barrett-Gonzalez, R., and Rolfe, S. (2009). "Parameters affecting behavior of CFRP overlay elements as retrofit measure for fatigue vulnerable steel bridge girders." *Proceedings of Second International Conference on Fatigue and Fracture in the Infrastructure*, Philadelphia, July 26–29, 2009.

Alemdar, F. (2010). "Use of composite materials to repair steel structures vulnerable to fatigue damage." Thesis, presented to the Univ. of Kansas, Lawrence, in partial fulfillment of the requirements of an M.S. in Civil Engineering.

ASTM. (2000). "Standard test method for tensile properties of polymer matrix composite materials." *3039D/3039M*, ASTM, West Conshohocken, PA.

Bassetti, A.,Nussbaumer, A., and Colombi, P. (2000a). "Repair of riveted bridge members damaged by fatigue using CFRP materials." *Proc. Advanced FRP Materials for Civil Structures*, Bologna, Italy, ICOM, Lausaunne, Switzerland, 33–42.

Bassetti, A., Nussbaumer, A., and Hirt, A. (2000b). "Crack repair and fatigue life extension of riveted bridge members using composite materials." *Proc. of Bridge Engineering Conference (IABSE)*, Egyptian Society of Engineers, Sharm El-Sheikh, Egypt, vol. 1, Egyptian Society of Engineers, 227–238.

Bassetti, A., Nussbaumer, A., and Hirt, A. (2000c). "Fatigue Life Extension of Riveted Bridge Members using Prestressed Carbon Fibre Composites." *Proc. Steel Structures of the 2000s (ECCS), Istanbul, Turkey*, Turkish Construction Steelwork Association/European Convention for Construction Steelwork, 375–380.

Buyukozturk, O., Gunes, O., and Karaca, E. (2004). "Progress in understanding debonding problems in reinforced concrete and steel members strengthened using frp composites." *Int. J. Construct. Build. Mater.*, 18(1), 9–19.

Colombi, P., Bassetti, A., and Nussbaumer, A. (2003a). "Analysis of cracked steel members reinforced by pre-stressed composite patch." *Fatigue Fract. Eng. Mater. Struct.*, 26(1), 59–66.

Colombi, P., Bassetti, A., and Nussbaumer, A. (2003b). "Crack growth induced delamination on steel members reinforced by prestressed composite patch." *Fatigue Fract. Eng. Mater. Struct.*, 26(5), 429–437.

Deng, J., and Lee, M. (2007). "Behavior under static loading of metallic beams reinforced with bonded CFRP plate." *Compos. Struct.*, 78(2), 232–242.

Hertzberg, R. W. (1996). *Deformation and Fracture Mechanics of Engineering Materials*, 4th Ed., Wiley, New York.

Jones, S., and Civjan, S. (2003). "Application of fiber reinforced polymer overlays to extend steel fatigue life." *J. Compos. Constr.*, 7(4), 331–338.

Kaan, B. (2008). "Fatigue enhancement of Category E' details in steel bridge girders using CFRP materials." Thesis, presented to the Univ. of KS at Lawrence, KS in partial fulfillment of the requirements of the M.S. in Civil Engineering.

Kaan, B., Barrett, R., Bennett, C., Matamoros, A., and Rolfe, S. (2008). "Fatigue enhancement of welded coverplates using carbon-fiber composites." *Proc. of the ASCE / SEI Structures Congress, Vancouver, BC,* ASCE, New York, 24–26.

Meier, U. (1992). "Carbon fibre-reinforced polymers: Modern materials in bridge engineering." *Struct. Eng. Int.*, 2(1), 7–12.

Nakamura, H., Jiang, W., Maeda, K., and Irube, T. (2009). "Experimental study on repair of fatigue cracks at welded web gusset joint using CFRP strips." *Thin-Walled Struct.*, 47(10), 1059–1068.

Nozaka, K., Shield, C., Hajjar, J. (2005a). "Design of a test specimen to assess the effective bond length of carbon fiber-reinforced polymer strips bonded to fatigued steel bridge girders." *J. Compos. Constr.*, 9(4), 304–312.

Nozaka, K., Shield, C., Hajjar, J. (2005b). "Effective bond length of carbon-fiber-reinforced polymer strips bonded to fatigued steel bridge I-girders. *J. Bridge Eng.*, 10(2), 195–205.

Sabelkin, V., Mall, S., and Avram, J. B. (2006) "Fatigue crack growth analysis of stiffened cracked panel repaired with bonded composite patch." *Eng. Fract. Mech.*, 73(11), 1553–1567.

Sebastian, W., and Luke, S. (2007). "Interface failure mechanics of elastically (advanced composite) reinforced steel members." *J. Struct. Eng.*, 133(5), 683–694.

Simulia (2011). ABAQUS FEA Version 6.8.2. Providence, RI. ⟨http://www.simulia.com⟩.

Tavakkolizadeh, M., and Saadatmanesh, H. (2003). "Fatigue strength of steel girders strengthened with carbon fiber reinforced polymer patch." *J. Struct. Eng.*, 129(2), 186–196.

Vilhauer, B. (2007). "Fatigue Behavior of Welded Connections Enhanced by UIT and Bolting." Thesis, presented to the Univ. of Kansas, Lawrence, in partial fulfillment of the requirements of the M.S. in Civil Engineering.

J. Compos. Constr. 2012.16:138-149.