DURABILITY OF STEEL-CFRP ADHESIVE JOINTS UNDER SUSTAINED LOADING AND WET THERMAL-CYCLES

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Abstract: The long term durability of CFRP strengthened steel structures is a key parameter for their safe use and effective design. The strengthened members can be subjected to different environmental conditions and loading scenarios during their service life, the effect of which on the failure mechanism of the strengthened members require fundamental investigations. This paper presents an experimental investigation into the effect of combined wet thermal cycle and sustained load on the bond strength of steel-CFRP joints, as well as on the mechanical properties of the neat epoxy samples. The results show that both thermal cycle and sustained load alone, has no significant impact on the failure strength; but adversely affect the mechanical properties of both neat epoxy samples and steel-CFRP joints when applied simultaneously.

Keywords: Steel, CFRP, Adhesive Bond, Thermal Cycle, Creep.

1 General Introduction

Large numbers of steel structures, like pipelines, bridges etc, are deteriorating due to corrosion or are coming to the end of their design life. Such structures are in need of retrofitting and replacement; and many of them are located in regions that regularly experience fluctuating thermal (hot-cold) conditions. Applications of Carbon Fiber Reinforced Plastic (CFRP) composites in the repair and rehabilitation of existing steel structures have gained significant attention due to their high strength to weight ratio, installation flexibility, and long term durability [1, 2]. However, FRP strengthened steel members are characterized by debonding failures, which are mainly governed by the weak adhesive layer that can be subjected to both shear and peeling stresses. As these members can be subjected to different environmental conditions and loading scenarios during their service life, it is critical to clarify and investigate the influence of different environmental conditions on their behaviour and bonding capacity.

A number of studies have been undertaken to investigate the impact of moisture content, elevated temperature and other environmental conditions on the behaviour of steel-CFRP joints [3-8]. Karbhari and Shulley [3] observed significant degradation in the bond strength of steel-CFRP joints upon exposure to hot water at 65˚C for 14 days. Dawood et al. [4] exposed steel-CFRP joints to accelerated environmental conditions that consisted of a one week dry cycle (ambient temperatures) followed by a one week wet cycle (in 5% NaCl solution at a temperature of 38˚C) over a 6 months period. They measured about 60% degradation in bond strength. Al-Shawaf et al. [5] measured about 50% degradation in the bond strength of steel-CFRP joints when the temperature of the specimens increased from 20˚C to 60˚C. Similar results were obtained by Nguyen et al. [6] for double strap steel-CFRP joints, in which the drop in bond strength was about 15% at 40˚C and about 50% at temperature greater than the glass transition temperature of the adhesive.

In all the aforementioned studies, the testing to failure of the specimens was after the exposure to such environmental scenarios. Thus, the influence of simultaneous exposure to environmental condition and mechanical loading, particularly a sustained one, is yet to be investigated. The influence of these combined loadings (environmental and mechanical) on the behaviour and failure modes of FRP strengthened steel structures is crucial for their safe use and effective design, and requires further investigation.

This paper presents the results of an experimental investigation of the effect of the combined wet thermal cycles and sustained loading on the bond strength of steel-CFRP single lap joints as well as, on the mechanical properties of neat epoxy samples.
2 Experimental Program

A total number of nine steel-CFRP single lap shear specimens are prepared with two part epoxy adhesive (Sikadur 330) with geometrical properties as shown in the Fig. 1. The bonded area of the steel-CFRP joint is 25 mm x 25 mm and the thickness of the adhesive layer is about 1.0 mm. Table 1 summarizes the test program of the steel-CFRP specimens. The control specimens were tested to failure immediately after the curing stage at a displacement rate of 1.27 mm/min as per ASTM D1002 [9] in a 10 kN capacity testing machine (Fig. 2). Two of the lap shear specimens (Set 2) were loaded up to 50% of the failure load (which was determined from the control testing) and the load were then kept constant for the next 21 days. Thus, the specimens were under sustained load and exposed to ambient temperature for three weeks, after which they are tested for the residual strength, similar to the control specimens. The third set consist of three steel-CFRP joints, which were exposed to only thermal cycle (10°C to 50°C) without any sustained load for 21 days and were tested after that for its residual strength. Each thermal cycle consists of two and a half hours of cold water cycle (at 10°C), and two and a half hours of hot water cycle (at 50°C). Two of the steel-FRP joints (Set 4) were loaded up to 50% of the failure load and the load were then kept constant for 21 days along with the exposure to thermal cycle environment (10°C to 50°C) in immersed conditions. The specimens were then to be tested for the residual strength after 21 days.

A total number of fourteen adhesive tensile coupon specimens are also prepared as per ASTM D638-10 and cured for 14 days. The dimensions of the specimens are shown in the Fig. 3. Table 2 summarizes the test program for the adhesive coupon specimens. Three of the specimens are control specimens which were tested immediately after curing in a 10 kN testing machine as per ASTM D638-10 [10]. Six of the specimens were exposed to sustained loading of 30%, 50%, and 70% (2 specimens each) for 21 days and were then tested in tension to failure similar to the control specimens. Three samples were exposed to thermal cycle (10°C to 50°C) without any sustained load for 21 days and were then tested for the residual strength. Three epoxy samples were exposed to sustained load (30%, 50%, and 70%) along with the thermal cycle for 21 days. The specimens were to be tested for the residual strength after the stipulated time.

2.1 Preparation of the lap-shear specimens:

The CFRP strips were cut to size (180 mm long by 25 mm wide) using a hacksaw with very fine blade; the steel plates were ordered pre-cut into size. The surface of the steel plates was prepared to cleaning standard St2 according to ISO 8501-01 [11]. The surface was hand grounded with P60 sandpaper until the shiny surface of the steel was seen and all mill scale removed. The surface was then cleaned with acetone to remove all grease, oil, and rust. The surface of the CFRP was also lightly sanded using P80 sandpaper to improve the bonding quality. The surface preparation procedure was applied consistently, and rigorously, to minimise potential variations in the data obtained through the CFRP-adhesive-steel bond.

To minimise bending near the bonded region, grips of 75 mm long and 25 mm wide were adhered at the ends of the steel and the CFRP to align the load line close to the mid-point of the adhesive bond [12], as shown in the Fig. 1. The adhesive was mixed according to the product data specifications, and was applied over the gripping area at the ends of both the steel and the CFRP plates. Two 1.0 mm spacers were placed on the gripping area to ensure that the specified uniform bond thickness was achieved. The grips were then placed on their respective substrate. Once the grips were placed into position, the adhesive was applied over the bonded (overlap) area onto the steel. The bonded region of the CFRP was then placed over the steel with proper alignment, and weights were placed over the bonded regions. This ensured a uniform bond thickness in the overlap region. Any adhesive squeezed out from the edges was carefully removed. The specimens were then placed in a controlled environment room for 14 days for curing at 23°C and 50% relative humidity. After curing, the thickness of the adhesive layer was measured at different locations using a vernier caliper and was found to be consistent with the specified one.

2.2 Material Properties:

The elastic modulus and the tensile strength of the CFRP laminate are given in the manufacturer’s specifications as 165 GPa and 2800 MPa, respectively. The elastic modulus of the steel is 207 GPa, and the yield and the ultimate strengths are 350 MPa and 430 MPa, respectively. The tensile properties for the adhesives were obtained from the testing of coupon specimens as per ASTM D638-10
[10]. The glass transition temperature of the epoxy used is 47°C as per manufacturer’s specification.

2.3 Thermal Cycle Apparatus:

Thermal cycle equipment was designed and manufactured to apply the sustained loading along with the wet thermal cycle on six specimens simultaneously. The apparatus basically consists of four different units – hot cycle unit, cold cycle unit, test tank, and the controller. The hot cycle unit is a water tank with a heating element and a temperature sensor and controller. The cold water unit consists of a water tank with a temperature sensor, and a chiller, which cools the water. The test tank has six loading frames to test the specimens independently, and is connected to hot cycle unit and cold cycle unit with hoses, pumps, and valves. The number of cycles, the duration of each cycle, and the circulation time can be controlled using a controller. The equipment is shown in the Fig. 4. In this experiment, the circulation time is two hours each for the cold and the hot cycle. It takes fifteen minutes each to fill the test tank with cold/hot water and fifteen minutes each to empty the test tank at the end of the circulation period. Thus, the cycle time for the cold water and for the hot water is 150 minutes (2 hrs 30 mins) each; which makes the time period of the thermal cycle to be five hours. The thermal cycle profile obtained from the apparatus is shown in the Fig. 5.

2.4 Instrumentation:

All the loads are measured using 20 kN range load cells. The total displacement of the steel-CFRP lap shear specimens are measured using 2.5 mm range LVDTs. Four 3 mm strain gauges were placed on each lap shear specimen, two on steel and two on CFRP to capture the load eccentricity, if any, and to use the value for verifying the theoretical model in future. The strains in adhesive coupon specimens are measured using 6 mm strain gauges. The temperatures of the test tank and of the specimens are measured using thermocouples.

3 Results:

3.1 Control testing (no sustained load – no thermal cycle)

3.1.1 Epoxy Samples

The stress-strain curve of the control specimens (no sustained load – no thermal cycle) of the epoxy samples are shown in the Fig. 6. The average failure stress is 38 MPa and the average initial elastic modulus is 4620 MPa. The average strain at the failure load is 12675 με.

3.1.2 Lap-Shear Specimens

The load-displacement curves of steel-CFRP single lap shear control specimens are shown in the Fig. 7. The average failure load is 4610 N, and the average stiffness is 7300 N/mm. The average failure stress can be calculated as the failure load divided by the bond area and is found to be 7.4 MPa. The failure is at the interface between adhesive and steel thereby indicating this as the weakest link.

3.2 Only sustained load – no thermal cycle

3.2.1 Epoxy Samples

The strain-time curve ( creep) for the long term testing of the epoxy samples, exposed to 30% sustained load for 21 days with no thermal cycle, is shown in the Fig. 8(a). The average initial strain is 1860 με, and the average total strain after 21 days is 4930 με. The creep strain, which is the total strain minus initial strain, is 3070 με and is about 165% of the initial strain. The figure also shows the unloading strain profile of one of the epoxy samples (A-0-30-2) when the load was removed after 21 days. The strain was measured for 7 days after unloading, and the recovered strain is observed as 2320 με, leaving in the sample a residual strain of 2850 με. It is worthwhile to note that the strain recovered is almost equal to the initial strain when the sample was loaded initially.

The strain-time curve ( creep) for the long term testing of epoxy samples, exposed to 50% sustained load for 21 days with no thermal cycle, is shown in the Fig. 8(b). The average initial strain is 3990 με, and the average total strain after 21 days is 12990 με. The creep strain is calculated as 9000 με, which is about 225% of the initial strain. Similar to the 30% samples, the recovered strain of one of the sample (A-0-50-2) was measured and is found to be 4420 με, leaving the residual strain of 8600 με in the sample.

The strain-time curve ( creep) for the long term testing of epoxy samples, exposed to 70% sustained load for 21 days with no thermal cycle, is shown in the Fig. 8(c). The initial strain for the specimen A-0-70-1 is 6080 με, and the total strain after 21 days is 22970 με. The creep strain is calculated as 16890 με, which is about 278% of the initial strain. Also, around 31% of the strain is recovered after
unloading. As can be seen from the Fig. 10, the strain values of the two specimens are inconsistent after 6 days and thus, another set of experimental data is needed to confirm the results.

Thus, it can be concluded from the above results that the creep strain increases when the applied sustained load is increased, and that the strain recovered after unloading is almost equal to the initial strain. Also, it takes about 6-7 days for the recovery of the strain to be completed. Thus, in order to measure the residual strength of the specimens, it should be tested at least 7 days after the specimen has been unloaded.

Fig. 9 shows the stress-strain curve for the epoxy specimens which were exposed to sustained loading for 21 days with no thermal cycle and were then allowed to recovered for 7 days and were then tested until failure. It can be seen that the failure stress for A-0-30-2, A-0-50-2, and A-0-70-2 is 38.8 MPa, 38.5 MPa, and 38.2 MPa respectively, which are very close to the failure stress of the control specimens (38 MPa). The initial elastic modulus for A-0-30-2 and A-0-50-2 is 4290 MPa, and 4395 MPa, respectively which is about 7% lower than that of the control specimens (4620 MPa). The initial elastic modulus of A-0-70-2 is 5270 MPa and has to be confirmed with another set of data. The strain at the failure stress for the three specimens is 11810 με, 11690 με, and 12640 με respectively. However, it should be noted that the residual strain calculated from Fig. 11 has to be added to these values in order to get the total strain at the failure stress. Thus, overall it can be seen that the sustained loading for 21 days has no significant impact on the tensile strength and on the elastic modulus of the epoxy samples. However, the samples should be loaded for more than 21 days, may be even a year period, to see the impact of sustained load before making any final conclusions from the above test results.

3.2.2 Lap-shear specimens

Fig. 10 shows the load-displacement curve for steel-CFRP joints after exposure to sustained loading of 50% for 21 days. The average failure load is 4410 N, which is about 4.5% lower than that of the control specimens. The average failure stress can be calculated as 7 MPa. The average stiffness is 8400 N/mm and is about 15% higher than that of the control specimens. The average displacement at failure load is 0.525 mm, which is about 17% lower than the displacement in case of control specimens. However, the residual displacement (due to the sustained load), which could not be measured in this testing, should be added to the displacement from the short-term testing in order to get the total displacement of the specimens at failure. There was no change in the failure mode of the specimens, as compared to the control one, indicating that the sustained load does not alter the failure mechanism of the steel-CFRP joints.

3.3 No sustained load – only thermal cycle

3.3.1 Epoxy Samples:

The stress-strain curves of the epoxy specimens, after exposure to 108 thermal cycles (in water) for 21 days, are shown in the Fig. 11. The average failure stress is 36.4 MPa which is about 4% lower than that of the control specimens (38 MPa). The average strain at the failure stress is 20740 με which is about 64% higher than that of the strain in case of control specimens (12675 με). The average initial elastic modulus is 3460 MPa which is about 25% lower than that of the control specimens (4625 MPa). Thus, the exposure to thermal cycles alone has no significant impact on the failure strength of the epoxy, but it makes the samples highly ductile in nature.

3.3.2 Lap Shear Specimens:

The load-displacement curves for the steel-CFRP joint specimens, after exposure to 108 thermal cycles (21 days) without any sustained load, are shown in the Fig. 12. The average failure load is 3925 N, which is about 15% lower than that of the control specimens. The average failure stress can be calculated as 6.3 MPa. The average stiffness of the specimens is calculated as 5815 N/mm, and is about 20% lower than in case of control specimens. This reduction in stiffness is attributed to the increasing ductile nature of the epoxy after exposure to thermal cycles (section 3.3.1). The observed failure mode of the specimens was adhesive failure at steel-adhesive interface, similar to the failure mode of the control specimens.

3.4 Both sustained load and thermal cycle

3.4.1 Epoxy Samples:

The strain-time curve for the epoxy specimens, exposed to thermal cycle (in water) and sustained loading simultaneously, are shown in the Fig. 13. It can be seen that the strain for all the three specimens first increases up to the initial strain as the loading is
applied, and then keep on increasing (creep) until the cold cycle starts. The strain then decreases instantaneously as soon as the temperature decrease (due to cold cycle) and this reduction is equal to the value $a\Delta T$ (around 675 $\mu$e). During the two hours of cold cycle, the specimens keep on creeping. As soon as the hot cycle started and the temperature of the specimens reached 47°C, all the three specimens failed instantly. Note that when only thermal cycles were applied (section 3.3.1), which also included the temperature of 47°C (greater than the glass transition temperature of the epoxy), no significant reduction in the failure strength was observed. Thus, the failure in this combined loading case may be attributed to the combined effect of sustained loading and the temperature higher than the glass transition temperature of the epoxy.

3.4.2 Lap Shear Specimens:

The displacement (LVDT reading)-time curves of the steel-CFRP joints, exposed to sustained loading of 50% along with thermal cycle, are shown in Fig. 14. The displacement first increases instantly when the load is applied; the specimens then start creeping until the temperature starts dropping due to cold cycle. As soon as the cold cycle starts (at about 1.3 hrs), the displacement starts dropping gradually and this drop is the resultant of thermal contraction and creep. Interestingly, just near to the end of cold cycle, there is a sudden drop in displacement. When the hot cycle starts after that, the displacement starts increasing instantly and the specimens failed soon after that. The failure, in this case as well, was adhesive failure (between steel and adhesive) similar to the control specimens. Note that when similar steel-CFRP specimens were exposed to only thermal cycle (section 3.3.2), there was only 15% reduction in the failure load of the steel-CFRP joint leaving behind a residual strength of 85%. While, when the specimens were exposed to only sustained load (section 3.2.2), there was only about 4.5% reduction in the failure load. But these two loadings, when applied simultaneously, have much more adverse effect on the steel-CFRP bond strength as the specimens failed even under 50% sustained load.

4 Conclusions:

The average bond strength of the control steel-CFRP joint is 4610 N. There is about 4.5% reduction in the bond strength of the steel-CFRP joints, which are first exposed to 50% sustained load for 21 days and then tested until failure. Also, there is about 15% reduction in the bond strength of the steel-CFRP joints, which are exposed to 108 thermal cycles (21 days) without any sustained load and then tested until failure. However, the steel-CFRP joints, which are exposed to both thermal cycle and 50% sustained loading simultaneously, failed within two hours of exposure. Thus, it is the combined effect of sustained load and environmental conditions which governs the failure, and not alone only the exposure to environmental conditions or sustained loading. Also, the observed failure mode in all the cases was adhesive failure between steel and adhesive, indicating that the thermal cycles and sustained load does not influence the critical link in the steel-CFRP joints.

The average tensile strength and the average elastic modulus of the control adhesive coupon specimens are 38 MPa and 4625 MPa, respectively. There is no significant reduction in strength and elastic modulus when the specimens are first exposed to 30%, 50%, and 70% sustained load at ambient temperature for 21 days, and then tested. However, there is about 4% reduction in strength and 25% reduction in elastic modulus after exposure to 108 thermal cycles between 10°C and 50°C without any sustained load. Thus, the conclusion which is drawn at this stage is that sustained load alone has no significant impact on the mechanical properties of adhesive specimens while exposure to thermal cycle impact elastic modulus of the adhesive specimens significantly along with very minor reduction in failure strength. However, when both sustained load and thermal cycle applied simultaneously, the specimens failed within two hours as soon as the hot water entered the test tank. Thus, it is the combination of sustained load and thermal cycles which govern the failure of adhesive specimens, just as the case of steel-CFRP joints.

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References


Tables:

Table 1: Experimental plan for steel-CFRP single lap shear joints

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<th>Specimens</th>
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<td>LS-0-0-1</td>
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<td>Set 1: Control specimens (no sustained load – no exposure to thermal cycle)</td>
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<tr>
<td>LS-0-0-2</td>
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<td>Set 2: 50% sustained load – no exposure to thermal cycle</td>
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<tr>
<td>LS-0-50-2</td>
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<td>Set 3: No sustained load - only exposure to thermal cycle</td>
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<td>LS-0-50-3</td>
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<td>Set 4: 50% sustained load - exposure to thermal cycle</td>
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Table 2: Experimental plan for neat epoxy specimens

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Figures:

Fig. 1: Steel-CFRP single lap shear specimen
Fig. 2: 10 kN Instron testing machine

Fig. 3: Adhesive coupon specimen

Fig. 4: Thermal cycle-sustained load apparatus

Fig. 5: Thermal cycle profile as obtained from the thermal cycle apparatus set-up and measured using thermocouples.

Fig. 6: Stress-strain curve for control adhesive coupon specimens.

Fig. 7: Load-displacement curve of steel-CFRP single lap shear control specimens
Fig. 8: Creep of epoxy sample exposed to sustained load for 21 days without any thermal cycle. (a) 30% sustained load; (b) 50% sustained load; and (c) 70% sustained load.

Fig. 9: Stress-strain curve of epoxy samples after exposure to sustained load for 21 days.

Fig. 10: Load-displacement curve of lap-shear specimens after exposure to sustained load for 21 days.

Fig. 11: Stress-strain curve of epoxy samples after exposure to 108 thermal cycles (21 days).
Fig. 12: Load-displacement curve of steel-CFRP single lap shear specimens after exposure to 108 thermal cycles (21 days).

Fig. 13: Strain-time curve of epoxy samples during exposure to thermal cycle.

Fig. 14: Displacement-time curve of steel-CFRP single lap shear specimens during exposure to thermal cycle.