Effects of Temperature and Sustained Loading on the Mechanical Response of CFRP Bonded to Concrete

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Abstract

Fiber reinforced polymer composites are commonly bonded to concrete structures for strengthening reasons, even though little is known about the evolution of bond strength while the strengthening systems are subject to sustained loads and elevated temperatures. This investigation uses single-lap shear specimens to examine the effects of sustained load and elevated temperature on the time-dependent deformation of a carbon fiber reinforced polymer (CFRP) composite bonded to concrete as well as the pull-off strength of the composite after the sustained loading period. Increased temperature during the sustained loading period led to increased slip of the CFRP, whereas increased curing time of the polymer resin prior to the sustained loading period led to reduced slip. Specimens that underwent sustained loading had increased pull-off strength and interfacial fracture energy following the sustained loading period. This beneficial effect was most significant for roughly 30 days of sustained loading. The analysis of strain distributions and fracture surfaces indicated that stress relaxation of the adhesive occurred in the 30 mm closest to the loaded end of the CFRP during sustained loading, which increased the pull-off strength provided the failure locus remained mostly in the concrete. For longer sustained loading times, the bond failure locus shifted to the epoxy/concrete interface, which diminished part of the strength increase brought on by the stress relaxation of the adhesive.

Keywords: Fiber reinforced polymer; concrete; bonded interface; temperature effects; sustained load; pull-off testing; fracture energy

1. Introduction

The need for rehabilitation and strengthening of reinforced concrete structures is increasing with the continued aging of civil infrastructure. Externally bonded fiber reinforced polymer (FRP) plates and sheets are widely used for strengthening deteriorated concrete structures due to the ease with which they can be applied to the concrete substrate. For instance, the external installation of FRP sheets can provide the required additional strength for an existing bridge superstructure to accommodate additional live loads, or to restore the designed load capacity of a damaged structure. Furthermore, since FRP composites have a much higher strength-to-weight ratio than steel reinforcement, using FRP does not significantly increase the dead load of the existing structure. Since the early 1990s, numerous research projects on the short-term response of flexural and shear strengthening of concrete structures using FRP have shown promising results on these systems [1, 2].

Although most of the research activity on concrete structures strengthened with externally bonded FRP sheets has been established based on predictive models for the maximum force needed to pull-off a bonded FRP sheet [3, 4], an increasing amount of recent research focusses on the characterization of bond behavior after various aggressive environmental exposures [5-8]. Of equal importance, the durability of the adhesive bond in the presence of sustained load and various temperatures over time should also be evaluated.

Jia et al. [9] investigated the bond behavior of glass FRP (GFRP) externally bonded to plain concrete prisms and subjected to a sustained four point flexural load corresponding to 24% of the initial debonding load. Severe decreases in interfacial fracture energy were observed for specimens exposed to either elevated temperature (50°C to 60°C) or freeze/thaw conditions during the sustained loading. Relatively moderate decreases in fracture energy were observed

for specimens subjected to indoor laboratory conditions and natural outdoor conditions during sustaining loading.

Diab and Wu [10] investigated bond creep and bond failure using double-lap-shear tests with rigid-molecule polymer fiber reinforced epoxy sheets externally bonded to concrete blocks. Sustained loads of 35% to 86% of initial pull-off strength and ambient indoor laboratory conditions were imposed. An increased redistribution of strain along the bonded region, a reduction in time to creep failure, and increased fracture energy were observed with increased sustained load.

Gullapalli et al. [11] investigated the influence of elevated temperature (40°C) and sustained load (approximately 80% of initial pull-off strength) on the single-lap-shear pull-off behavior of carbon FRP (CFRP) sheets externally bonded to concrete blocks. Exposure to only the elevated temperature before bond testing increased the pull-off strength. However, the combination of sustained loading and elevated temperature precluded the strengthening effect. A large increase in the transfer length (active bond zone) occurred during the sustained loading at 40°C, but not at 21°C.

Mazzotti and Savoia [12] investigated the residual strength of double-lap shear specimens with externally bonded CFRP plates after a 5-year period of sustained loading at 50% of initial pull-off strength and 20°C ambient temperature. Significant strain redistribution along the CFRP plate was observed over time. An increase in pull-off strength, beyond that expected due to concrete aging, occurred as well.

Time-dependent shear stress redistribution at the concrete-FRP interface has been reported in several papers [10, 13-17]. The phenomenon is generally attributed to the viscoelastic shear deformation of the polymer adhesive, which in turn is sensitive to the type of polymer, the stress level, the ambient temperature, and the degree of cure of the adhesive.

Stress redistribution can potentially affect the long-term performance of bonded CFRP strengthening systems at various ambient temperatures. However, neither the research nor the practicing engineering communities are certain on how the long-term bond stress redistribution affects the bond performance of FRP strengthened or repaired concrete structures.

The objective of the present investigation is to expand the body of data and provide new insights on the effects of curing time, service temperature, and sustained loading duration on the mechanical behavior of CFRP/concrete bonded connections. Single-lap shear specimens, consisting of CFRP bonded to concrete blocks and cured for different amounts of time (7 and 90 days), were subjected to a sustained load at different temperatures (21°C and 30°C) for various time periods (31 days to 153 days). After the sustained loading period, the CFRP sheets were loaded in tension to failure to assess the residual pull-off strength and failure mode. This work is part of a larger investigation that includes modeling, the results of which will be submitted for publication separately.

2. Experimental Program

Single-lap shear specimens were fabricated using concrete blocks ($127 \times 127 \times 254$ mm) which were cast in one batch and cured in a moisture chamber at 23°C and 95% relative humidity for 28 days. The average 28-day compressive strength of the concrete, according to two cylinder tests [18], was 34.0 MPa. Twenty-four single-lap shear specimens were fabricated, allowing for three specimens for each test condition as shown in Table 1. The specimen identification scheme in Table 1 consists of a three-part code A-B-C-n, where A represents the epoxy curing age in days prior to applying sustained loading (7 days or 90 days), B represents the temperature of the specimen during the sustained loading period or dwell period (RT for room temperature-21°C, HT for higher temperature-30°C), and C represents loading condition (C for control specimens having no sustained load during a so-called dwell

period and SL for specimens with sustained load). A 25-mm-wide, single layer of unidirectional carbon fibers was saturated with epoxy and bonded to each concrete block. After cure, the average thickness of the CFRP, including the polymer and epoxy, was 1.3 mm.

The CFRP composites bonded to the concrete blocks were cured in indoor laboratory conditions (35% relative humidity, 21°C) for 7 or 90 days prior to applying sustained loading. Epoxy curing time is considered a test parameter in this investigation. The curing times match those used by Jaipurkar [19] in a parallel investigation of the thermomechanical characteristics of the bisphenol A - isophronediamine epoxy material. The tensile elastic modulus of the epoxy at 22°C is 3.1 GPa after 7 days of cure at 22°C [19]. To measure the displacement of the CFRP sheet relative to concrete, each specimen was instrumented with several demountable mechanical (DEMEC) displacement gage points as shown in Fig. 1. The DEMEC gage can discern displacements as small as 2.54 μ m. DEMEC points fixed on the surface of the CFRP sheet are defined as target points (D5 and D6). Three reference points, denoted as R5, R6a, and R6b, were installed on steel plates fixed on the concrete block on both sides of the CFRP sheet. In the current work, displacement of the CFRP sheet at the end of the concrete block was measured by averaging the displacements of D6 relative to R6a and R6b.

[Figure 1 here]

2.1. Sustained loading

For the sustained loading set-up, the concrete blocks were clamped onto a steel frame (Fig. 2). The sustained load was applied to the specimens by means of hooks and tension springs. Steel doubler plates were bonded to the CFRP sheets to prevent local deformation where the hooks attach. The specimens were loaded up to 2.69 kN, which corresponds to 45% of the average experimental debonding failure load for 7d-RT specimens, measured during

pull-off bond tests. Load was determined based on the measured extension of the springs, which was periodically checked during the sustained loading period and re-adjusted if necessary. It was found that, during the sustained loading period, the applied load varied less than 2% from the initial load. The sustained loading frames were kept in two different climate-controlled chambers: 30% relative humidity at 21°C for the RT condition and 25% relative humidity at 30°C for the HT condition. The selected temperatures were close to the temperatures used by Jaipurkar [19] in a parallel investigation of the thermomechanical characteristics of the same epoxy material. By measuring the movement of each DEMEC target point with respect to its corresponding reference point shown in Fig. 1, the time-dependent displacement of the CFRP sheet along its length was evaluated. Control specimens were kept in the same climate controlled chambers as the sustained loading specimens for the same time duration, referred to as the “dwell period” in Table 1.

[Figure 2 here]

[Table 1 here]

2.2. Bond tests

After the sustained loading or dwell period, bond tests were conducted at room temperature using a computer-controlled, 49 kN hydraulic actuator under displacement control. The age of the bonded CFRP system at the time of the bond tests is reported in Table 1. Figure 3 shows the details of the bond test setup. Top and bottom plates secured the concrete block by means of bolts. Two linear variable differential transformers (LVDTs) were used to measure the relative slip between the CFRP sheet (at approximately 45 mm from the concrete edge) and the concrete. To remove the effects of possible block movement due to the pulling load, the LVDTs were mounted to L-channels which were attached to opposite sides of the concrete block using bolts. After the sustained loading period, each specimen was instrumented with

four electrical resistance strain gages bonded to the surface of the CFRP sheet (SG1...SG4 in Fig. 3). In addition, the slip profile along the CFRP sheet during the bond test was measured using the digital image correlation (DIC) method [20, 21]. The digital camera set-up is shown in Fig. 3c. The equipment provides for a spatial resolution of approximately 0.04 mm per pixel. The measurement resolution of the image analysis program, which is an open source MATLAB-based computer program [22] is 0.001 pixel. The theoretical displacement resolution in the correlated images is approximately 0.04 μm . During testing to failure, load, displacement, and strain signals were recorded continuously by a computer at a sampling rate of 2 Hz. Digital images were recorded at load intervals of approximately 0.9 kN until failure.

[Figure 3 here]

3. Experimental results and discussions

3.1. Sustained loading

The displacement of the DEMEC target point D6 on the CFRP sheet near the loaded edge of the concrete block is shown as a function of loading time in Fig. 4. It can be observed that the displacement increases with increased test temperature. This trend is very clear for all specimens regardless of the epoxy age. For the 7-day-cured specimens, the average displacement after 20 days at 30°C is about 58% greater than that for specimens at 21°C.

[Figure 4 here]

For the 90-day-cured specimens, the average displacement after 20 days at 30°C is 112% larger than that for specimens at 21°C. It was also found that after the instantaneous elastic displacement occurred, the 7-day-cured specimens at 30°C reached a larger but nearly constant displacement at the DEMEC point D6 in less time than the specimens at 21°C. These results are analogous to strains measured in sustained tensile loading tests of the plain epoxy

resin subjected to similar curing and sustained loading conditions [19]. That is, following a 7-day curing period at 22°C, tensile strain is higher at 30°C than at 22°C, but the strain rate decreases dramatically in a shorter amount of time in the former versus the latter. According to Jaipurian [19], the rapid decrease in strain rate for the 30°C test temperature is commensurate with the rapid increase in glass transition temperature (T_g) of the epoxy from an initial value of approximately 40°C after 7 days of curing at 22°C to 50-55°C within 10-20 additional days at 30°C. On the other hand, for epoxy maintained at 22°C, approximately 90 additional days beyond the initial 7-day cure are needed to attain the same increase in T_g (Fig. 5). The displacement results shown in Fig. 4 are supported by Ferrier et al. [15], who observed that the displacement rate is proportional to the difference between the sustained loading test temperature and the T_g of the adhesive, and by Meshgin et al. [13], who observed that the displacement rate decreases with increased curing time prior to sustained loading.

[Figure 5 here]

3.2. Bond tests

At the end of the sustained-loading period, all the specimens were subjected to pull-off loading to failure to ascertain the effects of curing time, sustained loading, and temperature during loading on the CFRP-concrete bond behavior. Load-displacement, peak pull-off force, interfacial fracture energy, stress redistribution, and fracture surface analysis results are presented in this section

3.2.1. Load-displacement relationships

Figure 6(a) shows typical load versus displacement behavior for RT specimens during pull-off testing, which were calculated for DEMEC target point D6 based on LVDT measurements minus the elastic elongation of the CFRP sheet. The initial displacement in this

graph is set to zero, regardless of the amount of residual displacement that remained after the sustained load was removed from the specimens. It can be seen that the 7-day-cured specimen failed in a more brittle manner than 90-day-cured specimen, based on the 7-day-cured specimen having less loaded-end displacement at failure. The residual displacements of these same two specimens, measured at unloading after conclusion of sustained loading period, can be seen in Fig. 6(b). Figure 6(b) indicates that the 7-day-cured specimen had more residual loaded-end displacement than the 90-day-cured specimen. Hence, it appears that a specimen with larger residual displacement after sustained loading will have less maximum displacement during the bond test. This observation is corroborated by examining all the available residual displacements and maximum displacements during pull-off tests in Fig. 6(c). The debonding process during pull-off tests started at the loaded end of the CFRP sheet and propagated near the concrete/epoxy interface with increasing force.

[Figure 6 here]

3.2.2. Peak pull-off forces

Peak pull-off forces from each bond test and averages for each group of specimens are reported in Table 2. The individual effects of sustained load, temperature, and aging on these results are also shown in terms of percent change in pull-off force.

[Table 2 here]

All the specimens that were subjected to sustained load showed some degree of improvement in peak pull-off force with respect to the control specimens, regardless of the number of curing days and the temperature during the sustained loading period. The results clearly indicate that sustained loading had a positive effect on the peak pull-off force. The largest increase in pull-off force (23%) was observed in the 7d-RT specimens, which coincidentally had the shortest sustained loading period (31 days at 21°C) of all tests. Graphing

all the peak pull-off force results in Fig.7, without consideration of curing time or temperature during sustained loading, shows an asymptotically decreasing positive effect of sustained load as the duration of sustained loading increases. A plateau of approximately 12% to 14% increase in pull-off force is approached for sustained loadings beyond 79 days.

[Figure 7 here]

Exposure to a higher temperature (30°C) without sustained load led to a slight increase in the peak pull-off force of the 7-day-cured specimens (8%), but negligible change in the 90-day cured specimens. As mentioned earlier, the epoxy in the 7-day-cured specimens can be expected to undergo a rapid increase in T_g during subsequent exposure to a 30°C temperature [19], which according to the present results provides a higher pull-off force that is nearly equivalent to that of specimens with a 90-day cure. In the 90-day-cured specimens, the lack of change in peak pull-off force with exposure to the higher temperature could be attributed to their more fully developed T_g prior to the increase in temperature. The results in Table 2 show that temperature effects are insignificant in specimens subjected to sustained load, although differences in the sustained loading duration make the interpretation of this observation not very straightforward.

The effects of curing time on peak pull-off force were generally positive, as shown in Table 2, particularly for the specimens subjected to 21°C without sustained load up till the time of bond testing (14%). The effect of curing time was less apparent in the specimens subjected to 30°C temperature after the initial 7-day cure at 21°C. Once again, these results could be explained by the slow increase in T_g in the RT specimens after the initial cure compared to the relatively quick increase in the HT specimens.

3.2.3. Interfacial fracture energy

The Mode II interfacial fracture energy (G_{II}) between the concrete and FRP, represented by the area under the bond shear stress-slip curve, is an important material parameter for characterizing and modeling interfacial bond behavior and failure. From the bond test results, G_{II} , was calculated using the approach of Dai et al. [23],

$$G_{II} = \int_0^{\infty} \tau ds = \frac{1}{2} A^2 E_f t_f \quad (1)$$

where the local interfacial bond stress, τ , is expressed in terms of the local strain, ε , or local slip, s , as follows,

$$\tau = E_f t_f \frac{d\varepsilon}{dx} = E_f t_f \frac{df(s)}{ds} f(s) = A^2 B E_f t_f e^{-Bs} (1 - e^{-Bs}) \quad (2)$$

$$\varepsilon = f(s) = A(1 - e^{-Bs}) \quad (3)$$

In Eqs. (1-3), A is an experimental curve-fitting parameter associated with the maximum strain of the FRP sheet, B is considered as the ductility index of the bond shear stress-slip relationship, and E_f and t_f are the modulus of elasticity and the thickness of the **impregnated** CFRP sheet, respectively. The CFRP modulus, E_f , was calculated as the slope of the stress-strain curve, using the strain data from the unbonded portion of the CFRP sheet (SG1, shown in Fig. 3) **along with cross-sectional dimensions recorded with a dial caliper**. The experimental parameters A and B were obtained by fitting the loaded-end strains and slips to Eq. (3). The Appendix lists the parameters of the fracture model for each specimen. Figure 8 shows representative experimental and curve-fitted strain-slip curves for 7D-RT specimens with and without sustained load.

[Figure 8 here]

The Mode II interfacial fracture energies evaluated by Eq. (1), listed in Table 3, range between 544 and 646 N/m and show that the specimens that underwent sustained loading have

higher interfacial fracture energy than the control specimens. Therefore, the sustained loading has a positive effect on the interfacial fracture energy, as one would expect from the positive effect of sustained load on the peak pull-off force capacity shown in Table 2 and from the analytical relationship between the fracture energy and peak pull-off force for linear elastic constituents as presented by Dai et al. [24] and Täljsten [25],

$$P_{max} = b_f E_f t_f A = b_f \sqrt{2 E_f t_f G_{II}} \quad (4)$$

where b_f is the width of the CFRP sheet. The presence of high temperature in specimens cured for 7 days or 90 days resulted in negligible changes in the interfacial fracture energy of single-lap shear specimens. As for the aging effect, the 90 day-cured specimens show slightly higher interfacial fracture energy values when compared with specimens cured for 7 days. The age of the epoxy may have contributed to this increase in G_{II} values. Comparisons between the experimental and analytical peak pull-off forces (Eq. 4) are shown in Fig. 9. It can be seen that good agreement is obtained.

[Table 3 here]

[Figure 9 here]

3.2.4. Stress redistribution

Figure 10 shows strain gage readings along the length of the bonded CFRP sheet at various applied forces as well as strain profiles created using the DIC method. When comparing the strain versus distance profiles in specimens with and without preceding sustained load, different trends can be observed. The control specimens in Figs. 10a and 10c show a trend of exponentially increasing strain towards the loaded end for the various applied loads. The transfer zone extends to about 50 mm from the loaded end for applied forces less than 2.67 kN. At higher applied loads, some reduction in the gradient of strain occurs near the loaded end,

indicating the onset of stable debonding. By contrast, the sustained load specimens (Figs. 10b and 10d) show a trend of bilinearly increasing strain towards the loaded end for applied forces less than 2.67 kN, with a lower gradient occurring over a distance of 30 mm from the loaded end. The reduction in gradient was particularly marked in the 7-day-cured specimen in comparison to the 90-day-cured specimen, which can be justified by the higher viscoelastic strain rate of the epoxy resin with less curing time [19]. Since the gradient in longitudinal normal strain is proportional to the magnitude of interfacial shear stress (Eq. 2), it is concluded that the shear stress concentration near the loaded end relaxed over a distance of 30 mm during sustained loading. For comparison, Mazzotti and Savoia [14] observed a relaxation zone of 10-15 mm length in double-lap-shear specimens with pultruded CFRP plates under sustained loads of about 50% of initial ultimate for up to five years at 20°C. Diab and Wu [10] observed a relaxation zone of roughly 70-80 mm length in double-lap-shear specimens with rigid molecule polymer FRP sheets after 4.3 days of room-temperature loading at 50% of initial ultimate. Mazzotti and Savoia [14] used a bond-breaker near the loaded end of the FRP, whereas Diab and Wu [10] and the current investigators did not, which may account for the smaller relaxation length in Mazzotti and Savoia's results if the bond breaker prevented crack formation in the concrete near the loaded end [14].

[Figure 10 here]

3.3. Analysis of fracture surfaces

Following bond testing, fracture surfaces of all tested specimens were examined, using digital image analysis, to evaluate the effects of the sustained loading and temperature on the failure mode. Both surfaces of the crack path (i.e., from the separated CFRP and concrete sides) were examined. The concrete/FRP bond interface can be idealized as a three-layered material system consisting of concrete, epoxy and FRP (Fig. 11). Crack propagation such a layered

system typically takes place in the concrete layer (cohesive failure in concrete), in the epoxy layer (cohesive failure in epoxy) or at the interface between the concrete and the epoxy (interfacial failure) [26].

[Figure 11 here]

A commercially available image analysis software, Photoshop CS4 (Adobe, San Jose, CA) was used for the analysis of the fracture surfaces from both concrete and CFRP sides. The procedure to obtain the failure mode of the fracture surfaces was as follows:

Step 1: Noise (e.g. visual distortion like grain in image) was removed and a 4×4 grid pattern of 6.25-mm square cells was created within each $25 \text{ mm} \times 25 \text{ mm}$ sample area. Seven such $25 \text{ mm} \times 25 \text{ mm}$ sample areas comprised each side of the crack path.

Step 2: Areas of epoxy were selected and all remaining unselected areas were removed.

Step 3: The ratio of the area of epoxy to total area in each 6.25-mm cell was quantified.

Step 4: The failure mode of each 6.25-mm cell was identified by comparing the characteristic values of the cells facing each other on opposite sides of the crack (concrete side and CFRP side).

Figure 12 illustrates the process of identifying the failure mode in each cell for one specimen and the percent of each failure mode over the entire crack surface.

[Figure 12 here]

The failure mode of each 6.25-mm cell was determined according to the following criteria:

- A cohesive failure in concrete (CC) was assigned to the cell when the ratios of epoxy area to total cell area on both sides of the failure plane were less than or equal to 10%.

- Cohesive failure in the epoxy (CE) was assigned to the cell if the epoxy-to-total area ratios on both surfaces were larger than 90%.
- Interfacial failure (IF) between the concrete and the epoxy was assigned to the cell in all cases except when cohesive failure in concrete or cohesive failure in epoxy were identified.

Once the failure mode for each cell location is determined, the percent of a given failure mode with respect to the entire crack surface can be obtained by dividing the number of cells having the failure mode by the total number of cells in the fracture path (112), as shown for an example case in Fig. 12.

The failure modes observed in the current investigation were mainly interfacial failure and concrete-cohesive failure. Cohesive failure in the epoxy was less than 10% in all cases. Figure 13 shows that the percentage of concrete-cohesive failure decreases and the percentage of interfacial failure increased with additional sustained loading duration, regardless of curing time and temperature during the sustained loading period. The Appendix lists the percent of each failure mode in each specimen. The evolution of failure mode can be attributed to the deterioration of the bond strength of the epoxy/concrete interface due to the sustained loading. A preliminary conclusion similar to this was made by Diab and Wu [10] for double-lap shear specimens under sustained loading at room temperature, although the more extensive results reported presently confirm and solidify the phenomenon and show a quantitative trend versus sustained loading time for the first time. Recall from Fig. 7 that the peak pull-off force is attained for specimens under a short duration of sustained load, and that control specimens are weaker than specimens subjected to sustained loads. Considering the fracture image analysis results together with the mechanical test results, it can be deduced that stress relaxation during the early stages of sustained loading increases the pull-off strength, whereas reduction of the

epoxy/concrete adhesive strength with longer sustained loading reduces the beneficial effect of stress relaxation.

[Figure 13 here]

4. Conclusions

Based on the experimental study conducted, the following conclusions can be made:

1. Elevated temperature (30°C) sustained loading results in larger displacement of the CFRP relative to the concrete, in comparison to sustained loading at 21°C, regardless of the curing time and epoxy age. In the 7-day-cured specimens, displacement of the CFRP reached a steady value in less time when the sustained load applied at 30°C versus 21°C. This behavior can be linked to results in a parallel investigation that showed that the glass transition temperature (T_g) of the epoxy resin increases rapidly at 30°C to a value well above the test temperature, whereas the T_g increases relatively slowly at 21°C.
2. In the bond tests conducted after the sustained loading or dwell period, peak pull-off forces were higher for the specimens with sustained loads than for the control specimens. However, this positive effect decreases as the sustained loading duration increases, reaching a plateau still higher than the control specimens after 79 days of sustained loading. The presence of higher temperature (30°C) without sustained loading leads to a slight increase of peak pull-off force only in the 7-day-cured specimens, which again can be linked to the rapid advance of T_g in these specimens at 30°C.
3. The results of the bond tests showed that the 90-day-cured specimens failed at a higher pull-off force and interfacial fracture energy than the specimens cured for 7 days, indicating a beneficial effect of epoxy curing time. The interfacial fracture energy also increases in the presence of sustained loading when compared to control specimens.

4. The analysis of strains by digital image correlation showed clear evidence of shear stress relaxation in the 30 mm closest to the loaded end of the bond line following sustained loading. In contrast, the control specimens did not show such evidence except at loads close to failure where stable debonding can be expected to occur.
5. Based on the analysis of fracture surfaces of tested specimens, a shift in failure mode from cohesive failure in concrete to an interfacial failure between epoxy and concrete was observed for specimens subjected to the longest periods of sustained load. These results indicate that, while stress relaxation associated with sustained loading increases pull-off strength as long as the failure locus remains mostly in the concrete, longer duration sustained loading degrades the strength of the epoxy/concrete interface such that some of the benefit of stress relaxation is lost as the failure locus shifts to the interface.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. 0826461. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

[Appendix here]

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474 Table 1. Specimens used during experimental program.
475 Table 2. Bond test peak loads, P_{max} .
476 Table 3. Interfacial fracture energy, G_{II} , by bond testing.
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Figure 1. Instrumentation of the single-lap shear specimen during sustained loading (all dimensions in mm).

Figure 2. Creep tests of single-lap shear specimens at (a) RT (21°C) and (b) HT (30°C).

Figure 3. Bond test setup: (a) photograph; (b) schematic; and (c) test set-up with digital camera. Dimensions in millimeters.

Figure 4. Effect of test temperature on displacement of bonded CFRP sheets at target point D6 for different curing ages: (a) 7 day and (b) 90 day. Average data from three specimens are plotted and scatter bars show the data range.

Figure 5. Glass transition temperature of epoxy versus aging time following an initial 7-day cure at 22°C [19].

Figure 6. Displacement data at target point D6: (a) load vs. displacement during pull-off tests of representative RT specimens; (b) displacement vs. time during sustained loading and unloading of representative RT specimens; (c) maximum displacement during pull-off tests vs. residual displacement upon unloading after sustained loading.

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Figure 11. Possible failure modes in concrete/epoxy interface.

Figure 12. Fracture surface analysis.

Figure 13. Percent of the failure surface composed of different failure modes for various sustained loading durations: (a) cohesive failure in concrete and (b) interfacial failure between the epoxy and concrete.

Table 1. Specimens used during experimental program.

Specimen ID	Number of specimens	Epoxy curing time ^a (days)	Temperature during sustained loading or dwell (°C)	Sustained loading or dwell period (days)	Specimen age at bond test ^b (days)
7d-HT-C	3	7	30	75	190
7d-HT-SL	3	7	30	75	91
7d-RT-C	3	7	21	31	190
7d-RT-SL	3	7	21	31	38
90d-HT-C	3	90	30	79	271
90d-HT-SL	3	90	30	79	170
90d-RT-C	3	90	21	153	271
90d-RT-SL	3	90	21	153	251

^a Curing time prior to sustained loading or dwell period.

^b Specimen age refers to the age of the bonded CFRP system at the time of bond test.

Table 2. Bond test peak loads, P_{max} .

Specimen ID	P_{max} (kN)	Average P_{max} (kN)	Effect (%) ^a		
			Sustained load	Higher temperature	Aging
7d-HT-C1	5.14	(a) 5.55	(b/a) +14	(a/c) +8	(b/d) +0
7d-HT-C2	5.95				
7d-HT-C3 ^(c)	-				
7d-HT-SL1	6.46	(b) 6.33			
7d-HT-SL2	6.21				
7d-HT-SL3 ^(c)	-				
7d-RT-C1	5.15	(c) 5.14	(d/c) +23	(e/g) -1	(e/a) +4
7d-RT-C2	4.83				
7d-RT-C3	5.43				
7d-RT-SL1	6.56	(d) 6.32			
7d-RT-SL2	6.24				
7d-RT-SL3	6.15				
90d-HT-C1	6.13	(e) 5.79	(f/e) +12	(f/h) -1	(f/b) +3
90d-HT-C2	5.95				
90d-HT-C3	5.28				
90d-HT-SL1	6.07	(f) 6.51			
90d-HT-SL2	6.96				
90d-HT-SL3 ^(c)	-				
90d-RT-C1	7.03	(g) 5.86	(h/g) +12	(g/c) +14	NA ^b
90d-RT-C2	5.17				
90d-RT-C3	5.39				
90d-RT-SL1	6.77	(h) 6.60			
90d-RT-SL2	6.42				
90d-RT-SL3 ^(c)	-				

^aNotation example: $b/a = \frac{(b-a)}{a} \times 100$

^bComparison (h/d) not made due to large difference in creep duration.

^cNo data due to testing error.

Table 3. Interfacial fracture energy, G_{II} , by bond testing.

Specimen ID	E_f (GPa)	G_{II} (N/m)	Average G_{II} (N/m)	Effect (%) ^a		
				Sustained load	Higher temperature	Aging
7d-HT-C1	26.52	544	(a) 544		(a/b) 0	
7d-HT-C2	NA	NA				
7d-HT-C3 ^(c)						
7d-HT-SL1	NA	NA	NA ^b			
7d-HT-SL2	NA	NA				
7d-HT-SL3 ^(c)	-					
7d-RT-C1	22.56	485	(b) 545			
7d-RT-C2	36.73	480				
7d-RT-C3	26.49	669				
7d-RT-SL1	23.49	811	(c) 639	(c/b) +17		
7d-RT-SL2	27.64	722				
7d-RT-SL3	53.10	385				
90d-HT-C1	42.49	545	(d) 565		(d/e) -1	(d/a) +4
90d-HT-C2	42.26	529				
90d-HT-C3	26.85	621				
90d-HT-SL1	NA	NA	NA			
90d-HT-SL2	NA	NA				
90d-HT-SL3 ^(c)	-					
90d-RT-C1	33.57	638	(e) 571			(e/b) +5
90d-RT-C2	21.17	645				
90d-RT-C3	38.96	431				
90d-RT-SL1	34.07	745	(f) 646	(f/e) +13		
90d-RT-SL2	39.63	547				
90d-RT-SL3 ^(c)	-					

^aNotation example: $b/a = (b-a)/a \times 100$

^bNA: data are not processed because LVDT data are not available

^cNo data due to testing error.

Figure 1. Instrumentation of the single-lap shear specimen during sustained loading (all dimensions in mm).

(a)

(b)

Figure 2. Creep tests of single-lap shear specimens at (a) RT (21°C) and (b) HT (30°C).

(a)

(b)

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(a)

(b)

(c)

(d)

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Specimen ID	Age of specimen (days)	Sustained loading duration (days)	$P_{max-anal}$ (kN)	E_f (GPa)	t_f (mm)	E_{ftf} (kN/mm)	G_{II} (N/m)	A (ϵ)	B (mm^{-1})	Failure mode (%)		
										CC ^b	CE ^c	IF ^d
7d-HT-C1	189	-	5.10	26.52	1.31	34.74	544	0.00561	6.8	13	0	87
7d-HT-C2	190	-	NA ^a	NA	NA	NA	NA	NA	NA	5	0	95
7d-HT-C3 ^(e)	-	-	-	-	-	-	-	-	-	-	-	-
7d-HT-SL1	91	75	NA	NA	NA	NA	NA	NA	NA	24	0	76
7d-HT-SL2	91	75	NA	NA	NA	NA	NA	NA	NA	6	0	94
7d-HT-SL3 ^(e)	-	-	-	-	-	-	-	-	-	-	-	-
7d-RT-C1	190	-	4.47	22.56	1.31	29.56	485	0.00579	7.6	- ^f	-	-
7d-RT-C2	190	-	4.95	36.73	1.16	42.61	480	0.00485	3.8	5	0	95
7d-RT-C3	192	-	5.01	26.49	1.10	29.14	669	0.00688	8.5	4	0	96
7d-RT-SL1	38	31	6.00	23.49	1.37	32.18	811	0.00710	6.1	50	0	50
7d-RT-SL2	38	31	5.92	27.64	1.36	37.59	722	0.00620	5.8	21	1	78
7d-RT-SL3	38	31	6.23	53.10	1.35	71.68	385	0.00328	4.3	7	0	93
90d-HT-C1	271	-	6.51	42.49	1.42	60.34	545	0.00425	3.2	21	0	79
90d-HT-C2	271	-	6.20	42.26	1.40	59.17	529	0.00423	1.6	32	0	68
90d-HT-C3	269	-	5.12	26.85	1.20	32.22	621	0.00621	8.6	21	0	79
90d-HT-SL1	170	79	NA	NA	NA	NA	NA	NA	NA	29	0	71
90d-HT-SL2	170	79	NA	NA	NA	NA	NA	NA	NA	32	0	68
90d-HT-SL3 ^(e)	-	-	-	-	-	-	-	-	-	-	-	-
90d-RT-C1	271	-	6.32	33.57	1.30	43.65	638	0.00550	3.8	13	0	87
90d-RT-C2	271	-	4.75	21.17	1.30	27.52	645	0.00685	4.8	16	0	84
90d-RT-C3	271	-	5.22	38.96	1.35	52.60	431	0.00405	10.5	6	0	94
90d-RT-SL1	251	153	6.55	34.07	1.30	44.29	745	0.00580	8.5	5	0	95
90d-RT-SL2	251	153	6.05	39.63	1.30	51.52	547	0.00461	8.6	14	0	86
90d-RT-SL3 ^(e)	-	-	-	-	-	-	-	-	-	-	-	-

^aNA=parameters are not calculated because LVDT data are not available^bCC=cohesive failure in concrete^cCE=cohesive failure in epoxy^dIF=interfacial failure^eNo data due to testing error^fNo failure mode results because digital images are not available