BOND BEHAVIOR OF CFRP STRENGTHENED STEEL STRUCTURES

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ABSTRACT

Recent research has focused on rehabilitation and strengthening of steel structures and bridges using fiber reinforced polymer (FRP) materials. The bond behavior of FRP materials to steel structures is quite different from that of concrete structures. Preliminary test results showed the occurrence of very high bond stresses for most strengthening applications due to the amount of strengthening required for steel structures and bridges. In this paper, surface preparation methods and means of preventing galvanic corrosion are discussed. The results of an experimental program for selection of suitable adhesives through determination of the development length is discussed as well as preliminary testing showing the importance of proper detailing of the ends of the FRP strips. The shear stress distribution determined in the experimental program is compared to analytical models using a stress-based approach. The remainder of the paper focuses on the current methods for determining bond stresses and their use for the design of FRP strengthening system for steel structures.

KEYWORDS

High modulus CFRP, steel bridge, strengthening, rehabilitation, bond stresses

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1.0 INTRODUCTION

Innovative methods are required for the strengthening and rehabilitation of steel structures that are deficient due to the demand to increase the specified load and/or deterioration as a result of corrosion. A considerable body of research has established the successful use of carbon fiber reinforced polymer (CFRP) materials for strengthening concrete structures. With the introduction of new high modulus CFRP materials, the possibility for providing a solution to the ongoing problem of infrastructure deterioration may be extended to steel structures as well. Bond stresses may be much more critical for steel structures than for concrete structures since more strengthening material is needed for steel structures to achieve a similar increase in strength due to the inherent high strength of steel and also since the debonding failure does not occur in the substrate as in concrete structures. Further complications may arise due to the potential for galvanic corrosion between the carbon and steel materials. Despite these challenges, since many structures built in the post-World War II era are already past their design life, the inventory of deteriorated steel structures and bridges in need of rehabilitation are extremely significant (Tang and Hooks, 2001). The aim of this paper is to examine the proper techniques for the bond of CFRP to steel structures and compare the results of the experimental program to analytical methods of determining bond stresses. The determination of these bond stresses is necessary for the design of the CFRP strengthening for steel structures.

2.0 BONDING OF HIGH MODULUS CFRP STRIPS TO STEEL STRUCTURES

Proper installation of high modulus CFRP strips is essential in ensuring both the long-term performance of the system and that the behavior of the system matches the intentions of the designer. A certain level of care and expertise is required to ensure that these goals are met. Research into the nature of bonding between FRP materials and metallic structures was first investigated by the aerospace and naval industries. Later adoption of the technique for civil engineering applications has typically used CFRP instead of GFRP due to the more reasonable necessary thickness of the applied strengthening material. The axial stiffness required for strengthening steel structures is much higher than for concrete or masonry structures that have limited tensile strength, justifying the use of much higher modulus strengthening materials.

2.1 Surface Preparation

Bonded joints are often the most effective way to join two different adherends, since the resulting stress concentrations at the joint are much lower than for bolted connections. Furthermore, the anisotropic nature of most CFRP materials would preclude bolting as a connection method. To ensure full utilization of the applied CFRP material, surface preparation of the steel must be undertaken to enhance the formation of chemical bonds between the adherend and the adhesive. This requires a chemically active surface that is free from contaminants. Most surface treatment involves cleaning, followed by removal of weak layers and then re-cleaning (Mays and Hutchinson, 1992). Degreasing is a necessary first step in preparing most metals to remove, oils and other potential contaminates. Brushing, ultrasonic or vapor degreasing systems are claimed to be most efficient in removing this surface contamination, especially when sufficient amounts of solvent are used (Hashim, 1999). Contamination may then be removed with the excess solvent, rather than simply redeposited on the surface as the solvent evaporates.

The most effective means of achieving a high-energy steel surface is by grit blasting (Sykes, 1982, Hutchinson, 1987, and Hollaway and Cadei, 2002). Parker (1994) found that for composite joints, those that were grit blasted had higher peel strengths than those that were hand abraded. Grits are found to have a clean cutting action that can expose a clean surface, unlike wire brushing. Grit blasting procedures using angular grit, removes the inactive oxide and hydroxide layers by cutting and deformation of the base material. The size of the grit will also affect the surface profile of the steel. Harris and Beevers (1999) confirmed that finer grit particles produced smoother surfaces than coarser particles in an investigation using three-dimensional profilometry measurements. For two of the three grits studied, smoother surfaces exhibited higher surface energy readings as determined from static contact angle measurements. However, the initial joint strengths were independent of the coarseness of the grit. Furthermore, the long-term durability was not affected by the surface profile.

Following grit blasting, the surface may be contaminated with fine abrasive dust. It has is generally been agreed that abrasive dust should be removed prior to bonding. Hollaway and Cadei (2002) state that the dust should be removed by dry wipe, or by a vacuum head with brushes and that solvent cleaning should be avoided. This is due to the assumption that solvent wiping only partially removes the dust, and redistributes the remaining dust on the entire surface. However, several different studies have shown that solvents may be used to clean the surface after grit blasting without resulting in poor bond performance (El Damatty et al. 2003, Photiou et al., 2004). If solvents are used, it may be beneficial that they be applied in excess so that any debris removed by the solvent is removed from the surface and is not redeposited after the solvent evaporates.

2.2 Durability of CFRP-Steel Bonded Joints

FRP materials typically have excellent resistance to corrosion and chemical attacks, resulting in the expectation of a long life of the repair with little or no maintenance required. However, the adhesive and steel may be affected by long term exposure to moisture, especially in conjunction with salts resulting from deicing of roadways or from ocean spray. The effects of moisture or temperature that is acting in conjunction with an applied stress, may influence the behavior of the joint due to stiffness change of the resin resulting from the exposure (Karbhari and Shulley, 1995). In general, adhesive joints subjected to high humidity, saturation with water or extreme temperatures, will result in a reduction of the joint strength. Despite the change in the mechanical properties of the adhesive, the primary mechanism for strength reduction in bonded steel joints in wet environments is the influence of interfacial attack in displacing the adhesive from the adherend (Hutchinson, 1987 and Hashim, 1999). Moisture diffusing through the adhesive layer is energetically attracted to high-energy substrate surfaces, resulting in adsorption of water molecules, thereby displacing secondary bonds between the adhesive and substrate. Compounding this effect is that moisture ingress occurs at the edges of a joint, where the bond stresses may be the highest.

Adhesion promoters, such as silanes, have been shown to increase the durability of steel-epoxy bonds without affecting the initial bond strength (McKnight et al., 1994). Similar findings have been reported for grit blasted aluminum surfaces (Allan et al., 1988). For aluminum naval structures, silane incorporated into the adhesives themselves was shown to be less effective than providing a separate silane layer. Silane adhesion promoters are also noted to greatly reduce the variability of bond performance, while protecting the freshly prepared surface from damage, exposure to environmental conditions and contamination prior to bonding the FRP material. Gettings and Kinloch (1977) found that durability was improved only when there was evidence of primary bonding between the polysiloxane primer and the steel surface. Due to the promising results associated with the use of silanes, they have been used in field applications such as the strengthening of bridge 1-704 that carries southbound traffic on Interstate 95 in Delaware (Miller et al., 2001).

Prevention of galvanic corrosion is necessary for the long-term durability of any CFRP strengthening applied to a metallic structure. In general, the requirements for galvanic corrosion are that the two metals must be in direct electrical contact, the metals must have sufficient potential difference, they must be bridged by an electrolytic solution and a cathodic reaction must be sustained on the noble metal (Francis, 2000). This electrolytic solution may be generated by the presence of water with a salt, fertilizer, acid or a combustion product. If all of these conditions are met, current will flow through the electrolyte from the anodic metal to the cathodic metal. The cathodic metal is then protected from corrosion, but the anodic metal may suffer even greater corrosion. The reactions that occur due to galvanic corrosion, are similar to those that would occur on a single metal, however the rate of attack is increased for the anode. Carbon is a very noble cathodic material that can drive the corrosion of many different metals galvanically coupled to it. Steel and aluminum have similar positions in the galvanic series, and behave anodically relative to the carbon. The composite itself may be degraded by the galvanic process (Miriyala et al., 1992). In this study, the polymer material was found to be degraded on the cathodic surface, although it was not known whether this was due to direct involvement in the cathodic reaction or due to chemical attack of the polymer by some product of the cathodic reaction.

2.3 Prevention of Galvanic Corrosion

Considerable research has been focused on the prevention of galvanic corrosion. In general, to prevent against galvanic corrosion the flow of corrosion currents must be prevented. This may be achieved by insulating the dissimilar metals from one another or by preventing a continuous bridge of electrolytic solution between the two by coating with a water resistant sealant (Evans and Rance, 1958). If the two metals are not in contact, galvanic corrosion cannot occur. Brown (1974) studied the corrosion of different aircraft metals connected to CFRP by adhesive bonding or bolting. For the specimens connected by adhesive bonding there was no accelerated corrosion attack. This behavior was claimed to be due to the insulating behavior of most structural adhesives in not allowing electrical contact between the two materials. Tavakkolizadeh and Saadatmanesh (2001) completed an experimental study to determine the CFRP/steel corrosion rate when subjected to seawater and deicing salt solutions. The effect of different epoxy thicknesses and the removal of fiber sizing agents with different solvents were also examined. The effect of a thin coating of epoxy (0.25 mm) was found to be significant as was the sizing applied to the fibers. In general, thicker epoxy films between the steel and CFRP surfaces were shown to significantly slow the corrosion rate of the steel.

To reduce the possibility of galvanic corrosion, a non-conductive layer, such as an epoxy film or GFRP sheet, can be used to isolate the carbon fiber from the steel. In the current study, it was found that a uniform, 1 mm adhesive thickness could be achieved between the steel surface and the CFRP strip by mixing a small amount of glass beads into the adhesive prior to application (Dawood, 2005). West (2001) concluded that either an adhesive layer or a GFRP layer effectively isolated the two components and protected against galvanic corrosion. Although accelerated tests have been developed to determine the performance of lab scale specimens, there is little correlation between these tests and typical environmental exposure. This is an area were further research needs to be directed.

A water resistant sealant on the surface can be used to prevent ingress of any electrolytic solution, and preventing one of the necessary conditions for galvanic corrosion to occur. Brown and De Luccia (1977) noted that, for aluminum to carbon fiber samples, the use of a water resistant sealant or the use of a GFRP barrier performed equally in a corrosive salt-spray environment, but that a combination of a nonconductive barrier plus a sealant was the most promising approach to control corrosion. This was similar to the technique that was later used by Allen et al. (1982) for protecting aluminum aircraft structures strengthened with CFRP material. A moisture barrier of aluminum foil was bonded over the strengthened area and extended past this area on all sides. The aluminum patch in turn, was protected by a chopped glass strand mat finished with additional epoxy resin. This ensured that the strengthened region would remain free from moisture.

Considerable attention has been focused on the use of a GFRP insulation layer, rather than relying on the insulating properties of the adhesive on its own. However, the introduction of GFRP material may be less durable than the adhesive. There are two possible reasons for this. First, moisture intake may be accelerated due to water traveling more quickly along the glass fiber-resin interface than through the bulk adhesive itself (Choqueuse et al. 1997). The second reason is that salts can leach out of the glass fibers themselves. This causes a concentration gradient that can draw more water into the interface or into voids within the joint. The pressure generated by this process can cause the voids to blister, resulting in damage to the surrounding material (Frieze and Barnes, 1996). Tucker and Brown (1989) have found that glass fibers placed within a carbon fiber composite result in the blistering of the composite by creating conditions favorable for the development of a strong osmotic pressure within the composite. Clearly, water being drawn within the bond line by osmotic pressure is not favorable for maintaining a durable bond. Other materials may be more suitable for this purpose. Hollaway and Cadei (2002) reported that a polyester drape veil was installed to provide insulation between the carbon fiber and the cast iron to prevent direct contact between the CFRP and the steel, although no durability information was given for this combination of materials. Finally, although fiber-glass or epoxy films can be used to provide effective insulation, Sloan and Talbot (1992) note that few materials retain their insulating properties for more than a few years due to wear, chemical breakdown or electrolyte absorption. A monitoring program could also be initiated to identify cathodic sites so that galvanic corrosion damage could be stopped or mitigated.

2.4 CFRP Detailing

For ease of shipping and handling CFRP strips are typically manufactured in finite lengths that are suitable for strengthening most typical short span girders. To facilitate the implementation of the strengthening system to longer span girders, it is necessary to develop an effective technique to splice adjacent lengths of the CFRP materials. The use of a bonded splice cover plate is a promising technique to ensure continuous transfer of forces across splice joints. However, the use of this technique requires a careful consideration of localized bond stress concentrations that may occur at or near splice locations. Other researchers have demonstrated that careful detailing of the ends of a CFRP strip can significantly reduce the bond stress concentrations that typically occur at or near the strip ends. Tapering of the CFRP strips at their edge avoids imposing a local stress concentration at the boundary of the joint. For lapped joints it was recommended that peel stresses should be designed out of the joint by tapering the ends of the overlap (Hart-Smith, 1980). In the case of joints made to FRP adherends, it was also noted that this would also reduce the possibility of an interlaminar failure within the FRP. Allan et al. (1988) recommended finishing steel to CFRP joints with a 10:1 taper (5.7 degrees) at their ends to reduce stress concentrations.

An alternate method of reducing the stress concentration at the end of the joint is to locally increase the adhesive thickness. Wright et al. (2000) found that increasing the thickness of the bond line resulted in a reduction in the stiffness of the adhesive layer, reducing the stress concentration at the ends of the joint and thereby increasing its overall strength. Slight edge preparation of the steel was shown to further reduce the stress concentration. Earlier work had shown that increasing the adhesive thickness was more effective than tapering the adherend (Price and Moulds, 1991).

It may be possible to combine the effects previously discussed to further reduce the stress concentration by producing a reverse-tapered joint. For this type of joint the adherend is tapered, while the adhesive thickness is also increased as a result of the taper. Price and Moulds (1991) found this type of joint to be superior for loads that are applied statically or cyclically. For steel plates bonded to aluminum the use of a reverse-taper improved the fatigue life by about a factor of four Allan et al. (1988). For repairs consisting of multiple plys of a thinner CFRP material, like sheets, the interlaminar shear and peel stresses can be reduced by reverse tapering of subsequent plys of material. This was accomplished by increasing the length of each ply so that the shortest layer is on the inside and progressively longer layers are towards the inside (Ong and Shen, 1992). Analytical modeling of single lap joints has also shown that reverse tapering is a highly efficient technique in reducing the stress peaks in both the adherend and in the adhesive, thereby improving joint strength (Hildebrand, 1994). More recently, finite element analysis has demonstrated that the use of a reverse taper and a spew fillet can significantly reduce the peak shear and peeling stresses which occur near the end of a bonded joint, with the majority of the advantage being achieved for taper and filet angles of 45^{o} (Belingardi et al., 2002). While the effectiveness of implementing a reverse taper has been established analytically, there are relatively few experimental studies that investigate the suitability of this type of detailing reported in the literature. Typically, in civil engineering applications, thick and stiff composite plates are used for strengthening as compared to the relatively thin and flexible composite materials used in aerospace applications. Consequently, the bond stresses can be more critical and proper detailing of the joint ends is essential.

3.0 EXPERIMENTAL PROGRAM

3.1 Introduction

There have been only limited published studies on the bond length of CFRP strips applied to steel flexural members. Nozaka et al. studied the bond behavior of cracked steel girders (2005). For the strips and adhesives studied, the failure was always by debonding. It was noted that the shear ductility at failure seemed to be the most important parameter in insuring a high CFRP strain at failure, since the adhesive would rapidly yield as the CFRP strip was loaded. This results in the CFRP strip having a high strain at failure since the ductility of the adhesive reduces the stress concentration at the end of the strip that can result in premature debonding. Debonding from the ends of the CFRP strip will occur if the adhesive stresses at the end of the strip are exceeded or if these stresses exceed the bond strength to the CFRP or steel. The development length found for the adhesives studied was found to be less than 203 mm. In another study, a total of seven steel beams were strengthened with standard modulus CFRP strips (Lenwari et al., 2006). The beams that were strengthened with the shorter CFRP strips failed due to debonding of the CFRP while the beams strengthened with 1200 mm long strips failed by rupture of the CFRP. The study indicated that the critical stress intensity factor near the end of the strengthening plate can be used to calculate the debonding strength of the strengthened member based on a fracture mechanics approach.

Only a limited number of studies have been reported that investigate the suitability of splicing FRP strips for civil infrastructure applications. Stallings and Porter (2003) recommend that splices should be located such that the maximum strain at the end of the splice on the main CFRP strip does not exceed a limiting value. Yang and Nanni (2002) recommend a minimum splice length to ensure rupture of CFRP strips, but used relatively thin strips in their study. Neither of the reported studies indicates that the CFRP splices were detailed in any way to reduce bond stress concentrations at the CFRP ends.

In the present study, the bond behavior of uncracked steel flexural members, typical of most steel structures, strengthened with high modulus CFRP strips was examined. These strips had a tensile elastic modulus of 338 GPa and an ultimate elongation of 3.32 millistrain, with an essentially linear stress-strain behavior until rupture. Additional specimens were tested to determine the performance of typical splice connections, considering the effect of different joint details.

3.2 Flexural Test Specimens for Bond

A flexural type of test specimen was used to study the bond performance for the adhesive bonding of high modulus CFRP strips. This type of specimen was used due to the expectation that the CFRP strips would generate significant normal, or peel stresses, and have similarly proportioned shear and normal stresses to the larger structures they represent. The test specimens consisted of a wide flange steel member, typically designated SLB 100 x 4.8. This designation represents the nominal depth in millimeters and the mass in kilograms per meter. An additional grade A36 steel plate was stitch welded to the compression flange to simulate the strain profile of a bridge girder that acts compositely with a concrete deck. Welding was completed using E70 grade weld material and 4.8 mm fillets on either side of the steel plate.

Strengthening of each specimen was completed by bonding the high modulus CFRP strip to the bottom of the tension flange. Each of the strips was cut to a width of 36 mm and the thickness of each strip was 1.45 mm. Surface preparation of the steel was completed by sandblasting, followed by cleaning with liberal amounts of acetone to remove any dust. Since the CFRP strips used did not have a peel ply, the strips were lightly sanded and wiped with methanol prior to bonding. The length of the bonded CFRP strip used was varied from 50-200 mm. Figure 1 shows the specimen dimensions.

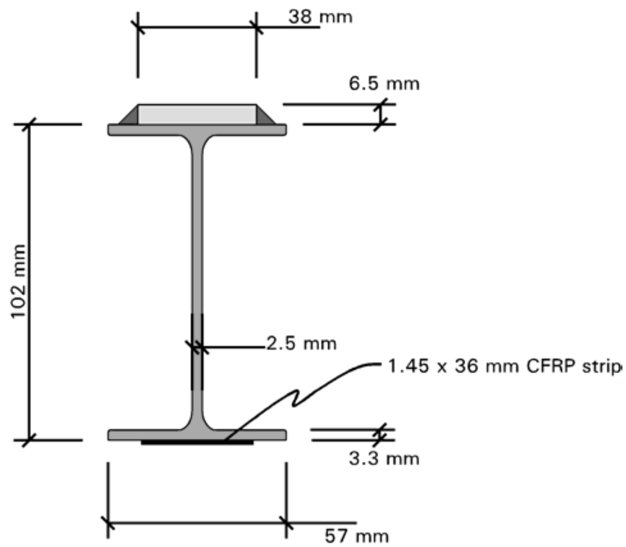

Figure 1 Cross-section dimensions of typical flexural test specimen for bond

Material properties for the adhesives used were typically not available from the manufacturers. The properties for the SP Spabond adhesive were determined in accordance with the ASTM D638-03 standard test method. The behavior of the adhesive in tension was approximately linear until failure with a tensile strength of 37.1 MPa, initial tensile modulus of 3007 MPa and a Poisson's ration of 0.38. More details of the material properties for the adhesive as well as material properties for the steel beam and steel cover plate are listed in Schnerch (2006).

A four-point bending test was used to load the beams, as shown in Figure 2, with the development length defined as the distance from one of the load points to the end of the CFRP strip, in a region of constant shear force and decreasing bending moment towards the end of the strip. Lateral bracing of the top flange was provided at the supports. Load was applied at a constant displacement rate of 0.75 mm/minute. In addition to measurement of the deflection using linear voltage displacement transducers, longitudinal strain was measured using electrical resistance strain gauges, with a 6 mm gauge length, bonded to the inside of the compression flange, inside the tension flange and on the CFRP strip. Strain gauges were positioned at midspan, at the load points, and every 25.4 mm from the load point to 6.4 mm from the end of the CFRP strip.

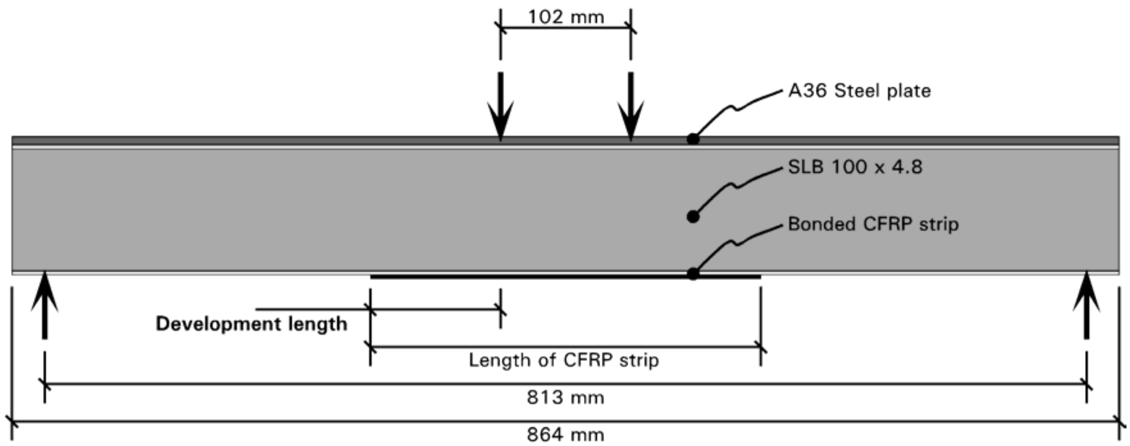

Figure 2 Loading configuration of typical flexural test specimen for bond

3.3 Tension Test Specimens for Spliced Connection

Three double-lap type shear coupons were fabricated and tested to investigate the bond behavior between CFRP strips. These specimens were tested to simulate the behavior of bonded cover-plate splice joints. Three different configurations of bonded joints were considered as shown schematically in Figure 3. The typical test specimen consisted of two 8 mm thick main plates that were fabricated by bonding together two 4 mm thick CFRP strips. The main plates were connected by two 4 mm thick splice plates as shown in Figure 3. Joint configuration A was fabricated with all strip ends square with no spew fillets. Joint configurations B and C incorporated reverse tapers and spew fillets, with angles of approximately 20 degrees, to help reduce the localized stress concentrations at various locations on the test specimens as shown. The width of the test coupons was 35 mm. The splice plates had an overlap length of 200 mm on either side of the joint and a 2 mm gap was maintained between the main plates at the splice location that was subsequently filled with adhesive. All of the coupons were instrumented with electrical resistance strain gauges, at the locations shown in Figure 3(a), to measure the distribution of the stresses in the splice plates throughout the bonded joint. An additional two strain gauges were installed away from the splice location to measure the strain in the main plate. The coupons were loaded in axial tension with a constant displacement rate of 0.5 mm/min. The CFRP strips used in this study had a modulus of elasticity of 460 GPa and the

SP Spabond 345 adhesive was used to bond the joints. A uniform adhesive thickness of approximately 1 mm was maintained by mixing a small amount of glass spacer beads into the adhesive prior to fabrication of the joints.

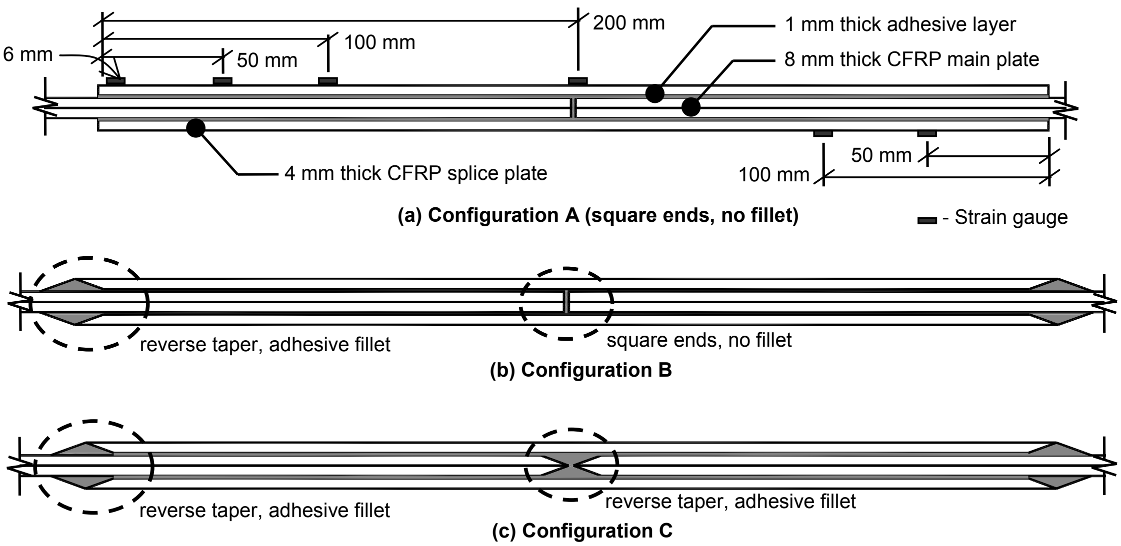

Figure 3 Detail of splice joint configurations for tension test specimens (side view)

4.0 Results of Flexural Test Specimens for Bond

Flexural specimens were loaded until a steel tension flange strain of 8 millistrain was reached. Prior to this level of strain being reached, the CFRP strip either ruptured, near its ultimate elongation for beams where sufficient development length was provided, or debonded from the steel for beams with insufficient development length. In determining the most suitable adhesives for bonding the CFRP strips to steel, the CFRP strip strain at failure in conjunction with observation of the failure mode provided the best indication of which adhesives were able to fully utilize the CFRP material at the shortest development lengths. Table 1 summarizes the results of the adhesive selection phase in order from the adhesive with the shortest development length to the adhesive with the longest. Typically, high CFRP strain at failure and rupture of the CFRP indicate complete utilization of CFRP materials.

Two adhesives, Weld-On SS620 and SP Spabond 345, were found to have the shortest development lengths of 76-102 mm. The remaining adhesives had development lengths as follows: the Vantico

Araldite 2015 and Jeffco 121 adhesives had a development length of 102-127 mm, Fyfe Tyfo MB had a development length of 152 mm and Sika Sikadur 30 had a development length of more than 203 mm. In all cases, debonding progressed extremely rapidly starting from one end of the CFRP strip to the other side of the strip. The failure surface typically was mixed with some adhesive remaining adhered to the steel and some adhesive adhered to the CFRP strip.

Table 1 CFRP strip strain at rupture/debonding for tested adhesives and development lengths

Adhesive	Development Length					
	203.2 mm	152.4 mm	127 mm	101.6 mm	76.2 mm	50.8 mm
Weld-On SS620	3.077 rupture	2.964 rupture	-	3.161 rupture	2.903 rupture	2.589 debond
SP Spabond 345	2.878 rupture	2.943 rupture	-	3.111 rupture	2.433 debond	1.833 debond
Vantico Araldite 2015	3.094 rupture	2.980 rupture	-	2.820 rupture	2.772 debond	-
Jeffco 121	2.981 rupture	3.276 rupture	2.662 rupture	2.438 debond	-	-
Fyfe Tyfo MB2	3.470 rupture	3.060 debond	-	2.096 debond	-	-
Sika Sikadur 30	2.814 debond	-	-	-	-	-

* underlined values are the average of two test results

Six of the specimens tested were instrumented with strain gauges positioned along the development length of the bonded CFRP strip on one side of the beam. These strain measurements were recorded at discrete locations. The difference in tensile strain between two gauge locations must be balanced by the shear force acting between the CFRP strip and the steel substrate, as noted by Garden et al. (1998). The average shear stress could then determined between the two gauge locations as,

$$\tau_{av} = E_{frp}\, t_{frp} \frac{\varepsilon_2 - \varepsilon_1}{x_2 - x_1} \quad (1)$$

where ε_2 - ε_1 is the difference in strain between two adjacent gauges and $x_2 - x_1$ is the distance between the gauges. The longitudinal strain at the tip of the CFRP sheet was taken to be zero in order to calculate the shear stress between the end of the strip and the location of the first strain gauge. As shown in Table 2, the specimen using the SP Spabond 345 adhesive had the highest shear stresses of the tests with one ply of CFRP strips. It is possible that some of the other adhesives could have developed higher shear stresses, had the CFRP strips not ruptured first.

Table 2 Maximum shear stress (MPa) and failure mode for beams strengthened by adhesive bonding of CFRP strips using different development lengths

Resin	plys	Development Length			
		254 mm	203.2 mm	127 mm	101.6 mm
Weld-On SS620	1	-	-	-	17.7 rupture
SP Spabond 345	1	-	-	-	36.7 rupture
	2	-	61.8 rupture	-	-
Jeffco 121	1	-	-	21.3 rupture	13.3 * debond
	2	49.9 rupture	-	-	-

* this average shear stress was determined over the last 25.4 mm of the CFRP strip, unlike the remaining values that were determined over the last 6.4 mm

4.1 Comparison to Predicted Behavior

The analysis of bonded joints in general has been investigated using analytical and finite element techniques. The advantage of analytical bond modeling is that since stress singularities at the material interfaces are avoided, consistent results can be achieved quickly (Xiong and Raizenne, 1996). Besides the need for significant computing time, which makes parametric studies tedious, difficulties can arise in modeling the adhesive since the elements within the adhesive tend to have high aspect ratios, and the results may vary significantly depending on the mesh used. Analysis methods have been completed to determine the critical shear and normal adhesive stresses based on compatibility of deformations among the beam being strengthened, the adhesive and the FRP strip. The solutions are for valid in the linear-elastic range of the materials. Due to the large difference in flexural stiffness between the beam being strengthened and the FRP material acting alone, simplifications can be made in the derivation of the adhesive stresses. The assumption of constant shear and normal stresses in the adhesive across the thickness of the adhesive layer leads to the result that the approximate solutions do not satisfy the zero boundary condition at the ends of the adhesive layer (Buyukozturk et al., 2004). One such method developed by Smith and Teng (2001) was used to compare the experimental interfacial stress values to those predicted by the analytical procedure, as shown in Figure 4. This test used the 101.6 mm development length and the SP Spabond 345 adhesive. Higher-order analysis, which accounts for the distribution of adhesive stresses through the adhesive thickness, may provide a more accurate solution at the very ends of the adhesive layer, however considering a safety factor of up to 17 may be necessary for the design of adhesive joints, this level of accuracy may not be justifiable (Institution of Structural Engineers, 1999).

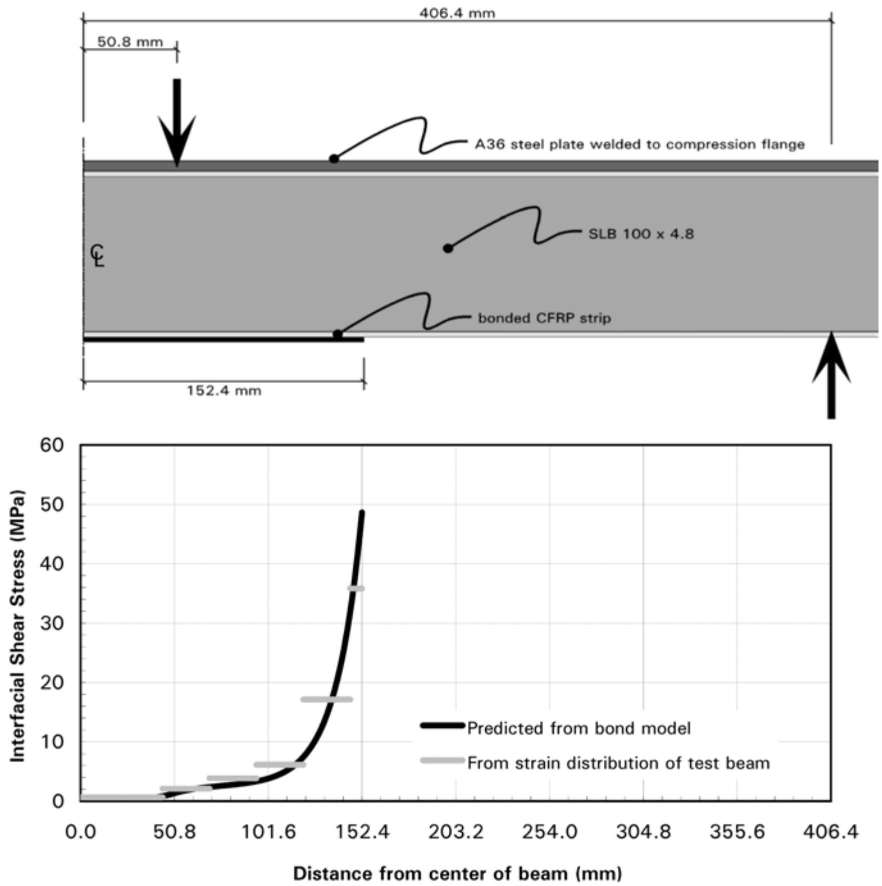

Figure 4 Comparison of predicted shear stress distribution and shear stress distribution determined from testing of beam using 101.6 mm development length

4.2 Results of Tension Test Specimens for Spliced Connection

The load-strain behavior at the center of the splice joint is shown for the three joint configurations in Figure 5(a). The initial stiffness of all three joint configurations was similar up to a load level of 40 kN. At the 40 kN load level, joint configurations A and B exhibited a sudden increase of the measured strain which was possibly due to cracking of the adhesive within the center of the joint as shown schematically in Figure 5(b). None of the other strain gauges along the splice plates exhibited a similar increase of strain, which suggests that the cracking occurred at the joint center. Cracking of the adhesive resulted in a corresponding loss of stiffness of the joint as can be seen in the Figure 5(a). Joint configuration C did not exhibit a similar increase of strain suggesting that cracking did not occur and that the reverse taper was effective in reducing the stress concentration at the center of the joint. Joint configuration A failed suddenly due to debonding of the CFRP splice plates at a load level of 90 kN while joint configuration B failed by debonding of the plates at a load level of 160 kN with additional cracking occurring within the joint at a load level of 144 kN. Debonding of the splice plates of joint configuration C occurred at a load level of 190 kN. The test results indicate that for the current system under investigation, implementing a reverse taper and a spew fillet significantly increased the capacity of the splice joint.

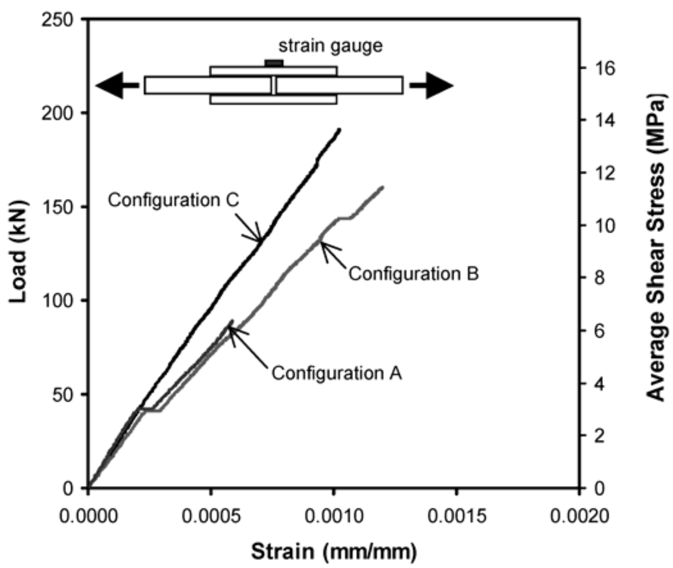

Figure 5 Load strain behavior at the center of the splice joints

4.3 Comparison to Predicted behavior

Based on the measured strains at the surface of the splice plates, the corresponding axial stresses at various locations along the splice plate were calculated. The measured stress distributions are shown in Figure 6(a) and (b), for joint configurations A and C, respectively at a load level of 80 kN. Albat and Romilly (1999) present an analytical model that can be used to calculate the distribution of axial stress in the cover plates of double-lap type shear coupons with square plate ends. The calculated stress distribution is also presented in the figure for reference purposes. Due to the presence of a localized shear stress concentration near the square plate ends at the center of the joint, the calculated stress distribution exhibits a sharp peak at this location as shown in Figure 6. Inspection of Figure 6 (a) indicates that the calculated stress distribution closely matches the measured trend of the stresses for joint configuration A, which was fabricated with square plate ends. Inspection of Figure 6 (b), however, indicates that for joint configuration C, which was fabricated with reverse-tapered plate ends within the center of the joint, the measured stress at the center of the splice was considerably lower than that predicted by the model. This further indicates that the presence of the reverse taper can help to reduce the localized shear stress concentration near the plate ends.

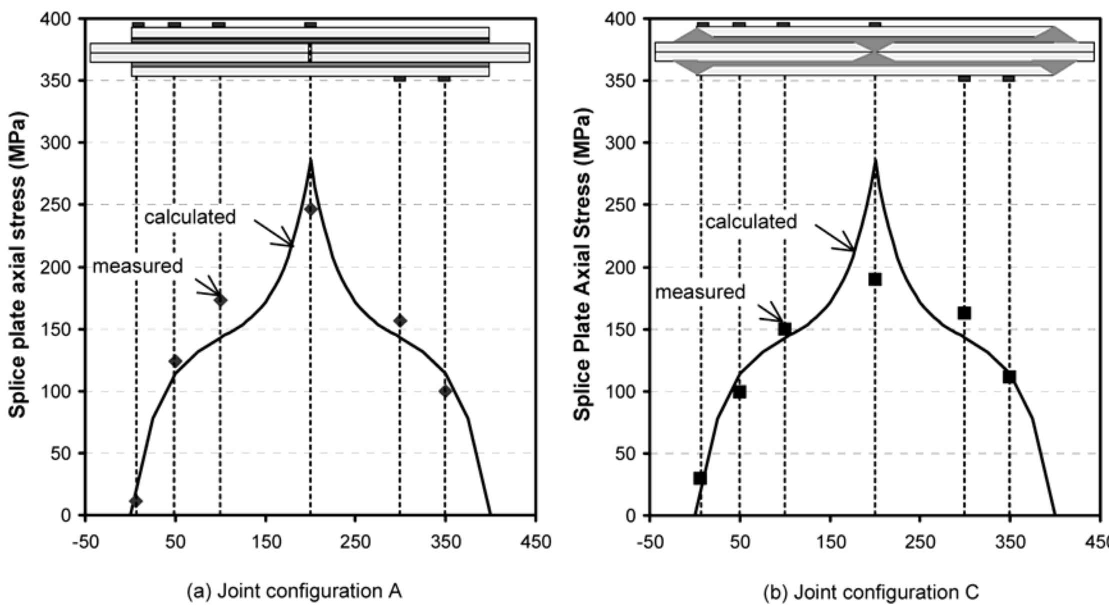

Figure 6 Comparison of measured and calculated axial stress distribution in the splice cover plate

The average shear stress between the strain gauges was determined using Equation (1) above. The average strain was taken to occur at the midpoint between adjacent strain gauges. The experimentally determined strain distributions for the three tested joints are shown in Figure 7. The calculated stress distribution, determined using the analytical model is also shown, whereby the experimentally determined shear stress distributions for all three joint configurations closely matches the calculated shear stress distribution. This indicates that the analytical model can be used to accurately predict the shear stresses for the bonded joints. It should be noted that the measured shear stresses are sensitive to the spacing between the strain gauges. Since the strain gauges in this study were placed with a relatively large spacing, the measured strain distributions did not accurately capture the reduction of the shear stress concentrations near the plate ends.

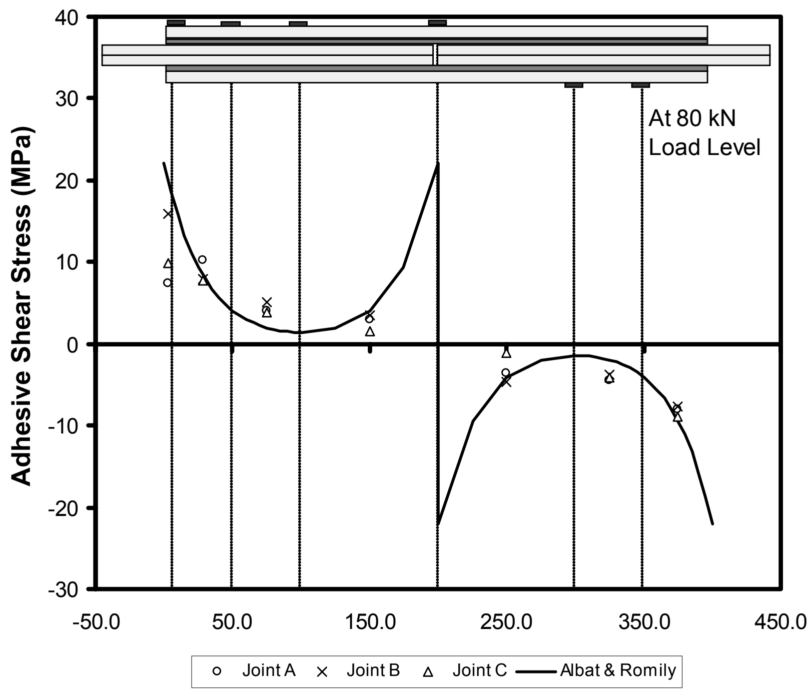

Figure 7 Experimental and analytical shear stress distributions

5.0 DESIGN FOR BOND

An elastic stress-based analysis is recommended for the design. Although, an elastic approach may neglect reserve capacity in the adhesive after yielding of the adhesive, it is desirable to have yielding of the section occur before the adhesive becomes inelastic since yielding of the member is more visually apparent then any non-linear behavior of the adhesive and steps can be taken to address the overloading of the structure, if any. It has further been recommended that the maximum bond stresses in an adhesive joint should not exceed 20-30 percent of the ultimate strength of the adhesive under repeated fatigue loading conditions (Cadei et al., 2004). Designing a joint beyond its elastic strength may also result in poor creep performance.

An analytical procedure was developed for determining the bond stresses. This procedure allows the analysis of beams with bonded FRP strips to the tension side of the beam. The analysis includes the effect of the applied loading, the thermal effects resulting from differing coefficients of thermal expansion, as well as any prestressing applied to the FRP strip before bonding. Thermal effects should be considered for any structure that is subjected to thermal changes. More details regarding the analysis, in addition to techniques to reduce the stresses at the ends of the CFRP strips may be found in Schnerch (2005).

As indicated by Cadei et al. (2004), the strength of the bond must be determined empirically since this strength depends not only upon the properties of the substrates and adhesives, but also upon the degree of surface preparation that is expected. The characteristic strength of an adhesive system can be established using small-scale single or double lap shear coupon tests. The test coupons should be prepared using the same materials, surface preparation techniques and application techniques as will be used for the strengthening project to ensure that the coupon test results are representative of the expected behavior. The maximum shear stress, τ, and normal stress, σ, can be determined from these preliminary tests using well established bond models such as those outlined for the case of double-lap shear specimens (Hart-Smith, 1980). Typically, the maximum shear and normal stresses are approximately coincident along the length of the adhesive joint. These stresses can then be used to determine the maximum principal stress, of the adhesive or interface. A design value can then be determined using an appropriate factor of safety considering the sudden debonding failure mode that does not give any warning prior to failure.

6.0 CONCLUSIONS

Surface preparation and detailing are essential to ensure satisfactory performance of bonded joints between steel and FRP materials, which are capable of sustaining the high interfacial stresses necessary to realize the full strength of these materials. The primary challenge towards the successful implementation of FRP materials for steel strengthening is the performance of the bond. It is not only necessary to consider the short term bond performance, but new research should attempt to correlate the performance of accelerated tests to long-term field performance.

Small-scale flexural tests were conducted to investigate adhesive bond performance. Considerable variation in the development length and maximum CFRP strain at failure was found among the adhesives studied. Several of the adhesives were able to achieve rupture of the CFRP strip at relatively short development lengths. The current study indicates that the development length is proportional to the number of plys of CFRP strips. Existing analytical techniques are the most suitable tools that are currently available to designers in describing the bond behavior of steel to CFRP bonds. These models predict a shear stress concentration at the end of the CFRP, which was confirmed in the current experimental program. The preliminary experimental results also confirm the findings of previous finite element studies that the stress concentration at the end the end of the strip can be significantly reduced by implementing a reverse taper and spew fillet. Adhesive selection and careful detailing are critical to the satisfactory performance of steel members strengthened with externally bonded CFRP strips.

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NOTATION

E_{frp} = Modulus of elasticity of FRP

t_{frp} = thickness of FRP strip

τ = shear stress

τ_{av} = average shear stress

σ = normal or peel stress