INVESTIGATION ON THE BEHAVIOR OF CFRP-TO-STEEL JOINT USING CARBON NANOTUBES MODIFIED EPOXY ADHESIVE

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ABSTRACT

In this study, the bond characteristics between Carbon Fibre reinforced polymer (CFRP) laminates and steel with carbon nanotubes modified epoxy (CNT-epoxy) adhesive were studied. A series of experiments with double strap steel joints bonded with pure epoxy adhesive and/or CNT-epoxy adhesive were conducted. Experimental results presented in this paper include bond strength, failure modes, CFRP strain distribution and bond-slip relationship. The results show that failure mode in all specimens was a combination of steel-adhesive interface failure, cohesive failure, epoxy-CFRP interface failure and CFRP delamination. It was found that, CNT-epoxy is more efficient than pure epoxy to transfer the load from steel substrate to CFRP laminates. This paper provides an insight on the application of CNT-epoxy structural adhesive in the strengthening and rehabilitation of steel infrastructures using CFRP.

KEYWORDS

Carbon nanotubes, CFRP, strengthening, Bond interface, steel structures.

INTRODUCTION

Strengthening of steel structures with adhesively-bonded Fibre Reinforced Polymer (FRP) laminates has attracted much recent research attention (Hollaway 2010; Teng et al. 2012; Zhao and Zhang 2007). Carbon FRP (CFRP) is commonly used for the strengthening of steel structures due to its comparable modulus with that of steel (Nguyen et al. 2011). Extensive research has been conducted on FRP-to-concrete bonded interfaces (Al-Safy et al. 2013; Dai et al. 2013; Yuan et al. 2004). In contrast limited research on CFRP-to-steel bonded interfaces has been conducted (Fawzia et al. 2010; Yu et al. 2012). The main challenge is to predict the behaviour of such composite systems, especially the bond between CFRP and steel (Nguyen et al. 2011). Xia and Teng (Xia and Teng 2005) demonstrated that the concepts of interfacial fracture energy at FRP-to-concrete bonded joint can be applied for CFRP-to-steel bonded joints. They reported a bond–slip relationship for CFRP laminate to steel bonded joints. Their research identified a simple bilinear bond-slip relationship which has a linear ascending branch followed by a linear descending branch. It is demonstrated that the behaviour of the bond at CFRP-to-steel bonded joints is affected by the type of epoxy. Yu et al. (Yu et al. 2012) revealed that for CFRP-to-steel bonded joints with different types of adhesives, different forms of bond–slip models need to be developed. They used two nonlinear adhesives with a lower elastic modulus but a larger strain capacity and two linear adhesives with a similar or even a higher tensile strength but small strain capacity for bonding the CFRP-to-steel joints. They demonstrated that the bond-slip curve of joint bonded with linear adhesive has an approximately triangular shape while that of joint bonded with nonlinear adhesive is trapezoidal shape.

Modified epoxies with nanoparticles such as CNTs are promising nanocomposites can be used to exploit the full potential application of epoxies in FRP strengthened systems (Korayem et al. 2013). This paper reports the effect of CNT-epoxy on the bond behaviours of double strap joints. A series of experiments on the double strap joints were conducted with regards to bond strength, failure modes, CFRP strain distribution and bond-slip relationship. This research provides an insight to promote the application of CFRP laminates in the strengthening and rehabilitation of steel infrastructure.
EXPERIMENTAL PROGRAMME

Materials

Epoxy adhesive, CNTs, CFRP laminates and steel plates were used to fabricate the double strap joint specimens. A two-part room temperature curing adhesive with commercial name of Araldite 2011, supplied by Huntsman Company (Australia), was used in this research. It is the standard diglicidyl ether of Bisphenol A with average molecular weight < 700 together with an amines based hardener. CNTs were multi-walled carbon nanotubes with 9.5 nm average diameter and 1.5 µm average length supplied by Nanocyl Company. CFRP laminates were intermediate modulus of unidirectional MBBrace Laminates grade 210/3300, manufactured by BASF. It has nominal elastic modulus of 210 GPa and nominal tensile strength of 3300 MPa, based on the manufacturer’s specifications (BASF 2013). Steel plates were hot rolled structural steel HA300 with a thickness of 10 mm and with the same width of 50 mm as the CFRP laminates. They have a nominal yield stress of 300 MPa. The material properties and dimensions of steel plates were selected in such a way so as to avoid steel yielding during the tension loading process.

Fabrication and testing of double strap joint samples

The CNT-epoxy adhesive were fabricated following the protocol developed elsewhere (Korayem et al. 2013) and adopted to fabricate the double strap joints in current study.

The double strap joints were prepared from two steel plates joined together by CFRP laminates using epoxy adhesive. Steel plates had a dimension of 200 × 50 × 10 mm (length × width × thickness). The specimen details on the adhesive and CFRP laminates are summarized in Table 1. Both CNT-epoxy and pure epoxy were applied to investigate the effect of CNTs on the bond behaviour. The thickness of adhesive was controlled as 0.4 mm for all the specimens. To avoid the uncertainty of the location of debonding failure and to form failure in specific side of the joint; joints with unequal bond lengths were fabricated in which one side was 50 mm shorter than the other side. Therefore the shorter length is defined as the bond length of the joint. Each set of joints with pure epoxy and/or CNT-epoxy adhesive consists of the bond length of 20, 40, 60, 80, 100 and 120 mm. Specimen designations, which start with ‘P’ indicate the pure epoxy adhesive and those with ‘C’ stand for CNT-epoxy adhesive. The number that follows the letter is the bond length.

The fabrication process of double strap joints was similar to fabrication method presented by Wu et al. (Wu et al. 2012) unless the curing was 48 hours at ambient temperature following by post curing for four hours at 120°C. Specimens were tested in tension based on ASTM D3528 standard procedure. The loading rate was set as 0.5 mm/min in an attempt to simulate the static loading condition. At least three samples were tested for each bond length and the average load was reported. To assess the strain distribution along the CFRP laminates, a set of strain gauges with a gauge length of 8 mm were mounted on the top surface of the selected specimens. In order to measure the displacement of the joints, two linear variable differential transformers (LVDT) were used. The test set-up and instrumentation is illustrated in Figure 1.

Figure 1. Test set-up and instrumentation
RESULTS AND DISCUSSIONS

Bond strength and failure modes

Table 1 summarizes the bond strength for all the specimens and their corresponding failure modes. The typical failure modes are shown in Figure 2. In short bond lengths, the bond strength of CNT-epoxy joints was slightly higher than that of pure epoxy joints while it became lower when bond length increases.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Bond length (mm)</th>
<th>Adhesive</th>
<th>Measured $t_a$ (mm)</th>
<th>$P_u$ (kN)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>P20</td>
<td>20</td>
<td>Pure epoxy</td>
<td>0.35</td>
<td>55.16</td>
<td>(a) + (c)</td>
</tr>
<tr>
<td>P40</td>
<td>40</td>
<td>Pure epoxy</td>
<td>0.37</td>
<td>95.04</td>
<td>(a) + (b) + (c)</td>
</tr>
<tr>
<td>P60</td>
<td>60</td>
<td>Pure epoxy</td>
<td>0.33</td>
<td>129.22</td>
<td>(a) + (b) + (c)</td>
</tr>
<tr>
<td>P80</td>
<td>80</td>
<td>Pure epoxy</td>
<td>0.33</td>
<td>142.34</td>
<td>(a) + (b) + (c)</td>
</tr>
<tr>
<td>P100</td>
<td>100</td>
<td>Pure epoxy</td>
<td>0.43</td>
<td>143.39</td>
<td>(a) + (b) + (c) + (d)</td>
</tr>
<tr>
<td>P120</td>
<td>120</td>
<td>Pure epoxy</td>
<td>0.37</td>
<td>142.78</td>
<td>(a) + (b) + (c) + (d)</td>
</tr>
<tr>
<td>C20</td>
<td>20</td>
<td>CNT-epoxy</td>
<td>0.35</td>
<td>60.41</td>
<td>(a) + (c) + (d)</td>
</tr>
<tr>
<td>C40</td>
<td>40</td>
<td>CNT-epoxy</td>
<td>0.40</td>
<td>100.27</td>
<td>(a) + (c) + (d)</td>
</tr>
<tr>
<td>C60</td>
<td>60</td>
<td>CNT-epoxy</td>
<td>0.46</td>
<td>131.06</td>
<td>(a) + (c) + (d)</td>
</tr>
<tr>
<td>C80</td>
<td>80</td>
<td>CNT-epoxy</td>
<td>0.44</td>
<td>135.45</td>
<td>(a) + (c) + (d)</td>
</tr>
<tr>
<td>C100</td>
<td>100</td>
<td>CNT-epoxy</td>
<td>0.43</td>
<td>131.83</td>
<td>(a) + (c) + (d)</td>
</tr>
<tr>
<td>C120</td>
<td>120</td>
<td>CNT-epoxy</td>
<td>0.47</td>
<td>135.78</td>
<td>(a) + (c) + (d)</td>
</tr>
</tbody>
</table>

$t_a$: adhesive thickness (0.4 mm for the intended thickness); $P_u$: ultimate load (bond strength); (a): steel-epoxy interface debonding; (b): cohesive failure; (c): epoxy-CFRP interface debonding; and (d): CFRP delamination.

As shown in Figure 2, all specimens failure starts from the joint where the adhesive has the highest shear stress along the bond length (Fawzia et al. 2010). Following the failure at the joint, cracks propagated along the weakest components of the joints, leading to the eventual failure at the end of the bonds.

Figure 2. Failure modes of joints with (top) pure epoxy and (bottom) CNT-epoxy adhesive for different bond length (a) 20 mm; (b) 40 mm; (c) 60 mm; (d) 80 mm; (e) 100 mm; and (f) 120 mm

As can be seen from Figure 2, the weakest components in the specimens with pure epoxy, i.e. P20, P40, P60, P100, and P120, are steel-epoxy interface, epoxy-CFRP interface, cohesive layer, and their combination, which is in agreement with those observed in previous work (Akbar et al. 2010; Bocciarelli et al. 2007). Interestingly, no single failure mode is dominated in all specimens. However, it seems that the epoxy-CFRP interface is a little bit weaker than the steel-epoxy interface, especially when the bond length becomes longer. For example, more epoxy layers left on the steel surface in P80, P100 and P120 than those in P20 and P60 except P40 where the air voids in the epoxy-CFRP interface leading to premature failure. In other words, the specimens with longer bond length intend to failure at epoxy-CFRP interface.
Similarly, the weakest components in the specimens with CNT-epoxy, i.e. C20, C40, C60, C100, and C120, are also steel-epoxy interface, epoxy-CFRP interface, and their combination. Apparently more epoxy layers left on the steel surface in C80, C100 and C120 than those in C20, C40 and C60. In addition, there is little CFRP fiber attached to the epoxy-CFRP interface whereas CFRP fiber can only be observed in the specimens P100 for pure epoxy.

**Axial strain distribution along the CFRP plate**

Axial strain distributions along the CFRP laminates are shown in Figure 3 for P100 and C100 specimens. It is clear that for both pure epoxy and CNT-epoxy adhesive, the axial strain of CFRP laminates decreases with the distance away from the joint at each load level. The shapes of the strain distributions are similar to those reported by Yu et al. (Yu et al. 2012) for soft and stiff epoxy adhesives. It is noted that the ultimate strain of C100, 5433 μ, is higher than that of P100, 4304 μ.

![Figure 3. Strain distribution along bond with (a) pure epoxy adhesive and (b) CNT-epoxy adhesive](image)

**Bond-slip relationship**

The bond–slip curves of the joints can be derived from the axial strain distribution using (Pham and Al-Mahaidi 2007)

\[
\tau_{\text{max}} = \frac{(E_i - E_{\text{ave}})}{(L_i - L_{\text{ave}})} E_s t_f \\
\delta_{\text{max}} = \sum_{i=1}^{n} \frac{(E_i + E_{\text{ave}})}{2} (L_i - L_{\text{ave}})
\] (1a) (1b)
where $\varepsilon_i$ is the reading of the $i$th strain gauge counted from the joint; $L_i$ is the distance of the $i$th strain gauge from the joint; $E_p$ is the elastic modulus of the CFRP laminates; $t_p$ is the thickness of the CFRP laminates; $\tau_{avg}$ is the shear stress at the middle point between the $i$th strain gauge and $i-1$th strain gauge, $\delta_{avg}$ is the slip along the bond length and $n$ is the number of mounted strain gauges on CFRP along the bond length.

Figure 4. bond–slip curves of joints bonded with pure epoxy adhesive (P120) and CNT epoxy adhesive (C120)

Figure 4 shows the bond–slip curves for P120 (pure epoxy) and C120 (CNT-epoxy). Both bond slip curves have an approximately trapezoidal shape with an ascending branch followed by a plateau and then a descending branch. However, the plateau branch is more pronounced in the joint bonded with pure epoxy. The peak shear stress, 23.84 MPa, in the joint bonded with CNT-epoxy is higher than that of the joint bonded with pure epoxy, 21.75 MPa. It is in agreement with the results in Figure 7 in Ref. (Yu et al. 2012), i.e. the higher tensile strength of epoxy adhesive resulting in larger peak shear stress within the bond.

CONCLUSIONS

In this paper, the mechanical performance of CFRP-to-steel double strap joints with pure epoxy and CNT-epoxy adhesives were examined. It was found that, for both CNT-epoxy and pure epoxy, bond failure was the combination of steel-adhesive interface failure, cohesive failure, epoxy-CFRP interface failure and CFRP delamination. In short bond lengths, the bond strength of CNT-epoxy joints are higher than that of pure epoxy joints while it became slightly lower when bond length increases. The ultimate axial strain along the CFRP laminates in the joints bonded with CNT-epoxy is greater than that of the joint bonded with pure epoxy indicating CNT-epoxy is more efficient than pure epoxy to transfer the load from steel substrate to CFRP. For both pure epoxy and CNT-epoxy adhesive, bond slip curves have an approximately trapezoidal shape. However, the plateau branch is more pronounced in the joint bonded with pure epoxy compared to that for joint bonded with CNT-epoxy.

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