ABSTRACT
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Dear Prof. Scott Smith and Prof. Jian-Fei Chen

We wish to submit the following paper for the JCC Special Issue in Celebration of the 10th Anniversary of IIFC.

Paper title: **Effect of Dynamic Loading and Environmental Conditions on the Bond between CFRP and Steel: State-of-the-Art Review**
Authors: X.L. Zhao, Y. Bai, R. Al-Mahaidi and S. Rizkalla

We look forward to receiving the peer review comments.

Thanks

Prof. Xiao-Ling Zhao
22 Feb. 2013
Effect of Dynamic Loading and Environmental Conditions on the Bond between CFRP and Steel: State-of-the-Art Review

Xiao-Ling Zhao, F.ASCE\textsuperscript{a}, Yu Bai\textsuperscript{a}, Riadh Al-Mahaidi, M.ASCE\textsuperscript{b} and Sami Rizkalla, F.ASCE\textsuperscript{c}

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\textsuperscript{b}Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, Australia
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ABSTRACT

Carbon fibre reinforced polymer (CFRP) has great potential in strengthening steel structures, and the bond between CFRP and steel is a critical issue in the strengthening technique. State-of-the-art reviews have been reported in the literature on the bond behaviour between CFRP and steel under static loading at ambient temperature. However, steel structures are often subjected to dynamic loading and harsh environment conditions, and the bond between CFRP and steel may be affected by these conditions.

This paper presents a state-of-the-art review on the effect of dynamic loading (e.g. fatigue, impact and earthquake) and environmental conditions (e.g. sub-zero temperatures, elevated temperatures, sea water, UV light) on the bond between CFRP and steel. The combined effect of applied loading and environmental conditions is also included. Directions for future research are indicated, and a comprehensive reference list is provided.

KEYWORDS: bond, CFRP, dynamic loading, environmental conditions, steel structures
1. INTRODUCTION

Carbon fibre reinforced polymer (CFRP) has high strength to weight ratio, and is resistant to corrosion and environmental degradation (Hollaway and Teng 2008). While CFRP has been widely used in strengthening concrete structures (e.g. Teng et al. 2002; Rizkalla et al. 2003; Oehlers and Seracino 2004), it has not been widely applied to steel structures. The knowledge gained from research on the CFRP-concrete composite system may not be applicable to the CFRP-steel system because of the distinct difference between the debonding mechanisms, and the unique failure modes (e.g. local buckling, fatigue) for steel members and connections. CFRP has great potential to strengthen steel structures in the field of Civil Engineering.

The bond between CFRP and steel is a critical issue in the strengthening technique. State-of-the-art reviews have been conducted (Hollaway and Cadei 2002; Zhao and Zhang 2007; Teng et al. 2012a; Teng et al. 2012b) on the bond behaviour between CFRP and steel under static loading at ambient temperature. However, steel structures are often subjected to dynamic loading and harsh environment conditions, as illustrated in Figure 1, and the bond between CFRP and steel may be affected by these conditions. Table 1 presents a summary of research on the bond between CFRP and steel. The majority of the research was conducted within the last 10 years. The most commonly used test set-up is a double-shear pull arrangement (also called double-strap joints), as shown in Figure 2. Other test set-ups include single-shear pull and single-lap joints, as described in Zhao and Zhang (2007).

This paper presents a state-of-the-art review on the effect of dynamic loading (e.g. fatigue, impact, earthquake) and environmental conditions (e.g. sub-zero temperatures, elevated temperatures, seawater, UV light) on the bond between CFRP and steel. The combined effect of applied loading and environmental conditions is also discussed. Directions for future research are indicated, and a comprehensive reference list is provided.
2. INFLUENCE OF FATIGUE LOADING ON THE BOND

Liu et al. (2010) performed tests to investigate the influence of fatigue loading on the bond between steel and CFRP sheet with both normal modulus (240 GPa) and high modulus (640 GPa) sheet. The specimens were tensioned to failure after enduring a pre-set number of fatigue cycles that ranged from 0.5 to 10 million at different load ratios ranging from 0.15 to 0.55. The load ratio is defined as the ratio of the maximum value of the applied load \( P_{\text{max}} \) to its static ultimate strength \( F_1 \). The influence of fatigue loading can be obtained by comparing the values of \( F_1 \) and the ultimate strength \( F_2 \) after a pre-set number of fatigue cycles. The bond strength ratio \( F_2/F_1 \) is plotted in Figure 3 against the pre-set number of fatigue cycles. It can be seen from Figure 3 that the reduction in bond strength was around 20% to 30% for normal modulus CFRP sheet. Almost no reduction in bond strength was observed for specimens with high modulus CFRP sheet, even when the load ratio was as high as 0.55 and the number of fatigue cycles reached 10 million. Liu et al. (2010) also confirmed that fatigue loading does not affect the failure modes in bond tests.

Tests were conducted by Matta (2003) on the influence of fatigue loading on bond between steel and normal modulus (166 GPa) CFRP plate. The test results are included in Figure 3. It can be seen that they lie in the same range as the results for normal modulus CFRP sheet.

A similar study was carried out by Wu et al. (2013) on the influence of fatigue cycle on the bond between high modulus (479 GPa) CFRP plates and steel. The bond strength ratio \( F_2/F_1 \) is also plotted in Figure 3 against the pre-set number of fatigue cycles, which reveals that the influence is minimal (less than 4.5%). Wu et al. (2013) examined microscope images of the fracture surface and found that the fatigue loading introduced damage only within a very small zone close to the joint, i.e., a local “fatigue damage zone” (see Figure 4). The length of this local damage zone was found to be less than 1% of the bond length, which explains to some extent why the influence of fatigue cycle is not significant. The effect of fatigue loading on joint stiffness was also investigated by Wu
et al. (2013). It was found that the reduction in stiffness is less than 10% due to accumulated damage caused by fatigue loading.

Miller et al. (2001) conducted fatigue tests on two full-scale bridge girders rehabilitated with CFRP plates for 10 million cycles at a stress range that might be expected in the field. No evidence of debonding was observed by visual inspection even after the 10 million cycles.

3. INFLUENCE OF IMPACT LOADING ON THE BOND

3.1 Effect of Impact Load on Material Properties

Significant variation in the material properties is expected under impact loading in comparison with quasi-static loads (see for example Lu and Yu 2003). Al-Zubaidy et al. (2013a) carried out an experimental investigation on the mechanical properties of unidirectional normal modulus CFRP sheet, Araldite 420 and MBrace saturant adhesives under impact tensile loads. The strain rate for quasi-static tests was $2.42 \times 10^{-4} \text{ s}^{-1}$ and $6.66 \times 10^{-4} \text{ s}^{-1}$ on CFRP and adhesives, respectively. The impact tests had a strain rate of 54.2, 67.2 and 87.4 $\text{ s}^{-1}$ for both CFRP sheet and epoxy, which is about 80,000 to 360,000 times that of static tests. The test set-up is shown in Figure 5, where a specially designed rig (Al-Zubaidy 2012) converts impact load to tensile force in the specimens.

The influence of strain rate on material properties (e.g. tensile strength, modulus of elasticity and strain at failure) and absorbed energy is shown in Figure 6. For CFRP, there is about a 20% to 40% increase in tensile strength. The increase in modulus of elasticity is about 20%, whereas the increase in strain at failure ranges from 7% to 24%. The energy absorbed increases as the strain rate increases and reaches up to 80%.

The influence of strain rate on material properties and absorbed energy for adhesives is also plotted in Figure 6. Araldite 420 has much higher increases in tensile strength and modulus of elasticity than MBrace saturant. However, the strain at failure for Araldite 420 reduces about 50% under such impact loading, whereas the strain at failure for MBrace saturant increases about 50% to 100%. More absorbed energy is observed for MBrace saturant than for Araldite 420. This is probably
because of the significant reduction in strain at failure in the case of Araldite 420 as shown in Figure 6 (c).

3.2 Effect of Impact Load on Bond Strength

Al-Zubaidy et al. (2012a;2012b) conducted double-shear pull tests to investigate the influence of impact loads on bond strength between CFRP sheets and steel. Both Araldite 420 and MBrace saturant were used as the adhesives in the testing program. The bond length varied from 10 to 100 mm. The number of CFRP layers was taken as one and three. The loading rate was around 2mm/min for static test and 4.26m/s on average for impact test. The effect of strain rate on bond strength is shown in Figure 7. It can be seen that more influence is observed for three layers of CFRP-steel system, with an average increase of 70% for Araldite 420 and 25% for Brace saturant. The influence on effective bond length is minimal.

FE modelling was reported in Al-Zubaidy et al. (2013b) where failures of both CFRP sheet and adhesive are considered and a cohesive element is utilised to model the interface. The FE gave reasonable predictions in terms of bond strength, effective bond length, failure patterns and strain distribution along the bond length.

3.3 Effect of Impact Load on Adhesion Bond Strength

The adhesion pull-off test is commonly employed, particularly due to its ease of application in both site and laboratory investigations, to evaluate the adhesion bond strength of adhesive. Al-Zubaidy et al. (2013c) performed a series of pull-off tests on CFRP sheet and steel under impact load (up to 5 m/s). The effect of CFRP layouts and various adhesives on these parameters was examined by adopting CFRP/steel samples with one and three CFRP layers using Araldite 420 and MBrace saturant adhesives. The higher degree of enhancement in the adhesion bond strength is realized for samples with one CFRP layer compared to that of specimens with three layers. This is related to the occurrence of CFRP delamination which accelerates with increased CFRP layers and loading rate. Overall, the increase in pull-off strength is about 100% on average within the dynamic loading
speeds tested. More research is required to investigate how to avoid CFRP delamination within the CFRP layer as well as throughout the subsequent layers to ensure a more adequate and safe strengthening/repair process.

4. INFLUENCE OF LARGE DEFORMATION CYCLIC LOADING ON THE BOND

A total of 12 double shear pull tests were carried out (Bai, T. et al. 2008) to study the post-yielding behaviour of CFRP-steel bonded joints under static and cyclic loading. Normal modulus CFRP sheet and Araldite 420 were adopted in the testing program. The geometry of the steel plates was carefully designed using finite element analysis to achieve steel yielding either within the bonded area or outside the bonded area.

The cyclic loading scheme is illustrated in Figure 8, and is similar to that defined in ATC-24 (1992). Only cyclic tensile loading was adopted in lieu of reverse cyclic loading because CFRP is weak in compression and susceptible to buckling. A specimen was first loaded at a constant value of 75% of yield load \( Q_y \) for 6 cycles. The following loading steps were uniformly divided into 4 stages with deformation increment of \((\delta_u-\delta_y)/4\). A static test was conducted to determine the yield load \( Q_y \) and the corresponding deformation \( \delta_y \), as well as the ultimate deformation \( \delta_u \).

It was found that specimens subjected to cyclic loading exhibit certain ductility compared with those under monotonic loading. Steel and adhesive interfacial debonding failure was observed in specimens with steel yielding outside the bonded area, whereas CFRP delamination failure mode was observed in specimens that had steel yielding within the bonded area. Deterioration of stiffness was not evident in each cyclic loading. The influence of large deformation cyclic loading on bond strength is plotted in Figure 9 by comparing the ultimate joint capacity under dynamic and static loading. Bond strength reduction is not more than 15% over a bond length ranging from 60 to 100 mm. A conservative estimation of 15% reduction may be concluded based on the limited test data.
5. INFLUENCE OF SUB-ZERO TEMPERATURES ON THE BOND

A study of the effect of sub-zero temperatures (0, -20 and -40°C) on the material properties of CFRP and adhesives and the bond behaviour between CFRP and steel was reported in Al-Shawaf et al. (2005, 2006) and Al-Shawaf and Zhao (2013). Normal modulus CFRP sheet and three types of adhesives (Araldite 420, MBrace saturant and Sikadur 30) were adopted in the testing program.

An increased brittleness of CFRP sheet was observed as the temperature reduced, as illustrated in Figure 10. The main feature in the failure mechanism of the sub-zero-tested specimens was the brittle mode characterised by a series of continuous material fragmentation and splitting associated with sudden breakage of the fibres. The influence of sub-zero temperatures on the material properties (modulus of elasticity, ultimate tensile strength and ultimate strain) of the CFRP sheet is shown in Figure 11 (a). It seems that the material properties of CFRP sheet do not vary significantly (within 10% as shown in Figure 11(a)) as the environmental temperature reduces from 20°C to -40°C.

The influence of sub-zero temperatures on the material properties of the three adhesives is illustrated in Figure 11 (b). There is a general increase in modulus of elasticity when the temperature reduces from 20°C to -40°C. The increased percentage is about 48% for Araldite 420, 90% for MBrace saturant and 16% for Sikadur 30. MBrace saturant, with the largest increase in modulus, has a reduction (40%) in ultimate tensile strength, whereas Sikadur 30, which has the smallest increase in modulus, has the largest increase (46%) in ultimate tensile strength. There is little change in the ultimate tensile strength for Araldite 420. The ultimate strain reduces as the temperature reduces for Araldite 420 (about 60% reduction) and MBrace saturant (about 80% reduction). The influence of sub-zero temperature on the ultimate strain is minimal for Sikadur 30.

It was found by Al-Shawaf and Zhao (2013) that no reduction in bond strength occurred at sub-zero temperatures down to -40°C for specimens with Araldite 420 and Sikadur 30. For specimens with
MBrace saturant the bond strength reduced about 40% when the temperature dropped from 20°C to -40°C.

6. **INFLUENCE OF ELEVATED TEMPERATURES ON THE BOND**

In comparison to applications under low temperatures, a steel/CFRP adhesively-bonded system appears to be more critical under elevated temperatures. This is because the strength and stiffness of the resin or adhesive decrease rapidly when the temperature exceeds its glass transition temperature \(T_g\), being less than 100°C for most cold-curing resin and adhesive products.

The mechanical degradation of resin may lead to a reduction of mechanical properties of the resulting FRP composites (Bai, Y. et al. 2008). Such behaviour becomes more significant for resin-dominated properties (for example compressive and shear strength) than for fibre-dominated properties (for example tensile strength in fibre direction) (Bai and Keller 2009). These researchers reported that the compressive strength of a GFRP composite reduced to 9.2% of that at room temperature and the shear strength reduced to 13% when the temperature was increased to 200°C. The tensile strength of a CFRP composite was examined under elevated temperature in Cao et al. (2009) and a 43% reduction was found when the temperature was increased to 55°C and maintained up to a temperature of 200°C.

In specific applications where a steel structure is strengthened with FRP composites, not only do the FRP composites in such structures degrade at elevated temperatures, but the adhesive layer between FRP composites and steel is also at risk. The latter factor may be even more critical because of the relatively lower glass transition temperature of the structural adhesives in comparison to that of the composites. Three different commercially-available epoxy adhesives were used in Al-Shawaf et al. (2009) to fabricate steel/CFRP double strap joints and the mechanical responses in tension of these joints were examined at 20, 40 and 60°C. Significant reductions in joint strength ranging from 20% to 30% were observed. CFRP rupture at the joint region was found to be the prevailing failure mode for the 20°C and 40°C exposures, while de-bonding failure became a generic trend for the joints
conditioned at 60°C (above the adhesive or resin $T_g$). This study provided evidence that the mechanical performance of steel/CFRP double strap joints subjected to elevated temperatures is largely dominated by that of the adhesive.

A series of steel/CFRP double strap joints was examined at elevated temperatures from 20°C to 50°C in Nguyen et al. (2011), with one or three layers of normal modulus carbon fibre sheet (namely CF1 or CF3) and different bond lengths ranging from 10mm to 150mm. In addition to providing evidence of the temperature dependence of ultimate joint capacity, this study further clarified the effects of bond length on joint mechanical performance under elevated temperatures. Figure 12(a) shows that at a given temperature, the joint’s ultimate capacity is increased with the bond length until a certain value is reached. The corresponding bond length is therefore defined as the effective bond length at this temperature. For the CF1 joints, it was found that the effective bond length was 22mm at 20°C, and increased to 48mm at 40°C and to 96mm at 50°C. Similar behaviour was also found for the CF3 joints, as shown in Figure 12(b), in which the effective bond length increased from 38mm at 20°C to 60mm at 40°C and 125mm at 50°C. The reduction of joint ultimate capacity is therefore a function of both temperature and bond length. Mechanism-based modelling was developed in Nguyen et al. (2011), and the modelling results compared well with the experimental data. A similar joint configuration has been examined in a recent study (Liu et al. 2012) with high modulus CFRP sheets. The results as shown in Figures 12(a) and (b) indicated that the effective bond length of steel and high modulus CFRP joints increased with temperature. For joints with normal modulus CFRP, however, the effect is less pronounced.

7. INFLUENCE OF SEA WATER EXPOSURE ON THE BOND

CFRP composites used to strength steel structures are inevitably exposed to moisture, and in some more critical cases, to other solutions such as sea-water during their service life. It is necessary to examine the strengthening performance of adhesively-bonded CFRP systems for such underwater applications as their long-term performance is of high importance.
An experimental investigation tailored to the offshore industry and techniques associated with underwater repair methods was conducted by Seica and Packer (2007). In this study, six steel tubes wrapped with CFRP composites were tested under a four-point bending arrangement and compared to the reference specimen without CFRP strengthening. The CFRP strengthened specimens were cured either in air or under water. Although the study focussed on strengthening efficiency, no serious de-bonding was found for the applications under water in the short term.

Environmental durability up to six months was evaluated by Dawood and Rizkalla (2010) for a series of steel/CFRP (high modulus CFRP plates) adhesively-bonded double lap joints. The specimens were subjected to combined cyclic water exposure (1 week wet/1 week dry cycles in a 5% NaCl solution at a temperature of 38°C) and a sustained load level of 15 kN (corresponding to 35% of the average ultimate strength of the control specimen without environmental exposure). To achieve simultaneous mechanical loading and water exposure, a water tank (see Figure 13) was specially designed using reinforced concrete to act as a self-reacting frame to balance the constant sustained load applied to the specimens. Different methods to enhance the bond durability were examined including 1) pre-treating the steel surface with a silane coupling agent (Detail AS), 2) inserting a glass fibre layer within the adhesive (Detail AG) and a combination of both (Detail AGS). The resulting residual bond strengths after different exposure durations are shown in Figure 14 and compared to those of joints without any bond protection (Detail A). It was found that specimens with Detail A showed a 60% degradation of residual bond strength, while those with Detail AS showed almost no degradation after 6 months of exposure. Although an additional layer of glass fibre in Detail AG improved the initial bond strength, a considerable reduction in bond strength was still observed after 6 months of exposure as shown in Figure 14. Again, a combination of < NOT CLEAR the addition of????silane in Detail AGS helped to retain the residual bond strength after water exposure.

A longer exposure of one year to simulated sea water (with 5% NaCl) and two temperatures (20°C and 50°C) was investigated for steel/CFRP adhesively-bonded joints by Nguyen et al. (2012a). The
specimens were regularly removed from the water tank after 2, 4, 6, 9 and 12 months of exposure and the residual bond strength in tension was measured. The results are shown in Figure 15. It was found that the bond strength degraded rapidly in the first 2 to 4 months of exposure and this reduction became much slower after 6 months. Also, a higher exposure temperature in sea water corresponded to a faster reduction in residual bond strength, particularly in the initial stage.

8. INFLUENCE OF UV LIGHT ON THE BOND

The CFRP composites used in strengthening steel structures are exposed to UV light during their service in outdoor environments. This exposure may affect the resin and/or the fibre, reducing the load capacity of the composite and the bond. The effects of UV exposure on different systems of FRP composites have been investigated using accelerated laboratory experiments and noticeable reductions of their mechanical properties have been observed as a function of UV intensity and exposure time (Nguyen 2012).

Steel/CFRP double strap joints similar to those investigated in Nguyen et al. (2011) and Liu et al. (2012) with a bond length of 100mm, were exposed to UV irradiation under a setting of 1.26 W/m²/nm @ 340nm for 124, 248, and 372 hours on each surface (Nguyen et al. 2012c). Such a maximum UV dosage (744 hours on both surfaces) is equivalent to one year of outdoor UV exposure of 250 MJ/m² in Victoria, Australia. The joints were tested in tension after exposure and the residual joint ultimate capacities are shown in Figure 16. The capacity reduced with exposure time, and the decrease was more significant in the first 124 hours of exposure on each surface and became much slower afterwards. The maximum decrease in strength was 18.7% after 372 hours of UV exposure on each surface.

Identical joints were exposed to associated thermal effects at 40°C alone in Nguyen et al. (2012c), i.e. the same temperature exposure as achieved during the UV exposure. The joint ultimate capacity was measured after exposure, as shown in Figure 16. The strength degradation of the joints
subjected to temperature effects alone was found to be very similar to that of those subjected to UV exposure. More research is needed to verify this phenomenon.

9. CONCLUSIONS

This paper has presented a state-of-the-art review on the effect of dynamic loading and environmental conditions on the bond between CFRP and steel. The main conclusions are as follows.

• The reduction in bond strength due to fatigue loading is about 20% to 30% for normal modulus CFRP sheet, whereas almost no reduction is observed in the case of high modulus CFRP sheet or plate.
• The increase in bond strength due to high strain rate loading is about 70% and 25% for specimens with Araldite 420 and MBrace saturant, respectively.
• The influence of large deformation cyclic loading on bond strength is about a 15% reduction.
• No reduction in bond strength is found at sub-zero temperatures down to -40°C for specimens with Araldite 420 and Sikadur 30. For specimens with MBrace saturant, the bond strength reduces about 40% when the temperature drops from 20°C to -40°C.
• Bond strength reduces significantly when the temperature exceeds the glass transition temperature of adhesives. The effective bond length increases as the temperature increases, especially for normal modulus CFRP.
• The bond strength degrades rapidly in the first 2 to 4 months of exposure and this reduction becomes much slower after 6 months. The application of a layer of glass fibre and a silane coupling agent helps to retain residual bond strength after water exposure.
• The maximum decrease in bond strength is less than 20% after 372 hours of UV exposure on each surface.

There is a need to study the combined effect of environmental conditions and mechanical loading on the bond behaviour and on the strengthening efficiency.
ACKNOWLEDGEMENTS

The authors acknowledge the support of the Australian Research Council (ARC) and the National Science Foundation (NSF). Most of the work summarized in this paper was conducted by the following PhD students supervised by the authors: Ahmed Al-Shawaf, Haider Al-Zubaidy, Tao Bai, Sabrina Fawzia, Hui Jiao, Hongbo Liu, Tien Nguyen and Chao Wu at Monash University and Mina Dawood and David Schnerch at North Carolina State University.

REFERENCES


## Table 1 Summary of research on bond between CFRP and steel

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<th>Type of bond test</th>
<th>CFRP (sheet or plate)</th>
<th>CFRP modulus (GPa)</th>
<th>Number of CFRP layers</th>
<th>Adhesive (modulus)</th>
<th>Bond length (mm)</th>
<th>Type of loading</th>
<th>Environmental condition</th>
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<td>CFRP sheet</td>
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<td>Araldite 420 (1901 MPa)</td>
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<td>Static</td>
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<td>3 types with modulus varying from 4013 MPa to 10793 MPa</td>
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<td>Static</td>
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<td>Araldite 420, Araldite 2015, Sika 30, Sika 330 (modulus varying from 1830 MPa to 11250 MPa)</td>
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<td>Static</td>
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<td>SP Spabond (3007 MPa)</td>
<td>50 to 200</td>
<td>Static</td>
<td>N/A</td>
<td>Schnerch et al. (2006)</td>
</tr>
<tr>
<td>Double shear pull test</td>
<td>CFRP plate</td>
<td>197</td>
<td>1</td>
<td>Sikadur 30 (4500 MPa) Sikadur 330 (3800 MPa)</td>
<td>300</td>
<td>Static</td>
<td>N/A</td>
<td>Colombi and Poggi (2006)</td>
</tr>
<tr>
<td>Double shear pull test</td>
<td>CFRP plate</td>
<td>479</td>
<td>1</td>
<td>Araldite 420 (1901 MPa) Sikadur 30 (9282 MPa)</td>
<td>30 to 250</td>
<td>Static</td>
<td>N/A</td>
<td>Wu et al. (2012)</td>
</tr>
<tr>
<td>Double shear pull test</td>
<td>CFRP plate</td>
<td>166</td>
<td>1</td>
<td>Sikadur 30 (2689 MPa)</td>
<td>200</td>
<td>Fatigue</td>
<td>N/A</td>
<td>Matta (2003)</td>
</tr>
<tr>
<td>Double shear pull test</td>
<td>CFRP sheet</td>
<td>250 and 640</td>
<td>3</td>
<td>Araldite 420 (1901 MPa)</td>
<td>40 to 60</td>
<td>Fatigue</td>
<td>N/A</td>
<td>Liu et al. (2010)</td>
</tr>
<tr>
<td>Double shear pull test</td>
<td>CFRP plate</td>
<td>479</td>
<td>1</td>
<td>Araldite 420 (1901 MPa)</td>
<td>60</td>
<td>Fatigue</td>
<td>N/A</td>
<td>Wu et al. (2013)</td>
</tr>
<tr>
<td>Full-scale bridge girders</td>
<td>CFRP plate</td>
<td>112</td>
<td>1</td>
<td>Plexus MA555 (107 MPa)</td>
<td>457</td>
<td>Fatigue</td>
<td>N/A</td>
<td>Miller et al. (2001)</td>
</tr>
<tr>
<td>Test Type</td>
<td>Material</td>
<td>Thickness</td>
<td>Bonding Agent</td>
<td>Maximum Load</td>
<td>Temperature</td>
<td>Source</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Double shear pull test</td>
<td>CFRP sheet</td>
<td>205</td>
<td>1 or 3</td>
<td>MBrace saturant (2229 MPa)</td>
<td>10 to 100</td>
<td>Impact</td>
<td>N/A</td>
<td>Al-Zubaidy et al. (2012a, 2012b, 2013a, 2013b)</td>
</tr>
<tr>
<td>Pull-off test</td>
<td>CFRP sheet</td>
<td>205</td>
<td>1 or 3</td>
<td>Araldite 420 (1901 MPa) MBrace saturant (2229 MPa)</td>
<td>N/A</td>
<td>Impact</td>
<td>N/A</td>
<td>Al-Zubaidy et al. (2013c)</td>
</tr>
<tr>
<td>Double shear pull test</td>
<td>CFRP sheet</td>
<td>205</td>
<td>3</td>
<td>Araldite 420 (1901 MPa)</td>
<td>100 and 150</td>
<td>Large deformation cyclic</td>
<td>N/A</td>
<td>Bai, T. et al. (2008)</td>
</tr>
<tr>
<td>Double shear pull test</td>
<td>CFRP sheet</td>
<td>205</td>
<td>3</td>
<td>Araldite 420 (2012 MPa) MBrace saturant (1482 MPa) Sikadur 30 (9515 MPa)</td>
<td>100</td>
<td>Static</td>
<td>Sub-zero temperature</td>
<td>Al-Shawaf et al. (2005, 2006), Al-Shawaf and Zhao (2013)</td>
</tr>
<tr>
<td>Double shear pull test</td>
<td>CFRP sheet</td>
<td>205</td>
<td>1 or 3</td>
<td>Araldite 420 (1901 MPa)</td>
<td>20 to 150</td>
<td>Static</td>
<td>Elevated temperature</td>
<td>Nguyen et al. (2011, 2012a)</td>
</tr>
<tr>
<td>Double shear pull test</td>
<td>CFRP sheet</td>
<td>205</td>
<td>3</td>
<td>Araldite 420 (2012 MPa) MBrace saturant (1482 MPa) Sikadur 30 (9515 MPa)</td>
<td>100</td>
<td>Static</td>
<td>Elevated temperature</td>
<td>Al-Shawaf et al. (2009)</td>
</tr>
<tr>
<td>Double shear pull test</td>
<td>CFRP sheet</td>
<td>640</td>
<td>1 or 3</td>
<td>Araldite 420 (1901 MPa)</td>
<td>20 to 100</td>
<td>Static</td>
<td>Elevated temperature</td>
<td>Liu et al. (2012)</td>
</tr>
<tr>
<td>Four-point bending test</td>
<td>CFRP sheet</td>
<td>230</td>
<td>3</td>
<td>Sikadur Hex 330 (50350 MPa), Sikadur Hex 306 (44900 MPa), Tyfo SW-1 (62500 MPa)</td>
<td>1800</td>
<td>Static</td>
<td>Seawater</td>
<td>Seica and Packer (2007)</td>
</tr>
<tr>
<td>Double shear pull test</td>
<td>CFRP plate</td>
<td>418</td>
<td>1</td>
<td>SP Spabond (2980 MPa)</td>
<td>200</td>
<td>Static</td>
<td>Seawater</td>
<td>Dawood and Rizkalla (2010), Dawood (2008)</td>
</tr>
<tr>
<td>Double shear pull test</td>
<td>CFRP sheet</td>
<td>205</td>
<td>3</td>
<td>Araldite 420 (1901 MPa)</td>
<td>100</td>
<td>Static</td>
<td>Seawater</td>
<td>Nguyen et al. (2012b)</td>
</tr>
<tr>
<td>Double shear pull test</td>
<td>CFRP sheet</td>
<td>205</td>
<td>1 or 3</td>
<td>Araldite 420 (1901 MPa)</td>
<td>30 to 100</td>
<td>Static</td>
<td>UV light</td>
<td>Nguyen et al. (2012c)</td>
</tr>
</tbody>
</table>
Figures

Figure 1 Schematic view of CFRP-steel composite system subject to dynamic loading and environmental conditions
Figure 2 Schematic view of double shear pull test specimen (adapted from Schnerch et al. 2004, Fawzia et al. 2006, Colombi and Poggi 2006)
Figure 3 Influence of fatigue loading on bond strength (adapted from Liu et al. 2010 and Wu et al. 2013)
Figure 4 Illustration of “fatigue damage zone” (adapted from Wu et al. 2013)

- Extra adhesive squeezed out of the bondline
- Exposed adhesive layer
- Imprints of fibres
- Fibres separated from the CFRP plate
- Striations generated from cyclic loading
Figure 5 Impact test set up at Monash Civil Engineering Laboratory (courtesy of Haider Al-Zubaidy at Monash University, Australia)
(a) Tensile strength

(b) Modulus of elasticity
**Figure 6** Effect of strain rate on properties of CFRP and adhesives (adapted from Al-Zubaidy et al. 2013a)
Figure 7 Effect of strain rate on bond strength (adapted from Al-Zubaidy et al. 2012a, 2012b)
Figure 8 Loading scheme (adapted from Bai, T. et al. 2008)
Figure 9 Influence of large deformation cyclic loading on bond strength (adapted from Bai, T. et al. 2008)
Figure 10 Effect of sub-zero temperature on failure mode of CFRP sheet (courtesy of Ahmed Al-Shawaf at Monash University, Australia)
(a) CFRP Sheet

(i) Modulus of elasticity
Figure 11 Effect of sub-zero temperature on material properties of CFRP sheet (adapted from Al-Shawaf et al. 2005, Al-Shawaf and Zhao 2013)
Figure 12 Temperature dependent ultimate joint capacity and effective bond length of joints with a) normal modulus CFRP and b) high modulus CFRP (adapted from Nguyen et al. 2011, Liu et al. 2012)
Figure 13 Test set up for bond specimens subject to combined loading and seawater exposure

(adapted from Dawood 2008)
Figure 14 Influence of seawater on bond strength (adapted from Dawood and Rizkalla 2010)
Figure 15 Bond strength reduction of steel/CFRP joints with a bond length of 100mm after sea water exposure (adapted from Nguyen et al. 2012b)
Figure 16 Bond strength reduction of steel/CFRP joints with a bond length of 100mm after UV exposure, in comparison to that after exposure to temperature only (adapted from Nguyen et al. 2012c)
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The maximum length of a technical paper is 10,000 words and word-equivalents or 8 printed pages. A technical note should not exceed 3,500 words and word-equivalents in length or 4 printed pages. Approximate the length by using the form below to calculate the total number of words in the text it to the total number of word-equivalents of the figures and tables to obtain a grand total of words for the paper/note to fit ASCE format. Overlength papers must be approved by the editor; however, valuable overlength contributions are not intended to be discouraged by this procedure.

### 1. Estimating Length of Text

A. Fill in the four numbers (highlighted in green) in the column to the right to obtain the total length of text.

**NOTE: Equations take up a lot of space.** Most computer programs don’t count the amount of space around display equations. Plan on counting 3 lines of text for every simple equation (single line) and 5 lines for every complicated equation (numerator and denominator).

### 2. Estimating Length of Tables

A. **First count** the longest line in each column across adding two characters between each column and one character between each word to obtain total characters.

- 1-column table = up to 60 characters wide
- 2-column table = 61 to 120 characters wide

B. **Then count** the number of text lines (include footnote & titles)

- 1-column table = up to 60 characters wide by:
  - up to 17 lines (or less) = 158 word equiv.
  - up to 34 lines = 315 word equiv.
  - up to 51 lines = 473 word equiv.
  - up to 68 text lines = 630 word equiv.

- 2-column table = 61 to 120 characters wide by:
  - up to 17 lines (or less) = 315 word equiv.
  - up to 34 lines = 630 word equiv.
  - up to 51 lines = 945 word equiv.
  - up to 68 text lines = 1260 word equiv.

C. Total Characters wide by Total Text lines = word equiv. as shown in the table above. **Add word equivalents** for each table in the column labeled "Word Equivalents."

### 3. Estimating Length of Figures

A. **First reduce** the figures to final size for publication.

**Figure type size can't be smaller than 6 point (2mm).**

B. **Use ruler** and measure figure to fit 1 or 2 column wide format.

- 1-column fig. = up to 3.5 in.(88.9mm)
- 2-col. fig. = 3.5 to 7 in.(88.9 to 177.8 mm)

C. **Then use** a ruler to check the height of each figure (including title & caption).

- 1-column fig. = up to 3.5 in.(88.9mm) wide by:
  - up to 2.5 in. = 158 word equiv.
  - up to 5 in. = 315 word equiv.
  - up to 7 in. = 473 word equiv.
  - up to 9 in. = 630 word equiv.

- 2-column fig. = 3.5 to 7 in.(88.9 to 177.8 mm)
  - up to 2.5 in. = 315 word equiv.
  - up to 5 in. = 630 word equiv.
  - up to 7 in. = 945 word equiv.
  - up to 9 in. = 1260 word equiv.

D. Total Characters wide by Total Text lines = word equiv. as shown in the table above. **Add word equivalents** for each table in the column labeled "Word Equivalents."

**Total**

- Total Tables/Figures: 4416
- Total Words of Text: 5355
- Total words and word equivalents: 9771
- printed pages: 8
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