Bond behavior of CFRP-to-steel bonded joints at mild temperatures: an experimental study

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Abstract

The performance of steel structures strengthened with externally bonded fiber-reinforced polymer (FRP) heavily rely on the interfacial shear stress transfer mechanism of the FRP-to-steel bonded interface. While much is known about the behavior of FRP-to-steel bonded joints under mechanical loading, little is known about the performance of such bonded joints at elevated temperatures. Almost all adhesives typically used in FRP-to-steel applications experience a change of their mechanical behavior at temperatures below 70°C. Therefore, gaining a sound understanding of the behavior of FRP-to-steel bonded joints at elevated temperatures is necessary. This paper presents a series of tests where carbon FRP (CFRP)-to-steel bonded joints are subjected to elevated temperatures. Outcomes of this study showed that, at elevated temperatures, the dominant failure mode of the CFRP-to-steel bonded joints is the cohesion failure within the adhesive. The bond strength was found to increase with the temperature until the Heat Deflection Temperature (HDT). The bond-slip behavior of the interface was found to undergo significant changes with increasing temperature. Specifically, the initial elastic stiffness and the peak shear stress were found to decrease as the temperature increases. The fracture energy was found to increase at temperatures below HDT but then decrease drastically when the temperatures exceeds the HDT.

Keywords

CFRP-to-steel; bond strength; bond-slip relation; elevated temperatures

Introduction

Fiber-reinforced polymers (FRPs) have become a popular material for the strengthening of existing structures. This is due to its many advantages, such as a high strength-to-weight ratio, excellent corrosion resistance, and ease of installation (Zhao and Zhang, 2007, Teng et al., 2012). Extensive studies have been carried out demonstrating the effectiveness of FRPs in strengthening of reinforced concrete (RC) structures (Bakis et al., 2002, Hollaway and Teng, 2008, Tomlinson and Fam, 2015, de Waal et al., 2017). FRPs have also shown promise for strengthening of steel structures (Cadei et al., 2004, Shaat et al., 2004, Schnerch et al., 2007, Rizkalla et al., 2008, Ghafoori et al., 2012, Hosseini et al., 2019). In steel members, where the flexural load capacity is strengthened using externally bonded FRP laminates, the effective stress transfer between steel and the FRP laminate is of great importance to achieve a good performance (Teng and Fernando, 2013, Zhou et al., 2017, Doroudi et al., 2019). As such, the bond behavior of FRP-to-steel joints has been extensively investigated under quasi-static monotonic loading (Matta et al., 2005, Yu et al., 2012, Fernando et al., 2013, Fernando et al., 2014) and cyclic loading (Doroudi et al., 2019). These studies revealed that the governing failure of FRP-to-steel bonded joints with adequate surface preparation is the cohesion failure within adhesive (Fernando et al., 2013). Therefore, the thermo-mechanical properties of the adhesive determine the behavior of FRP-to-steel bonded joints (Nguyen et al., 2011, Stratford and Bisby, 2012, Sahin and Dawood, 2016).

Bond-slip curves which depict the relationship between interfacial shear stress and shear slip are often used to characterize the constitutive behavior of the FRP-to-steel bonded interfaces (Yu et al., 2012, Fernando et al., 2015). For carbon FRP (CFRP)-to-steel bonded joints manufactured using linear adhesives, it was found that bond-slip behavior can be idealized using a bi-linear curve with a linear ascending branch and a linear descending branch (Yu et al., 2012). However, for CFRP-to-steel bonded joints made using low elastic modulus nonlinear adhesives, bond-slip behavior was found to be approximately tri-linear with a linear ascending branch, followed by a constant stress region, followed by a linear descending branch (Yu et al., 2012, Fernando et al., 2015). The area under the bond-slip curve is equivalent to the interfacial fracture energy under mode II loading, which is a key parameter determining the bond strength of the joint (Fernando et al., 2015). The bond strength of a CFRP-to-steel bonded joint with a sufficiently long bonding length was found to be dependent on the interfacial fracture energy, and the shape of the bond-slip curve was found to have no significant effect on the bond-strength (Fernando et al., 2015). Fernando et al. (2015) showed that the mode II interfacial fracture energy of a CFRP-to-steel bonded joint is directly related to the tensile strain energy of the adhesive, where adhesives with higher strain energy resulted in higher mode II interfacial fracture energy.

Different chemical structures of different adhesives imply that different adhesives will have different variation of properties with temperature. Research presented in Adams et al. (1992) has shown that temperature has a considerable effect on the adhesive properties in terms of the ductility and the strength. S&P Resin 220 (a solvent free, thixotropic two-component epoxy adhesive (Component A- Bisphenol A 20%-25%, 1,3bis(2,3-epoxypropoxy)-2,2-dimethylpropane- 5%-10%; Component B- Polyoxypropylenediamine-20%-25%, Piperazine-1%-2.5%, 3,6-diazaoctanethylenediamin and Triethylenetetramine- 20%-25%)) coupons cured at 22 ^{o}C and 55% relative humidity for one year, then subjected to cyclic thermal conditions between -15^{o}C and 60^{o}C for 240 days, the dynamic E-modulus increased by 22% (Silva et al., 2016). While for SikaPower-498 (Polyurethane based epoxy resin) (da Silva and Altenbach, 2010), cured at 175 ^{o}C for 25 minutes, both mode I and mode II fracture energy, elastic stiffness and strength was found to decrease with increasing temperature within the range between -30^{o}C and 80^{o}C (Walander, 2013). For some cementitious adhesive systems, the fracture energy was shown to initially increase with temperatures between 40^{o}C and 60^{o}C and then followed by a decreasing trend (Igbinedion et al., 1987). Results from the above research clearly indicate that the adhesive mechanical properties are significantly affected by the temperature and that the effects are dependent on the type of adhesive.

Strength and strain energy of the adhesives significantly depend on the chemical structure of the polymer chains forming the adhesive. Bonds in polymer chains can be categorized into two groups: 1) primary bonds, consisting of strong covalent intramolecular bonds which form the backbone of a polymer chain; and 2) secondary bonds, which are weaker bonds such as hydrogen bonds, dipole interaction, Van der Waals forces and ionic bonds (Mahieux and Reifsnider, 2001, Moussa et al., 2012). The contribution to the polymer strength provided by the primary bonds is significantly higher than that from the secondary bonds (Moussa et al., 2012). Primary and secondary bonds loose strength as the temperature increases but secondary bonds will relax at lower temperatures than the primary bonds. Relaxation of secondary bonds increase the molecular mobility, especially the differential movement between polymer chains. This enhances polymer ductility and can lead to an overall increase in toughness (Mahieux and

Reifsnider, 2001, Ashby and Jones, 2013). Glass transition temperature (T_g) is often used to assess the thermal stability of the adhesive. T_g is the temperature at which the molecular mobility increases and the adhesive transits from a glassy state to a rubbery state. For a specific application of an adhesive, the allowable service temperature should be lower than the T_g for a sound bonding performance (Shrivastava, 2018). Typically, the adhesives used in civil infrastructure applications are often "cold-curing", that is, adhesive systems able to achieve a suitable degree of cure and acceptable mechanical properties in reasonable curing times when cured at ambient temperatures (Moussa et al., 2012, Corcione et al., 2014). The T_g values of such cold-curing adhesives are relatively low (< 60 ^{o}C) due to the low curing temperature (Moussa et al., 2012) and relatively high amount of incomplete chemical reactions (compared to high temperature-curing adhesives) (Corcione et al., 2014). Which makes the adhesive more vulnerable to the temperature elevation, due to possible degradation of mechanical properties (Corcione et al., 2014). Therefore, a profound understanding of the thermal behavior of an adhesive is of great importance in selecting a suitable adhesive for a particular application.

Existing experimental studies on the bond behavior of CFRP-to-steel bonded joints at varying temperatures were carried out using single or double lap tests (Nguyen et al., 2011, Al-Shawaf et al., 2015, Yao et al., 2016). A third configuration used is the CFRP strengthened steel beam tests (Stratford and Bisby, 2012, Sahin and Dawood, 2016). However, only the global behavior of bonded joints at elevated temperatures was reported in these studies. A temperature depended bond-slip relation of FRP-to-concrete bonded joints has been proposed in Dai et al. (2013), which indicates the bond-slip relation of FRP-to-concrete bonded joints could change with respect to temperature. Most recently, He et al. (2020) showed that moderately elevated temperature could change the shape of the bond-slip relations of FRP-to-steel bonded joints. However, complete bond-slip relations of FRP-to-steel bonded joints at different temperature are still missing. Recent study by Zhou et al. (2019) used a theoretical approach and showed that the rate of interfacial fracture energy change and the loading rate both influence the behavior and the ultimate load carrying capacity of the CFRP-to-steel bonded joints. It was also found that for sufficiently large bonding lengths, the final load capacity is dependent on the interfacial fracture energy at the final temperature. Based on the results of this theoretical study, it is clear that to better understand the behavior of CFRP-to-steel bonded joints, understanding of the variation of constitutive behavior of the bonded interface with temperature is necessary (Zhou et al., 2019).

One clear conclusion which can be obtained from the existing studies is that almost all the adhesives used on CFRP-to-steel bonded joints show mechanical property variations at temperatures well below 70°C. Therefore, a sound understanding of the effect of temperature on the behavior of CFRP-to-steel bonded joints is necessary to better understand the performance of FRP strengthened steel structures.

This paper extends the study of Zhou et al. (2017) by conducting an experimental study aimed at investigating the effect of temperature on the behavior of CFRP-to-steel bonded joints, with special attention given to localized bond-slip behaviors. A series of single-shear pull-off tests of CFRP-to-steel bonded joints, as well as the adhesive tensile coupon tests were carried out at different target temperatures. The objective of this study is not to derive statistically valid parameters but to reveal the behavior experienced by CFRP-to-steel bonded joints as the temperature of the joint increases. To guide the future selection of the adhesive and assess the long-term durability of adhesively bonded CFRP-steel joints in the construction industry considering the temperature effect, more research is required to quantitatively obtain the bond behavior of CFRP-to-steel bonded when subjected to different temperatures for different adhesives.

Experimental Program

In this study, commercially available adhesive Sikadur 30 (Sika, 2020) (called S30 hereafter) was used to bond the CFRP plates to the steel plates. Adhesive S30 is one of the most commonly used adhesives in bonding CFRP plates to steel surfaces (Yu et al., 2012, Zhou et al., 2015, Doroudi et al., 2019). S30 is a two-component thixotropic, solvent-free epoxy-based adhesive. The mixing ratio of the adhesive is 3:1 (Resin: Hardener) in weight. Silica quartz fillers with dimension between 0.2mm to 0.5mm take up around 55% of the resin by weight (Moussa et al., 2012). S30 is a linear adhesive, and the bond-slip behavior of CFRP-to-steel bonded joints made using this adhesive was found to be bi-linear (Yu et al., 2012). Behaviors of CFRP-to-steel bonded joints with S30 have been well investigated under quasi-static monotonic loading (Yu et al., 2012), quasi-static cyclic loading (Doroudi et al., 2019) as well as fatigue cyclic loading (Ghafoori et al., 2012, Wang et al., 2019, Doroudi et al. 2020). Bond-slip relation for CFRP-to-steel bonded interfaces with S30 adhesive is well established, including the effect of geometric parameters (Fernando, 2010, Yu et al., 2012). Therefore, S30 was selected as the adhesive for bonding CFRP plates to steel plates in this study.

In order to determine the effect of temperature on adhesive properties, adhesive tensile coupon tests were carried out. The heat deflection (distortion) temperature (HDT) (i.e. the temperature which material starts to soften when exposed to a fixed load) of a polymer is often used to represent the upper stability limit of the material. While T_g is often used in the scientific world for thermal characterization of a polymer, HDT is often used by the adhesive manufacturers for thermal characterization of a polymer. Therefore, HDT is adopted in this study to better facilitate the comparisons with manufacturer data. When the temperature is beyond the HDT value, large deformations can occur without increasing the applied load, i.e., the critical softening of adhesive (Wong, 2003). Therefore, the temperature at which critical softening occurs, is often used to assess the structural properties of polymers. According to the manufacturer's data sheet (Sika, 2020), the HDT of S30 is around 47^{o}C when cured at ambient temperature (25^{o}C). Therefore, temperatures for conducting adhesive tensile coupon (cured at 25^{o}C) tests were selected as 25^{o}C, 35^{o}C, 40^{o}C, 45^{o}C and 55^{o}C. The limit temperature is defined by the maximum temperature increase associated to sunlight (~60^{o}C). In total 31 adhesive tensile coupon tests were carried out resulting in minimum of 3 adhesive tensile coupon tests at each temperature.

In addition to the adhesive tensile coupon tests, two control adhesive tensile coupons were instrumented and tested as temperature calibration tests. These temperature calibration adhesive tensile coupons were instrumented with three temperature gauges and heated under identical conditions. These two calibration tests allowed for an accurate understanding of the thermal conditions of the adhesive tensile coupons during testing. Temperature calibration of the adhesive tensile coupons was carried out before mechanical testing to ensure the samples were tested at the desired temperature. The temperature gauges and locations are shown in Fig. 1(a). Three thermocouples (Type K), labelled TC-Inside1, TC-Inside2 and TC-Surface, were attached to the adhesive tensile coupons. TC-Inside1 and 2 were embedded inside each end of the adhesive tensile coupon by drilling a small hole in the adhesive layer, while TC-Surface was attached to the surface of the adhesive tensile coupon at the middle of the bonded length. Using these thermocouples, the temperature gradient within the adhesive layer was carefully monitored. Heating conditions of these control tests were identical to those of actual adhesive tensile coupon tests.

To maintain the integrity of the adhesive tensile coupons, no thermocouples were embedded inside the adhesive tensile coupons used for mechanical testing. In the adhesive tensile coupon tests, only one thermocouple was attached to the surface of the adhesive tensile coupon.

Temperature calibration tests (presented in the following section) were used to determine the temperature of the adhesive tensile coupon from the surface temperature measurements.

In order to determine the effect of temperature on the behavior of CFRP-to-steel bonded joints, the single-shear pull off test set-up was used. As summarized in Table 1 (denoted by Test-1 to Test-12), the target temperatures for the CFRP-to-steel bonded joints were ambient temperature (25°C), 32.5°C, 40°C, 47.5°C, 50°C, and 55°C. While the target was to test minimum of two samples at each temperature, due to breakdown of the control system, an additional specimen (i.e. in total three specimens) was tested at 47.5°C, resulting in only one specimen being tested at 50°C. In addition to the 12 specimens tested under mechanical loading, an extra CFRP-to-steel bond joint test specimen was prepared and used for temperature calibration. Similar to the adhesive tensile coupon temperature calibration, in the CFRP-to-steel bond joint test specimen used for temperature calibration, three thermocouples (i.e., TCA-1, 2 and 3) were embedded in the adhesive layer along the bonding length during manufacturing (Fig. 1b). Three corresponding thermocouples were also attached to the steel plate (i.e., TCS-1, 2 and 3). The intention was to compare the temperature measurements from TCA-1 to 3 to those from TCS-1 to 3 to obtain a relationship between the temperature on the steel plate and that at the adhesive layer. Once this relationship was obtained, the temperature on the steel plate can be used to control the heating process for CFRP-to-steel bond joint tests at different target temperatures.

To maintain the integrity of the CFRP-to-steel bonded joints, no thermocouples were embedded inside the adhesive layer of the specimens used for bond joint tests. For the CFRP-to-steel bond joint specimens used for bond joint tests, each specimen was instrumented with three thermocouples which were attached to the steel plate along the bond length to capture the steel temperature, whilst another thermocouple was attached on the heating blanket. Relationship between the temperature on steel plate and that at the adhesive layer obtained from the temperature calibration tests (presented in the following section) was used to determine the temperature within the adhesive layer from the steel surface temperature measurements. Details of the sample preparations for adhesive tensile coupon tests and CFRP-to-steel bond tests, and the temperature control method are presented in the subsequent sections.

Sample preparation

Adhesive tensile coupon manufacturing

Dimensions of the adhesive tensile coupons were selected according to ASTM D638-14 (ASTM International, 2014) with a coupon thickness of 6.5mm. As shown in Fig. 2a, an aluminum mold consisting of a base plate and another top plate, was designed and manufactured to achieve the desired coupon shape. The top plate was assembled using four individual plates (I, II, III and IV in Fig. 2a). The top surface of the base plate and the sides of the molds were covered with Teflon tape to avoid any adhesion to the aluminum plates and make demolding of the adhesive tensile coupons easier (Fig. 2b). The adhesive was mixed as per manufacturer instructions and then slowly filled into the molds with a syringe to avoid trapping air bubbles inside the adhesive tensile coupons. When the molds were fully filled, the excess adhesive was scrapped away slowly to achieve a flat top surface. Another Teflon covered aluminum plate was then placed on top of the adhesive for curing. Adhesive tensile coupons were cured for at least three days at ambient temperature before demolding. Demolded samples were cured at ambient temperature for at least another three months before testing.

CFRP-to-steel bond test sample manufacturing

The preparation of a CFRP-to-steel bond test specimen is shown in Fig. 3. A 250×150×17mm steel plate was used in all specimens (Fig. 3b). Sika CarboDur S512 CFRP plates with 50mm width, 1.2mm thickness were used in all specimens. The bonding length of each specimen was controlled to be 200mm.

Both the steel and CFRP bond surfaces were adequately prepared prior to adhesive bonding as per methods proposed in Fernando et al. (2013). Adhesive was applied to both the CFRP bond surface and steel bond surface (Fig 3a). Spacer plates with 2.85mm thickness were used on both sides of the CFRP plate to control the nominal adhesive thickness of all the samples to be similar. A steel roller was run over the whole bonding length to squeeze out any excess adhesive. The bonded samples were left to cure for at least thirty days before testing. Thicknesses of the adhesive layers were measured using a 3D digital image correlation (DIC) system (Correlated, 2010) and are given in Table 1. The average adhesive thickness was measured to be 1.60mm with a standard deviation of 0.088mm (from 10 measurements along the bonding length of each specimen), showing excellent quality in thickness control of the specimens.

Test set-up and instrumentation

Adhesive tensile coupon test setup and instrumentation

Adhesive tensile coupon tests at elevated temperatures were conducted in an Instron environmental chamber. Images for strain measurements were captured through the observation window of the environmental chamber (Fig. 4a). Two mechanical grips, as shown in Fig. 4(b), were employed to apply the tensile load on the samples. A displacement-controlled load was applied at a rate of 0.1mm/min for all adhesive tensile coupon test samples.

A speckle pattern was painted on the surface of the adhesive tensile coupon for the strain measurement using the ARAMIS DIC system (Aramis, 2009) (Fig. 4c) on the side opposite to that with the thermocouple. To achieve a good contrast of the speckle pattern, the surface of the adhesive tensile coupons was painted with a thin layer of white paint before spraying the black speckles.

Single-shear pull-off test setup and instrumentation

For the single-shear pull-off tests of CFRP-to-steel bonded joints, a test rig similar to that of Doroudi et al. (2019) was employed. More details about the test set-up can be found in Doroudi et al. (2019) and Zhou (2019). On top of the universal beam, two rollers (Fig. 5a) were used to minimize any bending due to miss-alignment of the CFRP plate and ensure predominantly shear loading condition throughout the test. A heating blanket (Fig. 5b) was used to apply heating to the test unit. To minimize the heat loss and to achieve a stable temperature of the sample, the universal beam was covered with an insulation mat (Fig. 5a), as well as the back of the heating blanket (Fig. 5b). All CFRP-to-steel bond tests were carried out under displacement control at a rate of 0.05mm/min.

For the CFRP-to-steel bonded joints tests, each specimen was instrumented with three thermocouples which were attached to the steel plate along the bonding length to capture the steel temperature, whilst another thermocouple was attached on the heating blanket. Two strain gauges were attached 100mm away from the loaded end on both sides of the CFRP plate to check for any bending of the CFRP plate. Since thermal expansion of strain gauges may result in inaccuracies in strain readings, thermal correction for the strain readings based on manufacturer thermal correction factors were applied for the strain gauge strain readings. The strain of the CFRP plate was measured using the ARAMIS DIC (Aramis, 2009) system. For this, a speckle pattern as shown in Fig. 5c was applied on the surface of CFRP plate within the bonded region. From the measured axial strains of the CFRP plate, interfacial shear stress and shear slip was calculated using the following well known equations (Alexander and Cheng, 1996):

$$\tau_{i+1/2} = \frac{(\varepsilon_i - \varepsilon_{i+1})}{(L_{i+1} - L_i)} E_p t_p \tag{1}$$

$$\delta_{i+1/2} = \frac{(\varepsilon_i + \varepsilon_{i+1})}{4}(L_{i+1} - L_i) + \sum_{i=1}^{n} \frac{(\varepsilon_i + \varepsilon_{i+1})}{2}(L_{i+2} - L_{i+1}) \tag{2}$$

Where ε_i is the strain value at the ith data point extracted from the DIC analysis, counted from the loaded end of the CFRP plate; L_i is the distance of the ith data point from the loaded end of the CFRP plate; E_p and t_p are the elastic modulus and thickness of the CFRP plate; n is the number of data points counted from the free end of the CFRP plate to the current calculating point; $\tau_{i+1/2}$ and $\delta_{i+1/2}$ are the shear stress and slip at the middle point between the ith and $(i+1)$th data point.

In order to investigate the change in mechanical properties of the adhesive and therefore the behavior of CFRP-to-steel bonded joints at elevated temperatures, it is important to maintain a stable and uniform temperature over the full duration of the mechanical test. Therefore, an accurate and reliable technique for temperature control was necessary. The temperature of the system was regulated by switching the heat blanket on and off iteratively and comparing the temperature of the sample with the target temperature. To achieve this, an eight-channel heating pad (Fig. 6a) and temperature control software (Fig. 6b) developed in LabView (National Instruments, 2017) were used. Of the eight channels, the first channel was connected to the thermocouple on the heating blanket (which was used as the control signal), whose temperature was then used to set the heating profile. The control channel can be changed accordingly to achieve a stable temperature of the CFRP-steel test sample. While the other channels were used to record the temperature at other positions of interest (e.g. on the CFRP plate).

Temperature control and test procedure

Temperature control of adhesive tensile coupon test and test procedure

The adhesive tensile coupon tests were carried out inside an environmental chamber, which was first heated to the targeted temperature (i.e. 25°C, 35°C, 40°C, 45°C and 55°C). A low heating rate of 2 °C/min was used to avoid significant thermal gradients, which could result in internal stresses within the adhesive tensile coupon. The temperature was then regulated at a nearly constant value by switching on and off the heating fan. During the temperature calibration test, the temperature readings inside and at the surface of the adhesive tensile coupon were obtained using thermocouples. Readings from three thermocouples are compared in Fig. 7a. Slight variation between the temperature readings of the surface to that inside the adhesive tensile coupon as well as between readings inside the adhesive tensile coupon at two ends were observed during the tests (Fig. 7b). However, the maximum difference observed at any given time during the testing was less than 2°C. Therefore, resulting internal stresses within the adhesive tensile coupon were assumed to be negligible. Considering the small temperature difference between surface and interior of the adhesive tensile coupon and that the difference did not vary significantly in time it was concluded that the surface temperature could be used as an indicative measurement of the temperature within the integrity of the adhesive tensile coupon.

Before applying the tensile loading, the adhesive tensile coupon was placed in the environmental chamber with only one end gripped to avoid any initial stress induced by the thermal expansion of the adhesive tensile coupon. To achieve the required temperature, the environmental chamber temperature was set to the desired test temperature and left at that temperature for at least 5 minutes, as measured through calibration tests. At the same time, the temperature of the adhesive tensile coupon was constantly monitored to ensure the sample was not over heated as a result of the delay between temperature detection and heating of the environmental chamber. When a stable target temperature was reached, the free end of the sample was gripped. Tensile loading was then applied until the failure of the adhesive tensile coupon.

Temperature control of single-shear pull-off test and test procedure

The temperature profile readings for a specific test are illustrated in Fig. 8. The temperature on the heating blanket was initially used as the control signal until the desired test temperature was reached. The target temperature was reached approximately 30 minutes from the start of heating and after reaching the temperature, the heating blanket was turned off to avoid further increase in temperature within the adhesive. Next, the control signal was switched to the temperature in the adhesive (i.e., the temperature on the surface of the steel plate). At the same time, a constant temperature profile was input as the control signal to maintain the temperature of the steel at a constant value.

It should be noted that for all tests there was a time lag between the temperatures on the heating blanket and the steel. In the adhesive temperature control mode, the temperature of the heating blanket can increase significantly before the temperature of the adhesive starts to increase. Therefore, an appropriate temperature gradient, to ensure required temperature of the adhesive is achieved without considerably exceeding the target temperature, was selected by trial and error. Measurements of the temperature within adhesive and steel plate showed similar values (Fig. 8), indicating that the temperature measurements of steel plate can be used as an indicator for the temperature within adhesive.

For the single-shear pull-off tests, each instrumented sample was mounted on the testing frame after the alignment of the centerline of the CFRP plate and the actuator was carefully checked by a laser leveler. Once the setup was completed, the sample was heated to the desired stable temperature with the afore mentioned control method. During temperature increase, the CFRP plate was un-gripped until the target temperature was attained. The CFRP plate was then gripped and the load was applied until full debonding of the CFRP plate from the steel plate occurred. The strain in the bonding area was measured during both the temperature elevation and loading processes.

Obtaining bond-slip curves from DIC measurements

When CFRP axial strain obtained from DIC measurements are used to obtain bond-slip relation, processing of the data to get rid of the noise in measurements is necessary. Therefore, post-processing of the measurement data was carried out to obtain bond-slip curves from the measurement data. The representative bond-slip curve illustrating the bonded joints at a given temperature was obtained using a nonlinear regression analysis provided by MATLAB (The Mathworks Inc, 2017) curve fitting toolbox (smoothing splines with smooth parameter is 0.9999) to best fit the bond slip relations obtained at different positions (represented by dot cloud in Fig.9). Data points used to obtain the average curve and the regressed curve for Test-2 are shown in Fig.9. With goodness of fitting value 0.89, the regression results were considered to be adequate to represent the bond-slip relations of CFRP-to-steel bonded joints.

Evaluation of Interfacial Stresses

Existing literature on CFRP-to-steel bonded joints suggest that interfacial stresses due to differential thermal expansion between CFRP and concrete could result in increase of bond strength (Gao et al., 2012). Therefore, an attempt was made in the current study to investigate effect of interfacial stresses due to differential thermal expansion on the bond-strength of specimens tested at different temperatures.

Considering the change in stress state within the bonded interface due to differential thermal movements of the adherends, Gao et al. (2012) proposed the following equations to calculate the load-carrying capacity of CFRP-to-concrete bonded joints at elevated temperatures:

$$P_u = \frac{b_p \tau_f}{\lambda} - \frac{b_p \tau_f}{\lambda_1^2 \delta_1}\left(\alpha_p - \alpha_s\right)\Delta T \tag{3}$$

$$\lambda^2 = \frac{\tau_f^2}{2G_f}\left(\frac{1}{E_p t_p} + \frac{b_p}{E_s t_s b_s}\right) \tag{4}$$

$$\lambda_1^2 = \frac{\tau_f}{\delta_1}\left(\frac{1}{E_p t_p} + \frac{b_p}{E_s t_s b_s}\right) \tag{5}$$

Where δ_1 is the slip value at the peak shear stress, τ_f is the bond shear strength of the interface. E_p, b_p and t_p are the elastic modulus, width and thickness of the CFRP plate, whilst E_s, b_s and t_s are the elastic modulus, width and thickness of the steel plate. α_p and α_s are the thermal expansion coefficient of the CFRP plate and steel plate respectively. ΔT is the temperature change of the bonded joint.

While Gao et al.'s (2012) study focused on CFRP-to-concrete bonded joints, Eqs (3)-(5) are equally applicable to CFRP-to-steel bonded joints, thus used to calculate the load carrying capacity of the specimens investigated in this study. The values used in the calculation are listed in Table 2. The reference temperature was taken as 25°C.

Processing of Bond-Slip Parameters for Comparisons

Initial stiffness, peak shear stress, and interfacial fracture energy are the three key parameters of a bond-slip curve (Fernando, 2010, Yu et al., 2012). According to Fernando (2010), the interfacial fracture energy and the slip value corresponding to the bond shear strength can be expressed as follows:

$$G_f = 628 t_a^{0.5} R_a^2 \left(N / mm^2 \bullet mm \right) \tag{6}$$

$$\delta_1 = 0.3 \left(\frac{t_a}{G_a} \right)^{0.65} \sigma_{\max} \left(mm \right) \tag{7}$$

Where t_a is the adhesive thickness in mm, R_a is the tensile strain energy of the adhesive which is equal to the area enclosed by the tensile stress-strain curve and $\sigma_{\max}$ is the maximum tensile strength of adhesive. G_a is the shear modulus of an elastic adhesive. The maximum interfacial shear stress was found to be independent of the adhesive thickness (Fernando, 2010). However, it is clear from the Eqs (6) and (7) that both interfacial fracture energy and interfacial slip at peak shear stress, thus initial stiffness of the bond-slip curve depends on the adhesive thickness. If different specimens consist of different adhesive thickness, direct comparison of the initial stiffness and interfacial fracture energy may not reflect the effect of adhesive mechanical properties alone on bond-slip parameters. Therefore, the normalized interfacial fracture energy, maximum interfacial shear stress and the slip corresponding to the maximum interfacial shear stress is used in the comparisons of this study. Normalized bond-slip parameters can be given as follows:

$$G_{f,norm} = \frac{G_{f,test}}{t_a^{0.5}} \tag{8}$$

$$\tau_{f,norm} = \tau_{f,test} \tag{9}$$

$$\delta_{1,norm} = \frac{\delta_{1,test}}{t_a^{0.65}} \tag{10}$$

Where $G_{f,test}$, $\tau_{f,test}$, $\delta_{1,test}$ are the experimentally obtained interfacial fracture energy, peak shear stress and the interfacial shear slip at the peak shear stress respectively. When a bilinear bond-slip relation is assumed, the normalized stiffness of the ascending branch of the curve can be derived as:

$$K_{e,norm} = \frac{\tau_{f,norm}}{\delta_{1,norm}} \tag{11}$$

Test Results

Test results of adhesive tensile coupon test

Failed adhesive tensile coupons are shown in Fig. 10. Failure in most of the specimens occurred within the uniform width region, while in some specimens failure occurred outside the uniform width region close to the grips. Only the data from the adhesive tensile coupons where failure occurred within the uniform width region were considered in determining the stress-strain behavior of adhesive at different target temperatures. Representative stress-strain curves of the adhesive at different temperatures are shown in Fig. 11. It was found that: a) the average maximum tensile strength of S30 adhesive decreased with temperature; and b) the elastic modulus of the adhesive dropped significantly with temperature. At lower temperatures (<40°C), the tensile behavior of S30 was almost linear elastic. As the temperature increased, the adhesive started to exhibit significant nonlinearity in stress-strain behavior and the slope of the initial part of the curve (i.e. the elastic modulus) tends to reduce significantly; and c) the maximum strain corresponding to the final failure increased with temperature until 45°C. A similar trend can also be found in experimental results presented in Moussa et al. (2012).

Test results of the single-shear pull-off test

Failure mode

Fig. 12 shows the failed CFRP-to-steel bonded joints in the current study. The expected failure mode for a good quality CFRP-to-steel bonded joint at ambient temperature is the cohesion failure within the adhesive (Yu et al., 2012, Zhou et al., 2015). In the current study almost all the samples (with the exception of Test-1 and Test-9) also failed due to cohesion failure within the adhesive layer. Therefore, it can be concluded that temperatures up to 55^{o}C will have no effect on the failure mode of CFRP-to-steel bonded joints made using S30.

As the bond strength depends on the energy dissipated during the fracture process, fracture surface is important in comparison of the test results in understanding the effect of temperature on the bond strength of CFRP-to-steel bonded joints. Since investigating the adhesive mechanical property change with temperature on the bond behavior is of concern in this study, it was necessary to ensure failure always occurred as cohesion failure within adhesive. Considering the failure of the tested specimens mostly occurred as cohesion failure within adhesive, selection of the S30 adhesive for the investigation is justified.

While samples pre-dominantly failed due to cohesion failure within adhesive, samples tested at higher temperatures was found to have a relatively different fracture surface compared to that observed in specimens tested at lower temperatures. Fracture surface of specimens tested at higher temperatures were shown to be rougher than those at lower temperatures. In the tests of Yu et al. (2012), the fracture surface of the specimens with nonlinear adhesives were shown to be rougher than those with linear adhesives. As an increase in temperature changes the behavior of S30 adhesive from linear to nonlinear, this rough fracture surface resulting at higher temperatures may be attributed to the nonlinear adhesive behavior and a transition from brittle to ductile fracture within the polymer adhesive.

Test-1 and Test-9 exhibited a different behavior. In the case of Test 1 failure occurred due to delamination of the CFRP plate caused by an alignment error. For Test-9, adhesion failure was observed at the adhesive-steel interface. It is difficult to conclude that temperature had an effect on the change in failure mode as other specimens tested at the same or higher temperatures didn't show any signs of adhesion failure. Therefore, the adhesion failure of the Test-9 is considered to be due to potential surface quality issues resulting in lower adhesion strength.

Load-displacement

Results of Test-1 and Test-9 were excluded from the results analysis hereafter since they did not fail due to cohesion failure within adhesive and, hence, cannot be considered as samples reflecting the effect of adhesive mechanical properties on bond behavior.

Fig. 13 shows the load-displacement curves of samples tested at ambient and elevated temperatures. Displacement was taken as the slip at the loaded end calculated from the CFRP axial strain using Eq (2). During the temperature increase, a contraction of the CFRP plate was seen to occur, indicated by a negative strain at 100mm away from the loaded end in the bonding-free CFRP plate. A negative displacement of the CFRP plate (Fig. 13) at the loaded end (while the CFRP plate was un-gripped) was observed with the increase in temperature.

The stiffness indicated by the slope of the load-displacement curve reduces with temperature (Fig. 13), which is expected as the stiffness of the adhesive layer decreases with increasing temperature. The bond strength (i.e. the ultimate load) of the specimens was shown to increase until about 47.5^{o}C and then decreased (Fig. 13). This is different to the trend observed in adhesive tensile coupon tests, where adhesive tensile strength monotonically decreased with the temperature.

Existing studies have shown that bond strength keep increasing with the bond length until a certain threshold bond length (commonly referred to as the "effective bond length") is reached (Yu et al., 2012). Further increase in bond length does not result in increase of bond strength. Therefore, to ensure bond length does not affect the bond strength, bond length of the specimens should be kept larger than the effective bond length.

At ambient temperature (25 ^{o}C), there was an obvious plateau of the load-displacement curve after the maximum load was reached (Fig. 13). As the temperature increased, the plateau became less evident. For samples tested at a temperature above 40^{o}C, the load continued to increase until the ultimate failure. The plateau of the load-displacement curve is an indication of the bonding length being longer than the effective bonding length. The reduction of this plateau with an increase in temperature is an indication of the increase in effective bonding length (Stratford and Bisby, 2012). Above 40^{o}C, absence of the plateau in the load-displacement curve indicates that the effective bonding length is larger than the bonding length provided. Therefore, the load-carrying capacity observed for those specimens may not be the ultimate bond-strength, but ultimate load corresponding to the limited available bonding length. If a longer bonding length exists, a higher load-carrying capacity may have been achieved for CFRP-to-steel bonded joints tested at 47.5^{o}C. Therefore, it is difficult to conclude if the reduction in bond strength beyond 47.5^{o}C was due to reduction in mechanical properties of adhesives or due to the limited bond length. Considering significant increase in effective bond length beyond 47.5^{o}C, providing long enough bond length in a test specimen will be difficult. Thus, numerical approach may be necessary to appropriately investigate the change of bond strength beyond 47.5^{o}C for CFRP-to-steel bonded joints with S30 adhesive.

It has been shown in Gao et al. (2012) and (Gao et al., 2015) that the thermal stress caused by the different coefficient of thermal expansion will affect the bonding strength of FRP-to-steel bonded joints. To illustrate the temperature effect in the present study, a comparison of the test results and the theoretical predictions from Gao et al. (2012) is given in Fig. 14. The load-carrying capacities of samples with a similar adhesive thickness as presented in Zhou et al. (2017) are also included in this comparison. It can be seen that the average bond strength from the test results of the present study as well as the study from Zhou et al. (2017) become increasingly higher than the predictions from Gao et al. (2012) model with increase in temperature until 47.5°C. However, such trend is reversed that when the temperature exceeds 50 °C that the Gao, et al.'s (2012) prediction is much higher (from 5% at 50 °C to 40% at 55 °C) than the test results since a constant bond-slip relation assumption was employed in Gao, et al.'s (2012). This comparison implies that there could be other mechanisms contributing to the load increase resulting from the increase in temperature, in addition to the initial stress induced by the different thermal expansion coefficients. The thermal expansion coefficient of the CFRP plate was obtained by the strain gauge measurements 100mm away from the loaded end. The thermal expansion coefficient value obtained was found to be much smaller than that found in available data (0.3×10^{-6} $(^{o}C)^{-1}$) (Klamer et al., 2005). However, this lower thermal coefficient measured means the effect of the difference in thermal expansion coefficients, thus the effect on ultimate load is magnified. Therefore, the conclusion that only interfacial stresses induced by differential thermal coefficients of adherends cannot result in load increase observed during the experiments is still valid.

Strain and interfacial shear stress distribution

The strain distributions along the bonding length at different displacements for selected specimens are shown in Fig. 15. Results for the other samples can be found in Zhou (2019). When the bonded joints were tested at ambient temperature and 32.5°C, the strain at the loaded end increased with the loaded end displacing initially and then started to form a plateau closer to the loaded end (Figs 15a and b), which indicates debonding initiation. Subsequently, a further increase in the plateau region was seen, indicating debonding propagation towards the far end. As the temperature increased, the debonding initiation point was hard to observe from the strain distribution, and the slope of the strain distribution curve was shown to decrease (Figs. 15c-f). When the temperature was above 40ºC, it appeared that the whole bonding length was active in transferring load, and no plateau was identified (Fig. 15d-f).

The strain and interfacial shear stress distributions along the bonding length when the maximum load was reached for the selected samples are presented in Figs. 16(a) and (b) respectively. Results for the other samples can be found in Zhou (2019). Except for the sample tested at ambient temperature, the activated bonding length (i.e. length of regions with a gradient in strain distribution in Fig. 16a and length of non-zero interfacial shear stress regions in Fig. 15b) when the maximum load was attained increased with temperature. For those samples tested at higher temperatures (>40 ºC), the full bonding length (200mm) can be seen to be activated at the maximum load. This indicates that, 200mm bonding length may be less than the effective bonding length, and therefore the maximum load-carrying capacity of the CFRP-to-steel bonded joints could have been higher if a longer bonding length was provided.

The stain and interfacial shear stress distributions along the bonding length for each sample when the external force was 30kN are compared in Figs. 17(a) and (b) respectively. From Figs. 17(a) and (b) it is even more evident that for the samples tested at 32.5ºC and 40ºC, the regions active in resisting load were smaller than that of specimens tested at 47.5ºC and 50ºC. Meanwhile, the strain gradient and the interfacial shear stress were also smaller when the samples were tested at 47.5ºC and 50ºC, compared to those tested at lower temperatures.

Bond-slip relation

In this series of tests, the bond-slip relation at different locations along the bonding length were extracted from the strain readings on the CFRP plate using Eqs. (1) and (2). As demonstrated in previous sections, the bonding length of certain tested samples (i.e., samples tested above 47.5 ^{o}C) was smaller than the effective bonding length. For specimens with insufficient bonding length, a slip may exist at the far end of the CFRP plate, thus the slip calculated from the CFRP plate axial strain measurements may not reflect the actual slip. Therefore, only the strain distributions for samples when the strain at the far end is reasonably small were employed to calculate the interfacial shear slip and shear stress.

An initial negative shear stress can be observed when the samples were tested at elevated temperatures, due to the different thermal expansion coefficients between the CFRP plate and steel plate. However, the shear stress was small compared to the peak shear stress, indicating negligible influence of the initial stress state on the ultimate bond strength of the bonded joints. Nonetheless, to ensure effects of initial thermal stresses are excluded in interfacial fracture energy calculations, only positive stress region of the bond-slip curves was used to determine the interfacial fracture energy of the bonded joints.

Applying the nonlinear regression method as explained before, the average bond-slip curves of samples tested at different target temperatures were obtained and are shown in Fig. 18(b) (more curves are given in Zhou 2019). With Eqs (8)-(11), the key parameters determining the bond-slip relation can be normalized with respect to the thickness of the adhesive layer. Normalized bond-slip parameters (i.e. initial stiffness, peak shear stress, and interfacial fracture energy) according to Eqs. (8)-(11) from the test results of the current study as well as those reported in Zhou et al. (2017) (denoted by Test A1 to A4 in Table 1) are presented in Fig. 19. It can be seen that test presented in Zhou et al. (2017) aligns well with results from the present paper. It is evident from Fig. 19 that the reduction of the initial stiffness and peak shear stress were smaller when the temperature was below 40°C. When the temperature approached the heat deflection temperature (i.e. 47°C), the reduction in the initial stiffness and peak shear stress became much more significant.

For samples tested at higher temperatures (>47.5°C), a complete bond-slip relation cannot be obtained since the bonding length was less than the effective bonding length. As previously mentioned, the bond strength of FRP-to-steel bonded joints with a sufficiently long bonding length is proportional to the square root of the fracture energy (Fernando et al., 2014). Therefore, it can be qualitatively induced that the fracture energy will increase with temperature up until 47.5°C. However, as the bond-slip curves beyond this temperature could not be obtained, the variation of fracture energy above 47.5°C cannot be attained from the current test results. As such, the data points shown in Fig. 19 above 47.5°C may not represent the accurate interfacial fracture energy at that temperature. More research is required to better understand the variation of interfacial fracture energy with temperature.

Conclusion

This paper presented an experimental study aimed at investigating the behavior of CFRP-to-steel bonded joints at elevated temperatures. An experimental test setup was developed to perform single-shear pull-off tests at different target temperatures, where the thermal and mechanical conditions of the sample are carefully controlled and monitored. Tensile tests were carried out on adhesive tensile coupons to determine the adhesive tensile stress-strain behavior variations at elevated temperatures. Based on the experimental observations, the following conclusions can be drawn:

1) Tensile strength and elastic modulus of adhesive Sikadur 30 monotonically decreased with increasing temperature (up to 55°C). While, the epoxy adhesive (Sika, 2020)

tensile stress-strain curves were almost linear until failure at lower temperatures, it became nonlinear at higher temperatures.

2) Key parameters, such as the initial stiffness, maximum shear stress and the fracture energy, thus the bond-slip relation of CFRP-to-steel bonded joints was found to be significantly affected by the temperature variations. Both initial stiffness and peak shear stress of the bonded joints monotonically decreased with the increase in temperature. However, interfacial fracture energy was found to increase with the temperature until the temperature reached 47.5°C. While, the interfacial fracture energy was found to reduce above 47.5°C, it is not clear if this was due to lack of bond length. More investigations, especially at above 47.5°C temperature range are needed to better understand the variation of interfacial fracture energy with the temperature.
3) Increase in bond strength with the temperature was not only caused by the initial thermal stress caused by the difference in the thermal expansion coefficients of bonding constituents, but also because of the change in mechanical properties of the adhesive.

While the present study shed light into the importance of better understanding the effect of temperature on behavior of CFRP-to-steel bonded joints, more investigations are necessary to fully characterize the influence of temperature on the variation of the bond-slip behavior of CFRP-to-steel bonded joints with different adhesives. It is recommended to adopt a sufficiently long bonding length to obtain the bond-slip relation at higher temperature. A data base of the performance of structural adhesive should be established. Thus, appropriate adhesives can be chosen to avoid stiffness and strength degradation caused by temperature increases.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. These include data used to generate plots presented in this paper.

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Table 1. Details of tested samples

Test	Temperature (ºC)	Thickness (mm)	Bond strength (kN)	Elastic modulus (GPa)	Failure Mode
Cali	80.0	1.60	N/A	N/A	N/A
Test-1	25.0	1.58	40.0	177.2	FRP Delamination
Test-2	25.0	1.60	40.0	176.7	Cohesion Failure
Test-3	32.5	1.69	48.9	178.8	Cohesion Failure
Test-4	32.5	1.68	41.8	N/A	Cohesion Failure
Test-5	40.0	1.43	53.4	179.1	Cohesion Failure
Test-6	40.0	1.48	47.9	178.2	Cohesion Failure
Test-7	47.5	1.55	57.4	186.5	Cohesion Failure
Test-8	47.5	1.70	48.8	179.3	Cohesion Failure
Test-9	47.5	1.69	43.5	184.9	Adhesion Failure
Test-10	50.0	1.67	47.2	184.8	Cohesion Failure
Test-11	55.0	1.58	31.7	173.9	Cohesion Failure
Test-12	55.0	1.57	30.4	173.5	Cohesion Failure

Note: Sample Cali is for the temperature calibration of CFRP-to-steel bonded joints; Cohesion failure represents the cohesion failure within adhesive

Table 2. Parameters used in the prediction

E_p (GPa)	b_p (mm)	t_p (mm)	α_p ($^{o}C^{-1}$)	E_s (GPa)	b_s (mm)	t_s (mm)	α_s ($^{o}C^{-1}$)	τ_f (MPa)	δ_1 (mm)	G_f (N/mm)
180.0	50.0	1.2	-2.1×10^{-5}	200.0	150.0	19.0	1.2×10^{-5}	17.8	0.04	1.6