A REVIEW OF THE BOND CHARACTERISTICS BETWEEN STEEL AND CFRP LAMINATE UNDER STATIC AND IMPACT LOADS

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ABSTRACT

The use of FRP composites in civil engineering applications has gained considerable popularity over the past two decades. Significant work has been reported in the literature on FRP applications to strengthen concrete structures but less on their use to strengthen steel structures, and most previous studies have focussed on static load applications. This paper reviews the bond characteristics between CFRP and steel elements under both static and impact loads. Comparisons of different parameters are included.

INTRODUCTION

A huge number of structures worldwide are constructed with steel, including more than 47% of bridges in the United States. The National Bridge Inventory in the United States reported that steel bridges require improvement (Tavakkolizadeh and Saadatmanesh 2003). In addition, many steel structures such as bridges, offshore platforms and buildings may become deficient and deteriorated for different reasons such as ageing, use changing or increasing the daily traffic, which exceeds the capacity that designed for. Bocciarelli and Colombi et al. (2009) state that many structures are old and there is a reduction in their resistance to loads; 50% of the existing bridges in Europe need to be repaired for these reasons. These deteriorated structures can be repaired and strengthened using many types of solutions, including external post-tensioning, the use of steel jackets, replacement of damaged or degraded elements, the addition of new elements to relieve overloaded parts or the enhancement of load-carrying capacity by welding or bolting steel plates (Kalfat, Al-Mahaidi et al. 2013). These traditional strengthening methods are time-consuming and may not be adequate because they increase the dead load of structures. Therefore there is a need to find a material or method to strengthen structures without these disadvantages.

Advanced composite materials such as carbon fibre reinforced polymer (CFRP) is a good modern alternative material for the rehabilitation and strengthening of structures, and it appears to be an excellent solution (Hollaway and Head 2001, Bakis, Bank et al. 2002, Hollaway 2010). After the Second World War, the use of composite materials was limited to military, aerospace, automotive and marine applications, but composite materials have been explored and adopted for use in structural and semi-structural members (Zhao and Zhang 2007). CFRP possesses a superior combination of properties with respect to weight, strength, stiffness, durability, fatigue, impact and corrosion-resistance. CFRP is non-reactive, which means that it can be used in areas in which environmental deterioration occurs (Karbhari and Shulley 1995, Jones and Civjan 2003). Recent studies have focussed on the behaviour of CFRP under different types of loading and different parameters. Some researchers have studied the effect of fatigue loading on CFRP (Tavakkolizadeh and Saadatmanesh 2003, Liu, Zhao et al. 2005, Liu, Al-Mahaidi et al. 2009, Liu, Xiao et al. 2009, Kim and Harries 2011, Tsigkourakos, Silberschmidt et al. 2011), while others have studied static load on CFRP with steel or concrete and its effect on the bond between CFRP and structural members (Al-Saidy, Klaiber et al. 2004, Lenwari, Thepchatri et al. 2005, Colombi and Poggi 2006a, Colombi and Poggi 2006b, Bambach, Jama et al. 2009, Chiew, Yu et al. 2011, André, Haghani et al. 2012).

Some researchers have written on the state of the art in using FRP with both concrete and steel structures. For example, Hollaway and Cadei (2002) focussed on issues in bonding plate onto metallic structures. In addition, the paper studied some of the in-service problems correlated with advanced composite materials and metallic adherends, the durability of the advanced polymer composite and adhesive, the degradation of metallic structures has also studied in the review (Hollaway and Cadei 2002). Shaat, Schnier et al. (2004) wrote a state-of-the-art review on retrofitting of steel structures including naturally deteriorated cases, beams with artificial
notches, strengthening of intact beams, strengthening of steel/concrete composite flexural members and the retrofitting of thin-walled tubular sections. These researchers also studied the effect of fatigue load on FRP, the bond between FRP and steel structures and the durability of retrofitted systems. Zhao and Zhang (2007) studied the state-of-the-art in FRP strengthened steel structures, focusing on three essential points: the bond between FRP and steel structures; propagation of cracks in the FRP-steel system under fatigue load; and FRP strengthening of steel hollow sections. Another review paper by Buchan and Chen (2007) studied the blast resistance of FRP-strengthened concrete and masonry structures. Their major concern was the strengthening of FRP for different types of structural elements such as concrete beams, columns, slabs, walls and masonry walls. As this brief summary indicates, there is a lack of research into the effect of the use of FRP strengthening of steel structures to resist dynamic loads. Some studies have been carried out on the effect of strengthening by CFRP sheets on steel structures under impact load, but to date no study has focussed on the effect of CFRP laminate on steel structures under different load rates. This article includes a literature review of both experimental and analytical work on the bond between CFRP and steel structures under static and dynamic loads, and includes a comparison of both in relation to the length of CFRP, the strength of the bond, the failure modes and the effect of different load rates.

INVESTIGATIONS OF BOND CHARACTERISTICS BETWEEN CFRP AND STEEL BEAMS

This part of this paper focuses on the bond characteristics of specimens including double strap specimens, single-lap specimens, pull-off test specimens and bolted joints. To understand the bond between CFRP and steel structures, the present authors have selected papers with different types of load that simulate the situation of actual structures. Static tension, flexural and pull-off tests studied both experimentally and numerically are included in this paper in addition to impact tension studies with different load rates.

EXPERIMENTAL INVESTIGATIONS

Bond characteristics between CFRP and steel members under static tension load.

Tensile tests are among the most common basic tests conducted for testing composite materials. Many studies have focussed on the behaviours of different types of FRP composite materials with steel structures under static tensile loads. Studying this kind of load is important because it represents many applications in civil engineering. Jiao and Zhao (2004) studied the strengthening of butt-welded very high strength circular steel tubes using CFRP fabrics. The yield stress of this steel is 1350 MPa. Three types of epoxy resin (Sikadur-330, Araldite 420 and Araldite Kit K138) were used to bond a total of 21 specimens of CFRP-steel butt-welded joints using Baldwin universal testing machine with maximum capacity of 500 KN and a loading speed of 2 mm/min. These 21 specimens were tested under axial tensile load to obtain the shear strength of this bond. The researchers used SikaWrap Hex-230C which has a typical unidirectional tensile strength of 3500 MPa and Young’s modulus of 230 GPa with an ultimate strain of 1.5%. The joint was bonded by 5 layers of CFRP fabrics, as the thickness of one layer is 0.13 mm. Joints with Araldite 420 had the highest strength of the epoxy resins. The results showed that the ultimate load becomes higher as the bond length increases, but the increasing in load is close to be constant when the bond length exceeds 75mm. In comparison with the 7 failure modes mentioned in ASTM D5573, different failure modes were observed with the different epoxies. In general the common failure modes for these specimens were adhesive failure and fibre-tear failure. In order to avoid fibre-tear failure Araldite 420 was found to be the suitable epoxy for strengthening butt-welded VHS.

A pull-off test of CFRP to steel plate was conducted by Xia and Teng (2005), where a tensile force was applied to the FRP plate and the steel block was supported at the loaded end, as shown in Figure 1.

Figure 1 Pull-off test specimen and set-up (Xia and Teng 2005)
Three different adhesives were used in the test program, and for each adhesive, three coupons were tested in tension up to failure. The failure mode was mostly debonding in the adhesive layer adjacent to the FRP for the two adhesive thicknesses (1 and 2mm). The behaviour of the three adhesives was linearly initially, and then became slightly nonlinear and suddenly failed by rupture. However, a bilinear bond-slip model can approximate these experimental curves closely. The proposed bilinear model has three key points as a definition of the curve: the origin \((0, 0)\); the peak shear stress point \((\delta_1, \tau_f)\); and the ultimate point \((\delta_f, 0)\). The area below the curve is the interfacial fracture energy \((G_f)\), as shown in Figure 2.

![Bilinear bond-slip model](image)

Figure 2 A bi-linear bond-slip model (Xia and Teng 2005)

The peak and ultimate coordinate points were derived from the experimental results. When the adhesive has a high modulus of elasticity, the load-displacement curve shows higher initial slope, and vice versa.

Colombi and Poggi (2006b) studied the strengthening of bolted joints using adhesively-bonded CFRP laminates in three groups of specimens. The first group included three types of specimens: two specimens with continuous steel plates; and the third specimen including a 20mm diameter hole with double-sided CFRP laminate. The second group included strengthening a gap of two steel plates with CFRP. The third group was a bolted joint between CFRP laminate and steel plate. The CFRP used in this test was Sika Carbodur M614 and the adhesive was Sikadur 30, and the specimens were tested under static tensile load. The results showed slight difference between the yield load of the specimens without strengthening, and that of the reinforced specimens. For specimens with a 20mm hole the stress distribution along CFRP is shown in Figure 3.

![Stress distribution](image)

Figure 3: Distribution of stress along the CFRP at different values of loads (Colombi and Poggi 2006b).

For the double-lap specimens, the strain gauge near the applied load and far from the joint showed a nonlinear curve starting from 35 KN. This nonlinear curve is due to the properties of the adhesive (Sikadur 30), which had a non-linear response at the high loading levels near the reinforcement ends, while the other strain gauges near to the joint showed a linear stress-strain curve response. In the bolted joints (see Figure 4), Sikadur 330 and Sikadur 30 adhesives were used. The results for specimens with Sikadur 330 showed that the response was almost linear up to 84.1 kN and without debonding failure of the joint. When local composite failure occurred, the load increased up to 117.1 KN, identical to the yield load of the steel plate. Then, debonding occurred. However, the results of specimens with Sikadur 30 showed a different behaviour of the load displacement curve.
The failure mode that occurred with Sikadur 330 was combined of composite failure and CFRP debonding which were happened at the same load level.

![Figure 4: Bolted joint reinforcement (Colombi and Poggi 2006b)](image)

Fawzia and Al-Mahaidi et al. (2006) studied the characteristics of a double-strap joint between steel plates and normal modulus CFRP sheets. Normal modulus CFRP CF130 was used with 0.176mm thickness per layer. Three CFRP layers were used to bond the joint using Araldite 420. Four specimens of double strap joints between steel and CFRP sheets were tested under axial tensile load at a loading rate of 2mm/min. The effective bond length was the same bond length that studied in Jiao and Zhao (2004). Strain gauges were used to measure the strain distribution along the bond length, and as the load increased, the strain at the first and second gauges increased significantly. Then the gauges reading were very small and became almost zero at a distance of 75 mm from the loaded edge.

To establish an effective method for bonding CFRP to steel beams, Dawood and Rizkalla (2007) prepared six double-lap shear specimens to find a suitable method of bonding high modulus CFRP to steel beams to reduce bond stress concentration, which usually occurs near the ends of the laminate. The results of the double-lap shear specimens showed that all specimens failed by sudden debonding of the CFRP laminate, with some adhesive remaining on steel plate. In addition, the specimen with reverse tapers at the end of the laminate and at the middle of the joint (T2) showed an 80% increase in load capacity of the bonded joint compared with the square end and T1. The clamped specimens showed additional 80% increase comparing with (T2).

The axial capacity of a steel square hollow section (SHS) strengthened by CFRP sheet was investigated by Bambach and Jama et al. (2009). The SHSs were fabricated by spot-welding with different wall thicknesses (1.6mm and 2mm). High strength CFRP fabric (MBrace CF-130) was applied to the exterior of the SHS using Araldite 420 resin. The researchers investigated two different fibre applications: one layer was applied transversely, and the other was same to the direction of axial load. The specimens were tested under axial compression load. The axial capacity was increased 2 times the capacity of the steel section alone and increased in strength to weight ratio of up to one and a half times; buckling stress was increased up to 4 times that of steel section alone.

Another series of double-strap joint specimens were tested by Fawzia and Zhao et al. (2010). The researchers focused on the bond-slip models of double strap joints between CFRP and steel. In order to find the strain distribution, foil strain gauges (VMMCEA-13–240UZ-120) were used. Different parameters were considered such as: type of CFRP modulus (high or normal), type of adhesives (Araldite 420, MBrace saturant and Sikadur 30), number of CFRP plies (3 and 5), bond length and thickness of steel plate. The researchers investigated the bond-slip of specimens with different adhesives, and the results showed that specimens with Araldite and MBrace had the same initial slip (the slip at maximum shear strength) of 0.05mm, whereas it was 0.04mm for specimens with Sikadur adhesive, as shown in Table 1 below:

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Maximum shear stress (MPa)</th>
<th>Initial slip (mm)</th>
<th>Maximum slip (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Araldite 420</td>
<td>30</td>
<td>0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>Mbrace saturant</td>
<td>23</td>
<td>0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>Sikadur 30</td>
<td>22</td>
<td>0.04</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 1 Shear stress and slip values for the different epoxies (Fawzia, Zhao et al. 2010).

The bond failure of three types of joints of steel to CFRP (double-lap joint, single-lap joint and T-peel joint) was studied by (Chiew, Yu et al. 2011). The researchers used a high strength CFRP laminate with tensile strength of 2492 MPa and two-component saturant epoxy with a tensile strength of 15.5 MPa to bond the joint.
between CFRP and steel, and the joints were tested under axial tension load using an Instron 5500 universal electro-mechanical testing system. The maximum load capacity was increased by the increase of the bond widths. Adhesive to steel interface failure mode was occurred for all specimens as the bond between these two materials is the weakest point in the joint.

Wu and Zhao et al. (2012) studied the bond characteristics of double-strap joints between steel and ultra-high modulus CFRP laminate (MBrace 460/1500), the elastic modulus of which is 460 GPa and the normal tensile strength is 1500 MPa. Two types of adhesives were used (Araldite and Sikadur) to attach the laminate to the steel surface. The specimens were tested under static tension load to investigate the failure mode, effective bond length and bond strength of the joint. The failure mode for the specimens with Sikadur adhesive was cohesive failure, but two failure modes were observed for specimens with Araldite 420: delamination and CFRP failure. The bond strength was increased with the increase of bond length up to the effective bond length, which was 100-120 mm for Araldite and 70-100 mm for Sikadur specimens. The results showed a higher strain in the area near to the joint and the strain was gradually decreased away from the joint at each load level for both types of adhesives, in addition the shear stresses increased with the load increase and decreased as being far from the joint.

**Bond characteristics between CFRP and steel members under flexural load**

Colombi and Poggi (2006a) studied the effectiveness of the epoxy bonding of CFRP strips to HEA steel sections. An identical steel beam was tested as a three-point test as a reference for those which strengthened with CFRP strips. Sika Carbodur M614 was the CFRP used, and Sikadur 30 and Sikadur 330 were used to bond the CFRP to the steel beams. The results showed that for specimens with one CFRP layer and Sikadur 30, the enhancement in load was 9.2%, which is close to that of the specimens with Sikadur 330, while the increment was about 23% for specimens with two layers of CFRP laminate. In relation to the stiffness of the specimens, there was no increase in specimen stiffness for specimens with one layer of CFRP, but it was increased by 13.8% for specimens with two CFRP layers.

To find an effective method for bonding CFRP to steel beams, Dawood and Rizkalla 2007 prepared nine steel beams to find a suitable method of bonding high modulus CFRP to steel beams (see figure 5) to reduce the bond stress concentration which usually occurs near the ends of the laminate. The results of three-point tests showed that all specimens experienced sudden debonding of the splice plate, the debonding starting from one of the splice’s end and going towards joint, then propagating to the interface between the CFRP main plate and the splice plate. Different splice plate lengths of 200mm, 400mm and 800mm were used, but did not have a large effect on the load capacity of beams with square-ended joints. However there was a 17% increase in joint strength for beams with tapered ends.

![Figure 5 Plate-end details for tested specimens (Dawood and Rizkalla 2007)](image)

Three- and four- point load tests of CFRP strengthened steel beams were carried out by Deng & Lee (2007). Mild steel, CFRP laminate with a thickness of 0.3mm and Sikadur 31 adhesive were used to prepare the specimens. A servo-hydraulic Dennison 8032 testing machine with a capacity of 200 kN was used, and the results showed an increase in load when the bond length of CFRP increased from 300mm to 1000mm. The researchers compared two specimens with the same dimensions but the thickness of CFRP doubled in one, and the results showed that increased CFRP thickness causes a reduction in strength-enhancement, with the thicker CFRP causing a high stress concentration at the end of the laminate. A slight increase in strength (5%) for specimens with spew fillet at the end of laminate which is far less than that in lap joints as studied by (Adams,
Comyn et al.). The researchers showed that an increase in CFRP laminate length does not affect specimen stiffness, whereas it is lower for specimens with 6mm thick CFRP. Figure 6 shows the load-deflection curve of two specimens, where S305 is a specimen with 3mm thick CFRP, while S305D has 6mm thick CFRP.

![Figure 6 Load-deflection curves of different CFRP thicknesses (Deng and Lee 2007).](image)

A four-point test on a full-scale FRP-strengthened steel beams was studied by Yu and Chiew et al. (2011). The authors focused on different parameters such as: thickness of CFRP, bond length and adhesive thickness. A full-scale non-strengthened steel beam was tested to find the effect of FRP laminate. The results showed that the deflection of the bond decreases with the increase of laminate thickness, Table 2 shows the summary of the tests parameters and results.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>L (mm)</th>
<th>b (mm)</th>
<th>t (mm)</th>
<th>P (kN)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>1800</td>
<td>-</td>
<td>-</td>
<td>177.1</td>
<td>B</td>
</tr>
<tr>
<td>B2</td>
<td>1800</td>
<td>700</td>
<td>1.5</td>
<td>185.5</td>
<td>A</td>
</tr>
<tr>
<td>B3</td>
<td>1800</td>
<td>700</td>
<td>4.5</td>
<td>200.0</td>
<td>A</td>
</tr>
<tr>
<td>B4</td>
<td>1800</td>
<td>700</td>
<td>7.5</td>
<td>206.9</td>
<td>A</td>
</tr>
<tr>
<td>B5</td>
<td>1800</td>
<td>700</td>
<td>1.5</td>
<td>183.6</td>
<td>A</td>
</tr>
<tr>
<td>B6</td>
<td>1800</td>
<td>700</td>
<td>1.5</td>
<td>2.5</td>
<td>175.9</td>
</tr>
<tr>
<td>B7</td>
<td>2400</td>
<td>-</td>
<td>-</td>
<td>1208</td>
<td>B</td>
</tr>
<tr>
<td>B8</td>
<td>2400</td>
<td>750</td>
<td>1.5</td>
<td>1229</td>
<td>A</td>
</tr>
<tr>
<td>B9</td>
<td>2400</td>
<td>850</td>
<td>1.5</td>
<td>127.7</td>
<td>A</td>
</tr>
<tr>
<td>B10</td>
<td>2400</td>
<td>1050</td>
<td>1.5</td>
<td>134.1</td>
<td>A</td>
</tr>
<tr>
<td>B11</td>
<td>2400</td>
<td>1450</td>
<td>1.5</td>
<td>140.8</td>
<td>B</td>
</tr>
</tbody>
</table>

1 Beam yielding;  
2 Beam yielding followed by debonding of FRP laminate;  
3 Maximum load.

As the above table shows, there is increased load resistance of the beam when the thickness of the adhesive is constant and the thickness of FRP is varied from 1.5 to 4.5 mm, but no significant load increase at a FRP thickness of 7.5mm, whereas there is a decrease in load resistance when the adhesive thickness is increased. However, the load resistance increases as the bond length of the FRP laminate increases (Yu, Chiew et al. 2011).

**Bond characteristics between CFRP and steel members under dynamic loads**

A significant research effort has focussed on the strengthening of steel structures using FRP under different types of static load, but few researchers have studied the effect of the bond under dynamic load. The effect of static tensile and impact tensile loads on the strength of CFRP-bonded steel plate joints was studied by Al-Zubaidy and Zhao et al. (2011). These researchers used normal CFRP sheet with one and three layers and Araldite 420 adhesive to bond the CFRP to steel. Four series of specimens (see Figure 7) were tested under quasi-static load (2mm/min) and impact load with a loading speed of 3.35m/sec. The bond strength of the impact load with a speed of 3.35m/sec is more than that in static load; the ratio of bond strength for the impact test compared with the static test for both one and three layers of CFRP sheet was more than two when the bond length was beyond the effective bond length. The effective bond length was not affected by the increase in load rate, the effective bond length was found to be 30mm under static load and for one CFRP ply, whereas it was different with the three CFRP plies to be 50mm, which was the same as the loads for the impact tests. In terms of the failure mode, for 1 layer CFRP and a bond length less than the effective bond length, deboning between
CFRP and adhesive occurred in the static test and CFRP delaminating in the impact test. When the bond length exceeded the effective bond length of 30mm, CFRP rupture occurred in the static test, whereas CFRP rupture and CFRP delamination occurred in the impact test. The failure mode was a combination of de-bonding of CFRP and adhesive and CFRP delamination, that’s for specimens with 3 plies of CFRP and for bond lengths less than the effective bond length (50mm).

Figure 7: Schematic view of double-strap joint (Al-Zubaidy, Zhao et al. 2011)

An investigation of blast resistance of cracked steel box structures repaired with CFRP was studied by Pereira and Ghasemnejad et al. (2011). The researchers exposed a number of steel boxes repaired with CFRP to blast load, in each test one box had the front face facing the impact load and another box had side face facing the impact load. The test results showed that the pressure dropped rapidly at level ranged from 100 kPa to 800 kPa. The results also showed a comparison between the behaviour of CFRP to steel and CFRP to reinforced concrete, strengthening steel with CFRP can reduce the stress concentration near to the cracked area because the stress is transferred from the cracked zone to the CFRP patch. Using CFRP to strengthen steel to blast load prevents cracks growing and increase the structure life(Pereira, Ghasemnejad et al. 2011)

Al-Zubaidy and Al-Mahaidi et al. (2012) continued their study of the bond characteristics of double-strap joints between normal modulus CFRP and steel plate under impact loads, conducting more tests on these joints using MBrace saturant epoxy adhesive to bond the CFRP sheet to the steel surface. A number of specimens were tested under static and dynamic axial tensile loads to investigate the effect of impact load on joint with different load rates. For the static tests, the load rate was 2mm/min and for the impact test the load rates were 3.35, 4.43 and 5m/s. The results showed increasing in joint capacity for the two types of specimens (one and three layers of CFRP), the results also showed an increase at rate of (3.35m/s), but for load rates of 4.43 and 5m/s the bond strength started to slightly decrease. The effective bond length for the static test was 30mm for 1 ply of CFRP and 50mm for 3 plies of CFRP. However, the effective bond length for the dynamic test remained the same for one layer but there was a slight difference with three layers of CFRP (60mm). The authors attributed this to the low impact properties of MBrace epoxy. For the static tests, for one layer of CFRP the failure mode was steel and adhesive interface failure. However, there were different failure modes for the dynamic load. When the bond length was beyond the effective bond length, the failure modes were as follows:

- Load rate of 3.35m/s: combination of steel and adhesive interface failure and CFRP and adhesive interface failure.
- Load rate of 4.43 and 5m/s: combination of steel and adhesive interface failure and cohesive failure (adhesive layer failure).

Regarding the three layers of CFRP, the failure mode for the static test was steel and adhesive interface for bond lengths which are beyond the effective bond length, whereas it became a combination of steel and adhesive interface failure and cohesive failure when the bond length is more than the effective bond length. However, for the dynamic tests there were slight changes in failure modes. In these tests steel and adhesive interface failure combined with CFRP and adhesive interface failure could be defined as the dominant failure mode when the bond length was less than or equal to the effective bond length at loading rates of 3.35 m/s. When loading rates were increased to 4.43 m/s and 5 m/s, the failure modes were a combination of steel and adhesive interface failure and CFRP and adhesive interface failure for lengths less than or exceeding the effective bond length. Different failure modes are explained in Zhao and Zhang (2007) as (a) steel and adhesive interface failure, (b) cohesive failure, (c) CFRP and adhesive interface failure, (d) CFRP delamination. The effect of impact load on strain distribution for one and three CFRP layers and at all speeds of loading, decreased as the distance from the joint becomes larger, while linear and nonlinear behaviours were found for joints of 1 CFRP layer and 3 CFRP layers respectively.

NUMERICAL INVESTIGATIONS

A three-dimensional non-linear finite element analysis was used by Fawzia and Al-Mahaidi et al. (2006) to simulate static tensile load on steel/CFRP joints using the Strand7 software (Strand7 2007), and the analytical load carrying capacity and the strain distribution were found to be close to the experiment results. The coefficient of variation of the failure load for the experimental and analytical results was 0.033, which means
there was good agreement between them. The strain results obtained from the finite element analysis along the CFRP was close to the strain gauge results from the experimental test.

Haghani (2010) used a three-dimensional linear elastic analysis to model adhesive joints to be used in bonding CFRP laminate and steel. Two adhesive materials were modelled, Sikadur330 and Sto BPE Lim 567. The results showed that the transverse properties of the laminate do not significantly affect the strain distribution along the adhesive layer. The numerical results showed that there was a steel-adhesive interface failure mode for the specimens.

Fawzia and Zhao et al. (2010) used 3D non-linear FE analysis to model the tensile testing of steel to CFRP joints with a brick (solid) element using the Strand7 program (Strand7 2007). The same three types of adhesive (Araldite 420, MBrace saturant and Sikadur 30) that were used in the experimental tests were simulated to bond the CFRP sheet to steel plate. The results for shear stress and bond slip for Araldite 420 epoxy is shown in Figure 8 below:

![Figure 8: Shear stress vs. slip for Araldite 420 (Fawzia, Zhao et al. 2010)](image)

These researchers showed that the bond slip of the joint is not affected by the variation of bond length. Even if the bond length is up to 5 times the effective bond length, the initial slip and shear stress are not affected by the increase of strain values of the adhesive, but the maximum slip is higher for the higher strain, and the slip is affected by epoxy thickness.

Kadhim (2012) studied the effect of different bond lengths of CFRP laminate on the strengthening of steel continuous beams, using three-dimensional analysis to simulate a three-point test in the ANSYS program (ANSYS® Academic Research). Two types of elements were used to simulate the materials: brick and shell. The CFRP laminate was attached to the sagging and hogging region of the beam. The results showed that the ultimate strength of the beam was increased up to 73% when the laminate lengths at the sagging and hogging regions were equal to 40% and 60% of the span length respectively.

Two-dimensional nonlinear finite element software (ABAQUS) was used by Wu and Zhao et al. (2012) to simulate a double-strap joint of steel and CFRP using a cohesive element for the adhesive layer, while a bilinear plane strain quadrilateral element was used for CFRP and steel. The results showed that for specimens with CFRP bond lengths less than the effective bond length, failure started from the joint and propagated to the other end, and the failure load increased with increased bond length. However, for specimens with bond lengths more than the effective bond length, the failure load remained unchanged. The failure mode was within the adhesive layer for Sikadur adhesive specimens, however it was CFRP delamination and CFRP rupture for Araldite adhesive specimens, depending on the bond length. A comparison of the experimental slip results and those from FE analysis in different locations is shown in Figure 9. The softening zone is clear in finite element modelling, while it is not clear in the experimental curve because of the breakage of the strain gauges after failure.
To study numerically the flexural behaviour of the bond between CFRP and steel beams, which was experimentally investigated by Dawood and Rizkalla (2007), a three-dimensional non-linear finite element analysis was used by Seleem and Sharaky et al. (2010). One kind of element was used (brick) to simulate steel, adhesive and CFRP (see figure 10). The results of the numerical simulation were consistent with the experimental results for debonding load and stiffness for both specimens with a square splice plate and a tapered plate with adhesive fillet.

Seleem and Sharaky et al. (2010) continued the modelling to simulate another type of CFRP strengthening which is focussed near the supports, which was investigated experimentally by Schnerch and Rizkalla (2008), as shown in Figure 11.

The load deflection results of the numerical simulation approximated those of the experimental tests. The authors continued the testing by changing the length of CFRP from 2000 to 3500mm, and the results showed that there was no change in the failure load when CFRP bond length was more than 3000mm, while it decreased when the CFRP bond length decreased.
Yu and Chiew et al. (2011) simulated a four-point load on a steel beam strengthened by CFRP. Good agreement for the load–deflection and the strain–deflection relationships for both FE analysis and experimental results was achieved using a 3-D non-linear analysis with ABAQUS software (ABAQUS 2008).

Al-Zubaidy and Al-Mahaidi et al. (2013) simulated their experiments originally conducted in 2011 and 2012 (Al-Zubaidy, Zhao et al. 2011, Al-Zubaidy, Al-Mahaidi et al. 2012, Al-Zubaidy, Zhao et al. 2012) using the nonlinear FE software (ABAQUS). Static tests were simulated using Abaqus\Implicit code and Abaqus\Explicit code was used for the dynamic tests simulation. The steel, adhesive and CFRP were simulated as 3-D stress element, cohesive element and continuum shell element, respectively.

Due to the similarity of the specimens, one eighth of the specimen was simulated by applying symmetric boundary conditions to all nodes belonging to YZ, XY and XZ Cartesian planes (Figure 12). The result of this analysis showed that there is a good agreement between experimental and analytical analysis for the maximum load capacity, effective bond length, failure mode and strain distribution along the bond length of the joints.

Conclusion

This paper has included a summary of current research on the use of fibre reinforced polymers (FRP) to strengthen steel structures. This paper is a continuation of other reviews; Hollaway 2010. This paper has focused on the static and dynamic bond behaviour between CFRP and steel structures. Based on the review, several conclusions can be drawn as follows:

- Load enhancement is directly proportional to CFRP thickness for specimens in bending tests, while increased adhesive thickness causes decreased strength of bond.
- For tensile tests, the increase in joint capacity under impact load is double that in static tests for specimens for which the bond length is less than the effective bond length.
- Impact tension testing has no effect on the effective bond length of double strap specimens, i.e. the effective bond length is the same under static and impact tensile testing.
- Different failure modes occur for the double-strap joints under tensile load, depending on the strain rate, thickness of CFRP and bond length.
References


