Effect of Elevated Temperature on Bond Behaviour of High Modules CFRP/Steel Double-STRAP Joints

A. Al-Shawaf, R. Al-Mahaidi, X. Zhao
Department of Civil Engineering, Monash University, Victoria 3800, Australia

Abstract
This paper investigates and provides experimental evidence of the bond characteristics between CFRP and steel plates under elevated temperature exposures. A series of tensile tests was carried out on CFRP/steel plates specimens joined together in double-lap shear joints and subjected to a range of environmental temperatures between 20ºC up to 60ºC which would be usually encountered in civil infrastructure applications. High modulus (640 GPa) unidirectional carbon fibre plies were used in wet lay-up fabrication method to strengthen the composite matrix. Three different epoxy resins were used for the fabrication of the CFRP/steel specimens. The objective of the current experimental work is to determine the ultimate strength, failure patterns, elongation development and lap-shear stress and slip variation under those exposures. This will help in enhancing the competency of using CFRP in retrofitting steel structures at high-temperature environments, usually experienced in civil construction applications.
Effect of Elevated Temperature on Bond Behaviour of High Modules CFRP/Steel Double-STRAP Joints

A. Al-Shawaf, R. Al-Mahaidi, X. Zhao
Department of Civil Engineering, Monash University, Victoria 3800, Australia

1. Introduction

1.1 Research objectives

For the last decade, high modulus CFRP composites have been introduced, at an accelerated rate, in the rehabilitation of the majority of the world’s aging infrastructure. This progressive utilization of these composites has been remarkably aided by virtue of their advantages, amongst which are high stiffness-to-weight-ratio, enhanced fatigue life, corrosion resistance, controllable thermal properties and faster field application. However, there is a wide gap in terms of the durability issue of these materials that need to be bridged effectively in order to establish a comprehensive database for their usage in civil applications(Karbhari et al., 2000). Although FRP composites have acceptable resistance to environmental exposure conditions, yet the overall response of the FRP strengthening systems remains an outstanding issue that requires more research and investigations. The durability of any FRP strengthening system is closely related to the nature of the environmental exposure that the system is more likely to encounter throughout its serviceable lifetime. Environmental exposure factors that may have a detrimental effect on either FRP composites or the whole strengthening system may include effects of moisture, alkaline solutions, non-ambient thermal exposures, ultraviolet radiation, creep/relaxation, fatigue, and fire.

This paper presents results concluded from a series of double-lap shear tensile tests performed at Monash University in order to characterise the sole effect of short-term exposure to a range of elevated environmental temperatures, usually encountered in civil application environments, on wet lay-upped CFRP / steel plates. These specimens were loaded statically in axial tension under different exposures ranging from ambient up to 60°C-exposure. Three different commercially available epoxide resins were adopted in fabricating the double strap joints. The key objective of the current program is to investigate and contribute in the, currently very limited, database on the short-term response of CFRP/steel bond strength at elevated temperatures. Brief comparisons are presented on failure modes, joint capacity, strain distribution and correlation between peak lap-shear stresses and slip values of the double strap specimens made with different epoxies, at different temperatures.

1.2 Previous literature on FRP systems under elevated environmental temperature exposure

1.2.1 Elevated environmental temperature effect on FRP components

Thermal effects usually considered in civil applications include response of FRP systems to changes due to temperatures above the cure temperature for either the adhesive or the FRP resin matrix, freezing and freeze-thaw conditions and temperature variations and cycles. In terms of the Elevated environmental temperature thermal exposures, it is an established fact that resins and adhesives soften over a temperature range (i.e. glass transition temperature range), which causes an increase in viscoelastic response, a consequent reduction in elastic mechanical performance levels, and, in a number of cases, an increased susceptibility to moisture absorption(Karbhari et al., 2003). Although for some practical adhesives or FRP matrices whose glass transition temperatures are well above normal ambient temperatures, an increase in the operating temperature to a level below their
(Tg) range can actually result in a beneficial post-cure of the adhesive interface/or the FRP matrix (Veselovsky and Kestelman, 2002); yet a further increase in surrounding temperatures above the glass transition temperature can significantly degrade the performance of the FRP composite (ACI-Committee-440, 2007). Another issue to be considered in this regard is that the coefficients of thermal expansion of adhesives can be orders of magnitude different from those of bulk resins, adherends and/or composites. This will initiate inter-thermal gradients between these components, which in turn increase the potential premature debonding along the FRP composite-adhesive/adherend.

1.2.2 Elevated environmental temperature exposures for FRP/concrete strengthening systems

Previous research on the effect of elevated environmental temperature exposures, encountered in civil applications on adhesive bond properties for externally applied FRP systems, is generally categorized under “FRP durability” topic. The main published contribution, in terms of the elevated environmental temperature effect, has been focusing on FRP application to concrete members (Smith et al., 2005), (Wu et al., 2004), (Di Tommaso et al., 2001), (Hamilton and Dolan, 2000), (Ferrier and Hamelin, 1999) and (Toutanji and Gomez, 1997). Wu et al. (Wu et al., 2004) and Di Tommaso et al. (Di Tommaso et al., 2001) are the only cited experimental works performing destructive tests on the FRP/concrete prisms under the elevated-temperature exposures. Based on experimental results for double-lap shear joints between CFRP sheets and concrete prisms by Wu et al. (Wu et al., 2004), the maximum joint capacity and elastic modulus decrease gradually with temperatures ranging from 26°C to 60°C. In terms of the failure mode, the bulk of previous investigations have reported a premature debonding failure along the FRP-adhesive and concrete-adhesive interfaces for conditioning temperatures near to or higher than (Tg) for the adhesive. In other investigations, the possibility of a premature failure, due to excessive softening of the FRP laminating resin (i.e. matrix), has been addressed experimentally. Moreover, a general flexural requirement for FRP field implementation has been concluded. It defined the “upper use temperature” or the “material operational limit” of a given FRP laminating resin, as the temperature at which the flexural strength decreases to half the room temperature value (Karbhari et al., 2003).

1.2.3 Elevated environmental temperature exposures for FRP/steel joints

Literature abundance is different when it comes to steel adherends. There is a tangible scarcity in previous literature regarding the response to elevated environmental temperature exposures of FRP retrofitted steel systems in civil applications. This could be due to the relatively new introduction of the externally applied FRP strengthening to steel structures in civil infrastructure compared to aeronautical applications, for example. In the latter discipline, it is a fairly established technique in terms of environmental degradation and development of databases of test results for specific FRP composite systems (Hart-Smith, 1993), (Springer, 1988). Unfortunately, these databases couldn’t be utilized in civil applications due to the totally irrelevant service environmental exposures. For aeronautical applications, the routine service environments involve a range of temperatures between about -73°C to +180°C; while for civil construction applications, service temperatures range between -30°C to +60°C, depending on geographical location and subject to seasonal and daily fluctuations (Barkatt, 2001), (Jiang and Zhao, 2007).

Colombi et al. (Colombi et al., 2005a), (Colombi et al., 2006) have reported on an experimental program on the durability of CFRP/steel double strap shear joints under mechanical and environmental loads. Their joint configuration is similar to that of the current program. However, the principle conditioning scheme is different. It is useful to mention, in this context, that the conditioning scheme for most of the previously reported works is thermal cycling either between
two extreme temperatures (e.g. -20°C to +50°C, as for the latter investigation) or between ambient and upper extreme temperature, followed by conducting the nominated mechanical test at normal room temperature. For certain FRP systems and conditioning temperatures below those at which degradation due to oxidation and related chemical changes commence, and after the conclusion of thermal cycling regime, no degradation in the performance of the adhesive interface could be reported. This could be attributed to recovering much of the initial strength of the adhesive if cooled back to room temperature before testing the FRP joint to destruction (Blomquist, 1962). It is believed that testing under the conditioning temperature can better simulate the service bond/FRP composite behaviour in civil applications.

Yang et al. (Yang et al., 2005) and Karbhari and Shulley (Karbhari and Shulley, 1995) have investigated the effect of hot/wet cycling for 500-hour up to 3000-hour durations; and 65°C- hot water exposure for 14 days, respectively, on CFRP/steel joints. They came up with utterly inconsistent results. The former has reported an increase in the shear strengths of single-lap joint specimens upon the conclusion of the cycling process. Nonetheless, the latter has shown significant bond degradation in wedge-test of CFRP/steel specimens upon conclusion of the exposure.

2. The experimental program

The CFRP/steel double-strap specimens and the test method adopted for the current program has a good conformance with both ASTM standard (D3528-96) (ASTM, 2004a) and (D5868-01) (ASTM, 2004b). However, certain changes are implemented to count for adopting the wet-lay up FRP production methodology instead of the prefabricated FRP laminates. Moreover, the proposed overall dimensions for the double-strap joint-specimens (refer to Figure 1) were dictated by internal space availability for the assembly of the load-frame gripping system and the environmental chamber used for specimens’ conditioning as depicted in Figure 2.

2.1 Materials

The carbon fibre reinforcement adopted for the fabrication of the wet lay-up CFRP laminates were high modulus unidirectional carbon fibre sheets, with a nominal modulus of elasticity of 640 GPa, tensile strength of 2650 MPa, ultimate tensile elongation of 0.4%, and thickness of 0.19 mm according to the material data sheet supplied by the manufacturer.

![Figure 1- Geometry of double-strap CFRP/steel specimen showing strain gauges positioning](image-url)
Two mild steel plates with a 370 MPa tested yield strength, and nominal thickness of 4.85 mm were used in fabricating the CFRP/steel double strap joint specimens. Finally, the three epoxy resins chosen for the current program, as CFRP matrices and adhesives at the same time, are: (1) Araldite 420® A/B, with a tested Tg of 41.66°C, (2) Mbrace® Saturant, with a tested Tg of 55.5°C, and (3) Sikadur®-30, with a Tg of 62°C as per manufacturer’s data sheet. For more information on those adhesives regarding uses, advantages, technical and mechanical data; the reader is referred to their material data sheets (Huntsman, 2004), (BASF, 2004), and (Sika, 2004), respectively.

**2.2 Specimen’s fabrication and geometry**

A special steel rig was developed in the civil engineering laboratories of Monash university (refer to Figure 3) to produce the current program’s CFRP/steel specimens. It can efficiently cope with difficulties encountered with wet-lay up production method, and attain the maximum possible consistency and alignment for the specimens. It has the advantages of producing a uniform thickness, with flat outer CFRP surfaces for reliable strain gauging.

This rig was assembled on a steel bench top. It can produce a total of eight CFRP/steel specimens in one batch. All geometric dimensions for the rig were based on the target dimensions for the specimens (Figure 1). The four faces of the two steel plates were cleaned with acetone before and after conducting a surface preparation procedure to remove any stains, paint and rust and impart a rough texture. The roughening was achieved first by using a disc grinder to expose clean steel surfaces, followed by a ± 45° perpendicular shallow scratching of the cleaned surfaces (by a thinner grinding disc) to promote the CFRP/steel adhesion by increasing the mechanical interlocking with the interfacial epoxy layer. As it is shown in Figure 4, only one CFRP wet lay-up layer, with an overall thickness of 2 mm, could be processed at a time. Each CFRP layer is composed of a thin adhesive/matrix layer applied on the prepared steel surfaces, followed by impregnating a unidirectional CF ply over the wet epoxy. This sequence has been repeated in three sub-layers and topped up with an adhesive surface layer.
The whole sample was then cured for 14 days at room temperature. Cutting into the predetermined specimen’s width was achieved by means of a water-jet cutting machine to prevent any material distortion at the specimen’s edges if other heat-generating methods have been used, otherwise. Specimen’s designating label is interpreted as follows: first “H” character stands for “High modulus CF”, following character/s refer to type of epoxy for the specimen (i.e. “A” Araldite 420, “MS” MBrace Saturant, and “SD” Sikadur-30), then the specimen’s conditioning temperature, and finally, the number of specimen’s iterations.

![Figure 4- Schematic of the wet-lay up CFRP/steel double strap joint fabrication rig](image)

### 2.3 Test setup and thermal conditioning

Before testing, foil strain gauges were instrumented at the CFRP outer surfaces as depicted in Figure 1 to capture strain readings along the whole bondlength during load application. Some specimens, which were expected to fail by interfacial debonding, were either mechanically clamped on the non-instrumented bond side or wrapped transversely with CFRP to enforce failure to take place on the instrumented bondlength. All specimens were thermally aged inside an environmental chamber (refer to Figure 2), to their target temperatures, for a period of (45min. - 60 min.) and then tested individually in direct tension with a screw driven load frame under displacement control (2 mm/min) to failure. For each epoxy type, two or three specimens were tested at each target temperature (viz. 20°C, 40°C and 60°C). Determination of the required thermal soaking time, at each of the target temperatures and type of epoxy, was achieved on dummy specimens by utilizing an experimental calibration procedure similar to the one described in ASTM: D3528. The soaking time at each temperature was confirmed numerically, by performing a FEA on simulated CFRP/steel joint models.
3. Results and observations

3.1 Failure modes

Brief description for all failure modes encountered in the current program is provided in Table 1 with selective photos of failed specimens presented in Figure 5.

Table 1- Failure mode categories for the current program

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D I</td>
<td>Debonding @ SG end (Debonding)</td>
</tr>
<tr>
<td>D II</td>
<td>Debonding @ non-SG end (Debonding)</td>
</tr>
<tr>
<td>C</td>
<td>CFRP rupture @ joint (Cohesive)</td>
</tr>
<tr>
<td>M I</td>
<td>Mixed Mode I (SG end failure : Debonding @ SG face + CFRP rupture @ joint other face)</td>
</tr>
<tr>
<td>M II</td>
<td>Mixed Mode II (non-SG end Failure : Debonding one face + CFRP rupture @ joint other face)</td>
</tr>
<tr>
<td>M III</td>
<td>Mixed Mode III (partial debonding failure @ SG end both faces + CFRP rupture around joint)</td>
</tr>
<tr>
<td>M IV</td>
<td>Mixed Mode IV (partial debonding failure close to the joint + CFRP rupture around joint)</td>
</tr>
</tbody>
</table>

The predominant failure mode for series (HA) and (HSD) specimens conditioned at (20°C) and (40°C) is CFRP rupture at joint (refer to Table 2). For specimens belonging to the latter two series and conditioned at (60°C), the failure mode has been changed either to “debonding” or “mixed mode”. In general, CFRP/steel specimens fabricated with high modulus CF, with a comparable effective bondlength, and tested below their (T_g) are likely to fail by “CFRP rupture at joint” (Fawzia et al., 2004). As the conditioning temperature rises above (T_g) limit for the adhesive, it starts a physical conversion from glassy to rubbery state (i.e. softens). This conversion renders the interface the weakest link in the composite system (i.e. debonding failure is highly predominant above the adhesive’s T_g). The failure patterns for those two series disclose good conformance with the former generic trend. However, some deviation is evident such as that for (HA+60,1) which revealed an interfacial debonding for half of the bond width only. Another useful observation is the evolution in failure pattern from purely cohesive for (HSD+40) series to mixed mode for (HSD+60) series. The latter reflects the considerable drop in the interfacial adhesive’s mechanical properties as the operating temperature reaches its glass transition (i.e. Sikadur’s T_g = 62°C). The (HMS) series manifests a different pattern to the above, especially for exposures below its adhesive’s (T_g) (i.e. MBrace Saturant T_g = 55.5°C). The prevailing trend for (HMS+20) and (HMS+40) specimens is “mixed mode” instead of total CFRP rupture. Knowing that (HMS) series has identical carbon fibres, steel plates, fabrication procedures and testing conditions with (HA).
and (HSD) series, leaves the epoxide matrix / adhesive as the only variable. In other words, it is an established fact that the “adhesive microstructural and / rheological composition” plays the key role in the overall bond trend (Adams, 2005). Based on visual assessment and comparison of the average experimental ultimate load capacities for the three series at each conditioning temperature (refer to Figure 6), it is believed that the “MBrace Saturant” epoxy is inherently more brittle, glassy and has higher microcracking propensity, flaws and imperfections, than the others. This in turn will, inevitably, weaken the interfacial adhesive layer, thus enhancing the probability of the debonding failure.

Table 2-Specimen’s details, ultimate loads and failure modes

<table>
<thead>
<tr>
<th>Specimen designation</th>
<th>CFRP matrix / conditioning temperature (°C)</th>
<th>Pₚᵤₙₜ. (KN)</th>
<th>Avg. Pₚᵤₜ. (KN)</th>
<th>CV</th>
<th>Failure mode designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA+20,1</td>
<td>Araldite / 20</td>
<td>78.8</td>
<td>71.7</td>
<td>14.11</td>
<td>C</td>
</tr>
<tr>
<td>HA+20,2</td>
<td></td>
<td>64.5</td>
<td></td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>HA+40,1</td>
<td>Araldite / 40</td>
<td>57.1</td>
<td>62.5</td>
<td>12.09</td>
<td>C</td>
</tr>
<tr>
<td>HA+40,2</td>
<td></td>
<td>67.8</td>
<td></td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>HA+60,1</td>
<td>Araldite / 60</td>
<td>24.2</td>
<td>26.9</td>
<td>14.17</td>
<td>M III</td>
</tr>
<tr>
<td>HA+60,2</td>
<td></td>
<td>29.6</td>
<td></td>
<td></td>
<td>D II</td>
</tr>
<tr>
<td>HMS+20,1</td>
<td>MBrace Sat / 20</td>
<td>44.4</td>
<td>50.6</td>
<td>14.39</td>
<td>M I</td>
</tr>
<tr>
<td>HMS+20,2</td>
<td></td>
<td>58.6</td>
<td></td>
<td></td>
<td>M II</td>
</tr>
<tr>
<td>HMS+20,3</td>
<td></td>
<td>48.7</td>
<td></td>
<td></td>
<td>M I</td>
</tr>
<tr>
<td>HMS+40,1</td>
<td>MBrace Sat / 40</td>
<td>68.2</td>
<td>54.9</td>
<td>34.42</td>
<td>C</td>
</tr>
<tr>
<td>HMS+40,2</td>
<td></td>
<td>41.5</td>
<td></td>
<td></td>
<td>M I</td>
</tr>
<tr>
<td>HMS+60,1</td>
<td>MBrace Sat / 60</td>
<td>18.1</td>
<td>16.0</td>
<td>12.44</td>
<td>D I</td>
</tr>
<tr>
<td>HMS+60,2</td>
<td></td>
<td>14.1</td>
<td></td>
<td></td>
<td>D I</td>
</tr>
<tr>
<td>HMS+60,3</td>
<td></td>
<td>15.7</td>
<td></td>
<td></td>
<td>D I</td>
</tr>
<tr>
<td>HSD+20,1</td>
<td>Sikadur / 20</td>
<td>63.8</td>
<td>61.5</td>
<td>5.41</td>
<td>C</td>
</tr>
<tr>
<td>HSD+20,2</td>
<td></td>
<td>59.1</td>
<td></td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>HSD+40,1</td>
<td>Sikadur / 40</td>
<td>60.6</td>
<td>63.3</td>
<td>6.03</td>
<td>C</td>
</tr>
<tr>
<td>HSD+40,2</td>
<td></td>
<td>66.0</td>
<td></td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>HSD+60,1</td>
<td>Sikadur / 60</td>
<td>46.9</td>
<td>39.5</td>
<td>26.71</td>
<td>M IV</td>
</tr>
<tr>
<td>HSD+60,2</td>
<td></td>
<td>32</td>
<td></td>
<td></td>
<td>M IV</td>
</tr>
</tbody>
</table>
3.2 Temperature impact on joint capacities

Figure 6 depicts clearly the effect of short-term Elevated environmental temperature exposure on joint capacities for the current CFRP/steel double-strap specimens. It is shown that the (HMS) series has the lowest joint capacities compared to the other series, at all currently experimented exposures. The (HA) series manifests a different trend than that of (HMS) and (HSD) series as the exposure temperature increases from 20°C to 40°C. This could be explained as follows: In the adhesive's microstructural level, and during the course of setting of the adhesive, its volume decreases due to the volatilization of solvents, polymerization or physical structurization (Veselovsky and Kestelman, 2002). Consequently, internal stresses are created within the interface. The second contributor to those stresses is the thermal stress caused by differences of the coefficients of linear thermal expansion of the adhesive and the adherends. Internal stresses, within the adhesive, increase the porosity and flaws which, in turn, have a detrimental effect on adhesive-joint capacity. As discussed in 3.1 above, MBrace Saturant cured resin is believed to contain the highest flaw-ratio, followed by Sikadur and Araldite, in a decreasing order. This is confirmed experimentally since the (HA) series has the highest 20°-exposure ultimate load, followed by (HSD) and finally (HMS) series (refer to Figure 6). In terms of joint capacity enhancement, there is a widely used technique for decreasing the internal stresses, and hence increase bond capacity, is to increase the adhesive's rate of relaxation by means of heat treatment. In general, heat treatment / post-curing of adhesive joints at temperatures higher than ambient will produce a system more thoroughly cross-linked and containing fewer unreacted epoxy groups (Lee and Neville, 1957). Therefore, MBrace Saturant is conceived to respond more sharply (i.e. more relative increment in bond strength) than Sikadur when their temperatures are increased and maintained at (40°C) for one hour before testing. This behaviour is inferable from Figure 7, as joint capacity for the (HMS) and (HSD) series has increased by 8% and 3%, respectively. For the (HA) series at 40°-exposure, the joint capacity is demoted 13% due to its proximity to the (Tg) value for the adhesive/matrix (i.e. 41.7°C). As operating temperature is further increased to (60°C), the latter trend for the (HMS) and (HSD) series is rapidly overridden by the inherent substantive drop in their matrix's/adhesive's strength since their (Tg) value is either surpassed (55.5°C for MBrace Saturant) or approached (62°C for Sikadur). Nonetheless, (HSD) series seems to be the best option to adopt for extreme-temperature strengthening applications, with about 47% and 147% more joint capacity than the (HA) and (HMS) series, respectively.
3.3 Strain distribution along instrumented bondlength

Axial strain distributions captured at the CFRP surface, for representative specimens from (HA), (HMS) and (HSD) series, at each of the three exposure temperatures are presented in Figure 8, Figure 9, and Figure 10, respectively. As anticipated, the generic strain distribution trend at 20°-exposure, for the three types of epoxies, is that strain is maximum at the joint (i.e. at \( x = 0 \)) followed by a gradual decrements in strain level towards the other end of the joint (at \( x = 100 \text{ mm} \)) where it reaches a minimum. This trend is in good agreement with Hart-Smith’s model for strain distribution of stiffness-imbalanced joints (Hart-Smith, 1973).
Load transfer characteristics through adhesive joints are function of their individual geometrical configurations and the thermo-mechanical parameters for the adhesive and adherends. Therefore, since the geometrical aspects, carbon fibres, and steel plates for all current programs’ CFRP/steel joints are identical, the key differences between individual strain distribution trends of the 20°-exposure specimens are related to the thermo-mechanical attributes for the epoxies, and their implications on the microstructural characteristics of the CF/matrix and steel/adhesive interfaces. Specimen (HA+40,1), and due to its proximity to the adhesive’s (Tg), is manifesting a more ductile behaviour above (0.7 Pult.).

Consequently, shear deformations have been increased at the joint vicinity and decreased at x = 16 mm up to the right end. This in turn has decreased the load being transferred by the joint from x = 16 mm up to the right end. With further increase in temperature to 60°C (i.e. above Araldite’s Tg), the adhesive’s elastic and shear modulus have deteriorated markedly. Consequently, the strain level dropped by more than 100% throughout the whole bondlength disclosing more plastic behaviour (refer to HA+60,2 of Figure 8).

For the (HMS) series, the effect of increasing bond capacity when conditioned at 40°C is deducible from the relatively higher strain values for (HMS+40,1) of Figure 9. It seems that due to this post-curing effect, the improvement in load transfer capacity and ductile behaviour (as opposing to the 20°-brittle nature /refer to section 3.2) is more pronounced in the central part of the bondlength rather than close to the joint ends.

For specimen (HMS+60,3), where the Tg of the adhesive has been exceeded, there is almost no adhesion capabilities and, hence, load being transferred from x = 16 – 80 mm. Finally, for the (HSD) series (Figure 10), there is a close analogy in strain distribution between (HSD+20,2) and (HSD+40,2). However, the only difference is having higher strain levels for the latter due to the joint capacity’s enhancement with heating. This behaviour is similar to that of the corresponding (HMS) specimens, except for the inconsistency in the strain distribution profiles which is believed to be due to individual differences in adhesive’s responses with temperature, which could be well conceived in terms of: (1) the relatively higher (Tg) value for Sikadur than MBrace Saturant, and (2) the assumed less flaw- ratio for the cured Sikadur than MBrace Saturant (refer to relevant discussion in section 3.2).

The only 60°-exposure exception, amongst the three series, is for the Sikadur series (i.e. HSD+60,2). At this operating temperature, Sikadur has not yet reached its (Tg) value (i.e. 62°C), however its mechanical parameters are obviously degraded. As it is shown in Figure 10, from x = 16 mm onwards to the right, the adhesive is virtually ineffective, yet due to the considerably higher load being carried by the joint than the corresponding load for the (HMS) case, the shear deformations, and hence axial strain, have a predominantly sharp increase from x = 16 mm to the left end of joint (i.e. at x = 0).
3.4 Lap-shear stress vs. slip

Lap-shear stresses were essentially calculated from strain gauge readings along the bondlength (refer to Figure 1). They actually represent the average shear stresses at each 16 mm along bondlength (i.e. strain gauge intervals = 16 mm), thus are smaller than actual values in the composite specimen. Slip measurements by an externally attached LVDT were unattainable due to internal spatial restrictions of the environmental chamber, alternatively, they were found analytically by integrating the measured strain distribution along the CFRP length. Figure 11
reveals some useful bond-slip trends for typical specimens representing the three series, one at each of the current thermal exposures. In terms of the slip, the general trend is decrements in slip values with higher thermal exposures which could be attributed to the degradation in joint capacity as temperature is approaching/or exceeding the adhesive’s (T<sub>g</sub>) value. This is manifested in (HA) series /Figure 11. However, the 40°-exposure for (HMS) and (HSD) series is an exception to the above due to their joint capacity improvements relative to their 20°-exposure (refer to section 3.2). For the 60°-exposure, the sharp drop in slip values for (HA+60,2) and (HMS+60,3) relative to their corresponding values for the 40°-exposure is understandably related to the significant deterioration in the adhesive’s performance above their (T<sub>g</sub>) values.

Nonetheless, this trend is different for the (HSD) series. The comparable slip values for (HSD+60,2) with that for (HSD+20,2) is believed to be due to two simultaneous, opposite and equal effects: (1) the bonding capacity of the Sikadur is slightly decreased because the exposure temperature (i.e. 60°C) is yet below than (T<sub>g</sub>), hence less slip, and (2) when temperature is raised from (20°C) to (60°C), the ductility of the adhesive / matrix will definitely increase, giving rise to higher interlaminar shear deformations in the epoxy’s sub-layers across the CFRP wet lay-up layer which will result in a relatively higher axial deformations, and hence slip values. In terms of stiffness trend, it is evident from Figure 11 that (HMS+20,2) and (HMS+40,1) are both revealing a plastic behaviour just before failure; the former at 0.9 P<sub>ult</sub>. and the latter at 0.7 P<sub>ult</sub>. Operating temperature seems to have a slight impact in determining the end of the elastic region. However, (HA) and (HSD) series remain elastic at joint failure. Again, this could be mainly related to the type of adhesive and the dissimilarity in the failure modes (refer to section 3.1).

4. Conclusions

A useful literature review has been introduced as a brief preamble to the current experimental program. The experimental part has been presenting an investigation on the effects of the short-term elevated environmental exposures on some basic behavioural aspects of CFRP/steel double-strap joints produced by the wet lay-up method. Three different commercially available epoxide resins and two elevated environmental exposures, besides to the reference normal ambient temperature, have been adopted as variable parameters. A newly developed rig for fabricating the CFRP/steel double-strap specimens was introduced to control the geometry, CFRP layer thickness, and repeatability of the specimens. Results from a series of tensile tests, under the nominated thermal exposures, have been introduced and briefly discussed in an attempt to highlight the effects of all the above mentioned parameters on bond behaviour. The following conclusions can be drawn based on the results and discussions presented formerly in this paper:

- The prevailing failure mode encountered for the (HA) and (HSD) series at the 20° and 40° - exposures was CFRP rupture at joint which is the optimum mode from the standpoint of joint reliability. It is definitely an indication of steel-compatible adhesive and good steel’s preparation procedure. However, the exception was the corresponding (HMS) series specimens which could be regarded as an indication of the resin’s incompatibility with steel adherends.
- Debonding-failure is the generic trend for CFRP/steel specimens conditioned above their adhesive/matrix’s (T<sub>g</sub>). This conclusion applies to the majority of (HA) and (HMS) specimens at 60°-exposure. However, mixed-mode failure could occur due to the close proximity between the adhesive’s (T<sub>g</sub>) and the operating temperature, as in (HSD+60) specimens.
- For identical wet-lay upped CFRP/steel joints, joint capacity is mainly governed by adhesive type and its inherent microstructural characteristics. Accordingly, joints having “Araldite 420” epoxy, as their adhesive/matrix, have disclosed highest average capacity at normal ambient exposures, followed by “Sikadur-30”, and “MBrace Saturant”.

Paper No. 002 – Page 13
In general, there is an inverse proportionality between operating temperatures and joint capacity with a significant deterioration in the latter above the adhesive’s (T_g), as in the (HA) series. (HMS) and (HSD) series joints exhibit minor enhancement with temperatures below their adhesive’s (T_g) value. Adhesive’s post-curing effect is believed to be the rational justification for this phenomenon.

The generic strain distribution trend is analogous to the stiffness-imbalanced joints of Hart-Smith’s adhesive double-lap model.

Different adhesives have different strain profiles at operating temperatures above ambient and below their (T_g) values. This is mainly due to adhesive individual responses with temperature. In general, ductility and shear deformations tend to increase with temperature; simultaneously, bonding capabilities decline above certain service temperature where the post-curing effect is maximal. Above the adhesive’s (T_g) value, and as a result of increased adhesive’s softening and deterioration in its shear modulus, the strain level almost totally declines except for a narrow part at the joint to cope with the remaining joint capacity.

CFRP’s slip values decrease as thermal exposures approach/exceed the adhesive’s (T_g) value, due to the detrimental effect of heating on adhesive’s bonding capacity. However, this effect is slightly reversed if post-curing joint enhancement is anticipated. Alternatively, for some joints conditioned below the adhesive’s (T_g) value, the increase in slip due to adhesive’s increased ductility and hence higher interlaminar shear deformations is compromised by a drop due to the continuous decrement in joint capacity with higher temperatures.

Calculating lap-shear stress and slip from strain readings has yielded acceptable, conservative and consistent values which correlate well with changes in operating temperatures.

5. Acknowledgements

This project is sponsored by an Australian Research Council (ARC) Discovery Grant. The authors would like to acknowledge the kind assistance of Jim Mitchell and Silvio Mattievich in setting up and operating the environmental chamber and the Instron testing machine at the department of materials engineering /Monash University, also they wish to thank Kevin Nievaart for facilitating the progress of the experimental part at both the civil and Instron laboratories. Finally, special tribute is due in memory of Graeme Rundle, the x-civil laboratories manager, for his distinguished contribution in executing the experimental activities.

6. References

ACI-Committee-440. 440R-07 Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures: American Concrete Institute (ACI), Committee 440, 2007: 100.


Hart-Smith LJ. Innovative concepts for the design and manufacture of secondary composite aircraft structures. 5th Australian Aeronautical Conference. Melbourne, Australia, 1993.


