The topics of ACUN conferences cover all aspects of the science and technology of novel composite materials, from materials fabrication, processing, manufacture, structural and property characterization, sensor technology/structural health monitoring, theoretical analysis, modeling and simulation, to various applications in aerospace, automotive, civil infrastructure, packaging, ship-building, and recreational products.

ACUN conferences have a historical background:

In 1998 at an ICCE Conference in Las Vegas USA, Dr. Sri Bandyopadhyay (UNSW, Australia), Prof. Sami Rizkalla (then of University of Manitoba, Canada), Dr. Piyush Dutta (CRREL, USA), and Prof. Debes Bhattacharyya (U Auckland, NZ) discussed the possibility of a totally new class of composites conference.

This led to the birth of ACUN conferences: ACUN-1 in 1999, ACUN-2 in 2000, ACUN-3 in 2001, ACUN-4 in 2002 and ACUN-5 in 2006 all held at University of New South Wales - Australia.

The ACUN-3, ACUN-4 and ACUN-5 conferences held at UNSW were ranked by majority delegates from 21 countries as amongst the World's top 5 to 10 conferences they attended in their entire career.

ACUN-5 conference proceedings are available on the website: http://www.simpas.unsw.edu.au/pmp/acun-5/home.htm
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MINING INFRASTRUCTURE

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Experimental Investigation on FRP to Steel Adhesively-bonded Joint under Tensile Loading

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ABSTRACT: Due to various advantages of Fibre-Reinforced Polymer (FRP) decks, the FRP to steel composite girder system is being increasingly used in the construction of new bridges as well as the rehabilitation projects of old bridges. This paper focuses on the mechanical behaviors and failure modes of the adhesively-bonded joints between FRP sandwich decks and steel girders. A tensile-shear loading device was designed and presented herein. The adhesively-bonded joints were experimentally investigated under tensile loading. The average ultimate failure load of surface pretreated specimens was 17.62 kN, which was 9.83% higher than that of un-pretreated specimens. Further comparison on failure modes confirmed that the surface pretreatment can improve the bonding quality between FRP composites and adhesive layer, and correspondingly increase the strength of the whole adhesive joint under tensile loading.

1 INTRODUCTION

Fibre-reinforced polymer (FRP) composite materials are being increasingly used in many civil engineering applications as a competitive alternative for conventional materials like steel, wood and concrete. One conspicuous utilization of FRP composites is FRP bridge decks, which offers tremendous potential to meet critical needs for rehabilitation and new construction of pedestrian and highway bridges. This is mainly due to the advantages of FRP decks which allow the lightweight of bridge superstructures, the ease of installation, minimum traffic disturbing, large tolerance for environmental corrosion, long service life time, as well as low maintenance cost. Current commercially available FRP decks can be classified into two categories according to the types of assembly and construction: sandwich panels and multi-cellular type panels (Zhou and Keller 2005), as shown in Figure 1.

To be cost effective, the FRP decks are usually supported by steel girders, as shown in Figure 2. Steel girders enhance the ductility of this composite bridge system after failure loading achieved, which compensate for the brittle characteristics of FRP composites. Between the FRP decks and steel girders, adhesively bonding technique is usually employed as a preferable connection method. Comparing to bolted or stud connections, adhesively-bonded connections can reduce construction time, save weight by eliminating fasteners, introduce more uniform load transfer and provide better long-term performance. Bolted connections usually result in much higher stress concentrations where cracks occur, while adhesive connections are a more material-adapted connection.
technique since larger surfaces can be glued together, thus reducing stresses. This kind of FRP composite girder system was utilized during recent years (Cassity et al. 2002, Luke et al. 2002, Knippers et al. 2010). In Knippers's research (Knippers et al. 2010), it was employed as a flyover across the federal road B3 in Germany. The high durability of the FRP composites and the fast assembly of the bridge were decisive factors for this application. Through the experimental investigations (Cassity et al. 2002), the degree of composite action between cellular FRP decks and steel girders was studied and subsequently adopted in a rehabilitation project of an old and deteriorated bridge. Through these projects, valuable experience was gathered concerning in-site constructions, and the good performance of FRP composite decks was confirmed.

Figure 2. FRP composite deck to steel girder bridge system (Schollmayer 2009)

Regarding to the mechanical performance of adhesively bonded joints, researches (Keller and Vallee 2005a, b, Vallee and Keller 2006) were conducted, focusing on the adhesively bonded single-lap joints and double-lap joints. These adhesive joints composed of pultruded GFRP composite profiles glued by epoxy adhesives. Parametric studies were conducted experimentally and numerically on the overlap length, the adhesive layer thickness, the adherend thickness and the degree of chamfering of the adherends. The results indicated that the combination of local through-thickness tensile (peeling) and shear stresses was the most severe stress-state and usually initiated the failures in the outer fiber-mat layers of the adherends below the joint edges. Further researches (Vallee et al. 2006b, a) offered a probabilistic strength prediction method on the adhesive joints under quasi-static axial tensile loading. Unfortunately the technical background and researches on the adhesively bonded joints between FRP decks and steel girders have not been documented adequately in literatures. The researches (Gurtler 2004, Schollmayer 2009) investigated the mechanical behaviors of FRP-steel composite girder system in the longitudinal bridge direction and transverse direction respectively, but not particularly for the adhesive joint part. The research presented in this paper was focusing on the adhesively-bonded joints between FRP sandwich decks and steel girders. A tensile-shear loading device was designed with the capacity to provide the combination of tensile and shear loads in six different ratios. The mechanical behaviors and failure modes of adhesively-bonded joints under tensile loading were investigated experimentally, considering different surface pretreatment methods on FRP sandwich decks and steel girders.

2 TENSILE-SHEAR LOADING DEVICE

Generally, there are three typical stress states for the adhesive joint between FRP decks and steel girders:

1. shear stress \( \tau \): due to the composite action between FRP deck and steel girder in the longitudinal direction of bridge, the decks and steel girders trend to bend together to carry the traffic load. Thus, the adhesive joint are under the shear stress condition to transfer the loading from FRP decks to steel beams, as shown in Figure 3a);

2. tensile stress \( \sigma \): in the transverse direction of bridge, loading on other traffic lanes causes up-lift forces on adhesive joints, which results in tensile stress, as shown in Figure 3b);

3. combination of above two stress states with different ratios of contributions from tensile stress state and shear stress state.

Figure 3. Typical stress states of the adhesive joint

Depending on the above three stress states, a smart loading device was needed for providing tensile
The adhesively-boned joint between FRP deck and steel girder was extracted for experimental investigation as shown in Figure 4.

A 190mm x 90mm piece of sandwich bridge deck was adhesively bonded to the convex shape steel support. In the middle of sandwich deck was the 38.1mm Balsa SB150, a core material produced from certified kiln-dried balsa wood in the ‘end-grain’ configuration. The surface layers were three layers of 0.94mm EQX1200, which are the glass-fibre reinforced laminated polymer composites (54% glass content by weight). The sandwich profiles were manufactured by resin vacuum infusion. The thickness of 90mm x 90mm adhesive layer was 6mm. The dimensions of adhesive joint were determined depending on the actual conditions of composite bridges as well as limitations of loading equipment. In order to fix the adhesive joint to the loading system, other accessorial components were designed as shown in Figure 5. The steel support was grilled with 4 holes to be connected to steel blocks by bolts. For the sandwich decks, no hole was made, since the discontinued part in decks will cause more stress distribution distortion, which was not actual in applications of composite bridges. In order to fix the adhesive joint to the loading system, other accessorial components were designed as shown in Figure 5. The steel support was grilled with 4 holes to be connected to steel blocks by bolts. For the sandwich decks, no hole was made, since the discontinued part in decks will cause more stress distribution distortion, which was not actual in applications of composite bridges. All the accessorial components were manufactured by steel. Comparing with the FRP composites and adhesive materials, the deformation of the steel components can be neglected during tests, due to the high stiffness of steel material. To fix the sandwich deck part, it was designed to be fastened by two purple-color L-shape steel plates through four bolts to the top steel block, as shown in Figure 5a). While, the steel support was fastened directly through four bolts to the bottom steel block, as shown in Figure 5b). The two steel blocks were fastened to circular steel plates, as shown in Figure 5c). The circular steel plates were separated into two pieces. Three bolts were employed to transfer the loading uniformly. By loading the different angles of circular steel plates, the specific stress-state can be achieved in the adhesive joint, such as pure tension, pure shear and combination of both. Correspondingly, six loading conditions were feasible through this well-designed loading system.

![Figure 4. FRP-steel adhesively bonded joint](image)

A 190mm x 90mm piece of sandwich bridge deck was adhesively bonded to the convex shape steel support. In the middle of sandwich deck was the 38.1mm Balsa SB150, a core material produced from certified kiln-dried balsa wood in the ‘end-grain’ configuration. The surface layers were three layers of 0.94mm EQX1200, which are the glass-fibre reinforced laminated polymer composites (54% glass content by weight). The sandwich profiles were manufactured by resin vacuum infusion. The thickness of 90mm x 90mm adhesive layer was 6mm. The dimensions of adhesive joint were determined depending on the actual conditions of composite bridges as well as limitations of loading equipment. In order to fix the adhesive joint to the loading system, other accessorial components were designed as shown in Figure 5. The steel support was grilled with 4 holes to be connected to steel blocks by bolts. For the sandwich decks, no hole was made, since the discontinued part in decks will cause more stress distribution distortion, which was not actual in applications of composite bridges. In order to fix the adhesive joint to the loading system, other accessorial components were designed as shown in Figure 5. The steel support was grilled with 4 holes to be connected to steel blocks by bolts. For the sandwich decks, no hole was made, since the discontinued part in decks will cause more stress distribution distortion, which was not actual in applications of composite bridges. All the accessorial components were manufactured by steel. Comparing with the FRP composites and adhesive materials, the deformation of the steel components can be neglected during tests, due to the high stiffness of steel material. To fix the sandwich deck part, it was designed to be fastened by two purple-color L-shape steel plates through four bolts to the top steel block, as shown in Figure 5a). While, the steel support was fastened directly through four bolts to the bottom steel block, as shown in Figure 5b). The two steel blocks were fastened to circular steel plates, as shown in Figure 5c). The circular steel plates were separated into two pieces. Three bolts were employed to transfer the loading uniformly. By loading the different angles of circular steel plates, the specific stress-state can be achieved in the adhesive joint, such as pure tension, pure shear and combination of both. Correspondingly, six loading conditions were feasible through this well-designed loading system.

![Figure 5. Tensile-shear loading device](image)

**3 EXPERIMENTAL INVESTIGATION**

The FRP-steel adhesively-bonded joints were experimentally investigated under tensile loading. The test setup were shown in Figure 6. A SCHENCK Hydropuls testing machine with a capacity of 200 kN in tension was employed and controlled by the INSTRON 8400 controller. The whole tensile-shear device was loaded by jacks through two hinged joints, which could avoid the additional bending moment due to eccentric loading. The quasi-static experiments were performed under LVDT (linear...
variable differential transformer)-control at the rate of 0.001 mm/sec and the failure took approximately 13 minutes for the strongest specimens. Two LVDTs were assigned on each side of the loading system, as shown in Figure 6, which measured the displacement between the top and bottom loading device. What is more, three displacement sensors were assigned on both sides of adhesive joints, to track the vertical deformation between FRP sandwich deck and steel support during the whole test process, as shown in Figure 7 and Figure 8. Six replicated specimens were prepared as shown. Before making the gluing, three of specimens were pretreated on the surfaces of FRP sandwich deck and steel supports by using sandpapers and acetone. For comparison, the other three specimens were glued without any surface pretreatment. The surface pretreated specimens were indicated as SP-specimens in the following chapters, and un-pretreated specimens were described by UP-specimens.

Figure 6. Experimental set-up

Figure 7. Adhesive joint specimen

Figure 8. Assignment of six displacement sensors

4 RESULTS AND DISCUSSION

For the UP-specimens, the loads increased almost linearly up to failure. As listed in Table 1, the average ultimate failure load was 16.04 kN, the deviation from the three specimens was within 3%, which means the test results were reliable.
Table 1. Ultimate failure loads of six adhesive joints

<table>
<thead>
<tr>
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<th>UP01</th>
<th>UP02</th>
<th>UP03</th>
<th>Average</th>
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<tbody>
<tr>
<td>Failure load (kN)</td>
<td>15.69</td>
<td>16.43</td>
<td>16.04</td>
<td>16.05</td>
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<table>
<thead>
<tr>
<th></th>
<th>SP01</th>
<th>SP02</th>
<th>SP03</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure load (kN)</td>
<td>19.37</td>
<td>17.93</td>
<td>15.57</td>
<td>17.62</td>
</tr>
</tbody>
</table>

Figure 10 shows the load-displacement curves of three adhesive joint specimens, which were measured by the LVDTs. It is manifest that the curves from UP-specimen01 and UP-specimen02 agree well with each other. But for the UP-specimen03, the stiffness is a bit different from the other two curves, which could be due to the deviation of material properties and quality of gluing between FRP sandwich deck and steel support. It is obvious that the three curves are almost parallel to each other in the stable load increasing stage. It can be explained that at the beginning of loading, the friction between each component of loading device made the initial stiffness of specimens different from each other. However, when the loading is large enough beyond the friction, the stiffness of three adhesive joints was more or less the same.

Figure 9 shows the measurement of vertical deformation between FRP sandwich deck and steel support on the UP-specimen01 from six displacement sensors. Tests on other specimens have the similar mechanical behavior in the vertical direction. It is clearly seen that the measured data from displacement sensors DS-01, DS-03, DS-04 and DS-06 are close to each other, while the deformation from DS-02 and DS-05 are relatively smaller. It implies that the edge part of bonding area deformed larger than the middle part. However, the total deformation through the adhesive joint was in a very small scale. Figure 9 also shows that, besides the pure tensile loading, a certain amount of additional bending moment was also applied during the whole testing process, with the deformation from DS-01, DS-03, DS-04 and DS-06 deviating from each other. It means the loading was not applied exactly centrically on the adhesive joint, which cannot be avoided in such a small scale test.

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For the SP-specimens, the load-displacement curves were plotted in Figure 10. For comparison, the three curves of UP-specimens were also included in the same figure. It is manifest that, besides the similar stiffness with UP-specimens, a certain extent of ductility was achieved after the failure of SP-specimens, especially for the SP-specimen01. The degree of ductility was closely related to the failure mode. Figure 11 shows the failure modes of SP-specimens comparing with UP-specimens. It can be clearly observed that the failure plane for un-pretreated adhesive joint was through the interface between the FRP sandwich deck and adhesive layer. For the SP-specimens, the failure plane partly moved to the delamination of FRP composites, as shown in Figure 12.
The average ultimate failure load of SP-specimens was 17.62kN, which was 9.83% higher than that of UP-specimens. It means that the surface pretreatment can improve the bonding quality between FRP composites and adhesive layer, and correspondingly increase the strength of the whole adhesive joint under tensile loading. What is more, from Figure 11a), it can be found that the areas of FRP delaminated parts are different among SP-specimens. SP-specimen01 attained the largest FRP delaminated area which covered almost the whole bonding area, while SP-specimen03 attained the smallest. That is why the SP-specimen01 owned the maximum ultimate failure load, better ductile performance and even higher stiffness. Thus, the conclusion can be easily drawn that the strength and ductility of the surface-pretreated adhesive joints are closely related to the FRP delaminated area.

5 CONCLUSION

FRP sandwich deck to steel support adhesively bonded joints were experimentally investigated under the tensile loading condition. The mechanical behavior of adhesive joint specimens with surface pretreatment (SP) and un-pretreatment (UP) were compared. For UP-specimens, the joints failed in a brittle mode, which occurred between FRP sandwich deck and adhesive layer. The average ultimate failure load of UP-specimens was 16.04 kN. For SP-specimens, the failure of adhesive joint was triggered by delamination of FRP composites, which resulted in a relatively ductile failure mode. The average ultimate failure load of SP-specimens was 9.83% higher than that of UP-specimens. The further discussion confirmed that strength and ductility of the surface-pretreated adhesive joints were closely related to the FRP delaminated area. Therefore, the sufficient surface pretreatment on FRP sandwich decks and steel girders is necessary to improve the mechanical performance of the adhesively bonded joints under the tensile loading.

REFERENCES


