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BOND BEHAVIOR OF CFRP STRENGTHENED STEEL BRIDGES AND STRUCTURES

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ABSTRACT

Recent research has focused on strengthening steel structures using FRP materials. The bond behavior of steel structures strengthened with FRP materials is different than that of concrete structures. Additionally, very high bond stresses are likely to occur for most strengthening applications due to the amount of strengthening required for steel structures. In this paper, surface preparation methods and means of preventing galvanic corrosion are discussed as well as current methods for determining bond stresses and their use for design. These methods are compared to experimental results, showing good agreement, and the direction of future work in this area is proposed.

KEYWORDS

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

INTRODUCTION

With the introduction of new, high modulus CFRP materials, the possibility exists for the practical strengthening of steel structures. Many older steel bridges are in need of strengthening and/or rehabilitation due to corrosion caused by the use of de-icing salts. Transportation departments, facing difficult cost controls, may favor a system that will allow the restoration or increase in traffic loads without the need to replace the existing structure. Additionally, increasing numbers of cellular phone users and their requirements for improved service has required cellular phone companies to increase the number of antennas on steel monopole towers. This trend has been exasperated by the reluctance of communities to allow new monopoles to be built. Addition of new antennas increases the wind load acting on the structure, and strengthening is often required to match this demand. By strengthening with high modulus CFRP materials, service interruptions may be minimized and the monopole can retain its original appearance. An extensive body of research work has been completed on the bonding of FRP materials to concrete structures, but the bonding of FRP materials to steel structures requires additional consideration to ensure its long-term performance.

BONDING OF 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 carbon fiber due to the more reasonable necessary thickness of the applied strengthening material.

Surface Preparation

Bonded joints are often the most effective way to join two different adherends, since the resulting stress concentrations at the joint are 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, unlike wire brushing, that can cut into the metal exposing a clean surface. 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 evenly 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.

Durability and Prevention of Galvanic Corrosion

FRP materials typically have excellent resistance to corrosion and chemical attacks, resulting in 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 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. It is also noted that despite the change in the mechanical properties of the adhesive, the primary mechanisms 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 (Allen et al., 1988). This application relevant to naval structures also showed that silane incorporated into the adhesives themselves is less effective than providing a separate silane layer. Silane adhesion promoters are noted also 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, which 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 sustained 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 bimetallic 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. Galvanic corrosion is recognizable by a buildup of corrosion at the joint between the dissimilar metals. Additionally, the composite itself may be degraded by the galvanic process (Miriyala et al., 1992). The polymer material in this study 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.

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. Suggestions to reduce the possibility of galvanic corrosion were to use a non-conductive layer between the carbon and the steel, by either a GFRP sheet or epoxy film. West (2001) also 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 showed that 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 significant 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. Part of the reason for inserting the glass fiber in the first place is to ensure that there is adequate bondline thickness. 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.

EXPERIMENTAL PROGRAM

Introduction

There has been only one published study on the bond length of CFRP strips applied to a flexural member Nozaka et al. (2005). In this study the focus was on cracked steel girders. 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. The development length found for the adhesives studied was found to be less than 203 mm. In the present study, the bond behavior of uncracked steel flexural members 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.

Test Specimens

A flexural type of test specimen was used to study the bond performance for the adhesive bonding of pultruded CFRP strips. This type of specimen was used due to the expectation that the CFRP materials 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 strips 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. The length of the bonded CFRP strip used was varied from 50-200 mm. Figure 1 shows the specimen dimensions.

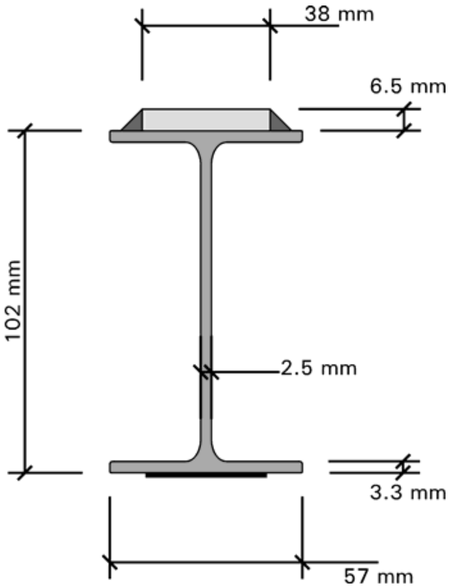

Figure 1 Cross-section dimensions of typical SLB bond specimen

The configuration used for testing was a four-point bending test, 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. The constant moment region was 102 mm in length with a span of 813 mm. Lateral bracing of the top flange was provided at the supports. A spherically seated bearing block was used to ensure loading was applied uniformly to the beam. Load was applied at a constant displacement rate of 0.75 mm/minute.

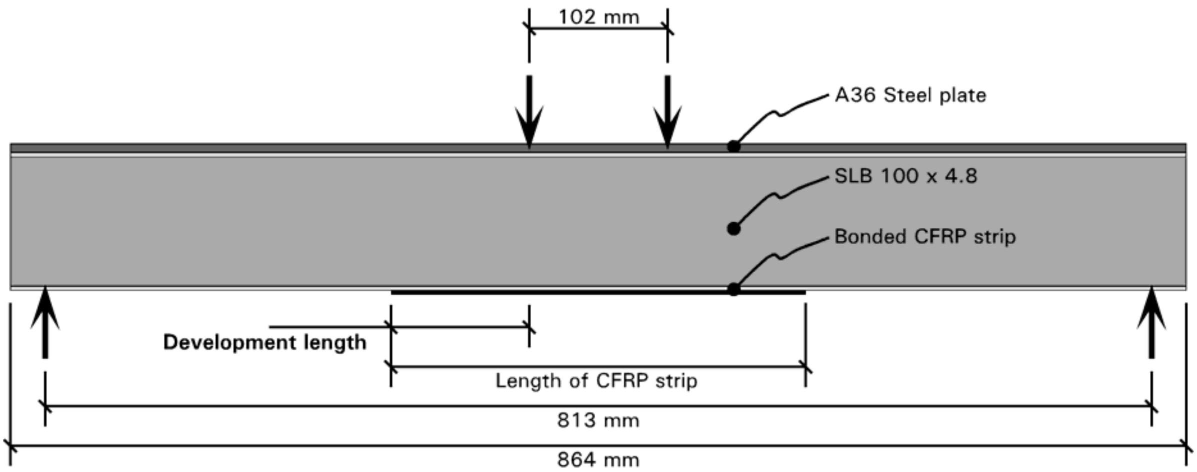

Figure 2 Loading configuration of typical SLB bond specimen

Results

Specimens were loaded until a steel tension flange strain of 8 millistrain was reached, as shown in Figure 3. Prior to this level of stain being reached, the CFRP material 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.

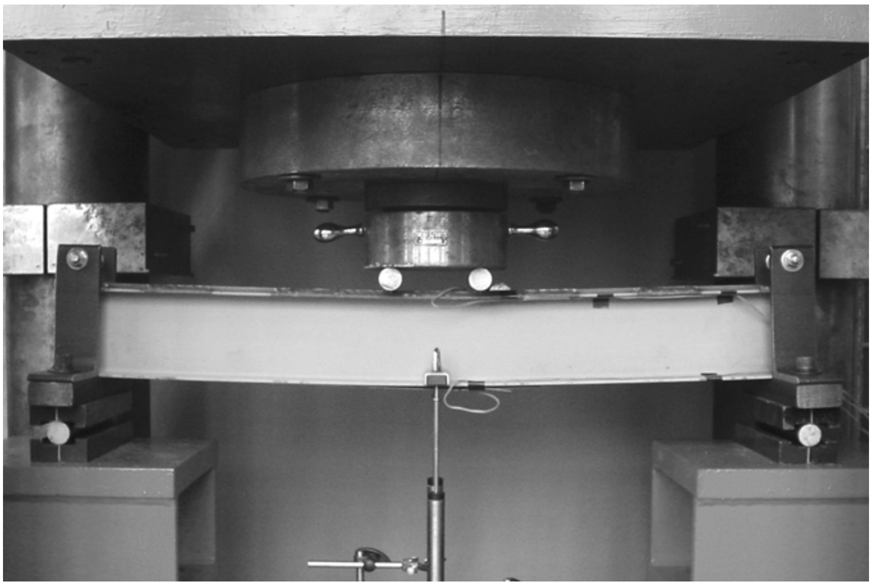
Figure 3 SLB bond specimen at ultimate tension flange strain

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. 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.

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

Adhesive	Development Length					
	203 mm	152 mm	127 mm	102 mm	76 mm	51 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 plate and the steel substrate, as noted by Garden et al. (1998). The average shear stress could then determined between the two gauge locations as,

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

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 Jeffco 121 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 mm	127 mm	102 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

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. Higher-order analysis, which account 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)

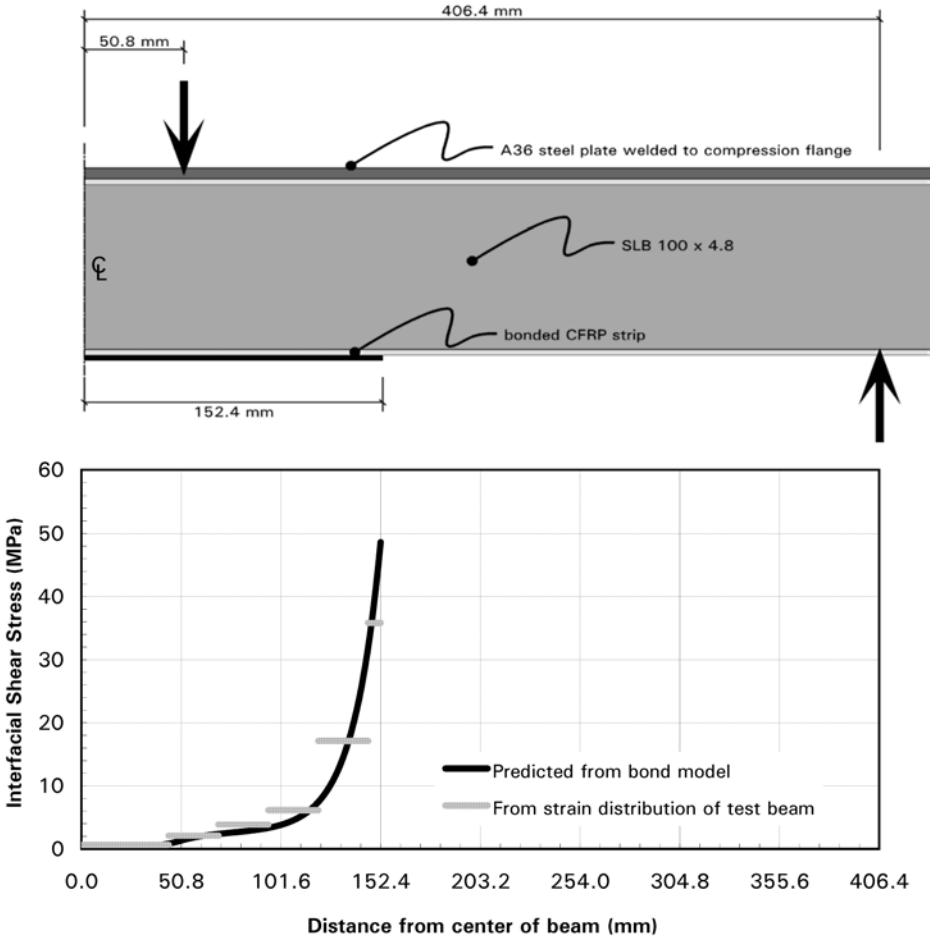

Figure 4 Comparison of predicted shear stress distribution and shear stress distribution determined from testing of beam using 101.6 mm development length

CONCLUSIONS

Surface preparation is essential in providing a bond between steel and FRP materials, that is 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. Existing analytical techniques are sufficiently accurate for use by designers in describing the bond behavior of steel to CFRP bonds.

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