Temperature Effects on the Fatigue Life and Tensile Strength of Structural Adhesives

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Abstract. In recent decades, structural adhesives have become widely used in the field of construction for the purpose of retrofitting existing structures using composite materials such as fibre reinforced polymers (FRP). The available standards for strengthening structures utilise the adhesive properties as listed in manufacturer’s technical sheets. However, members with adhesively bonded CFRPs are sometimes exposed to loadings or conditions that may differ to the scenarios used to measure these material properties. Steel and concrete bridges are usually exposed to cyclic loading associated with elevated temperatures, for example, while the manufacturer’s technical sheets provide material properties under quasi static loading and ambient temperatures. There is thus a lack of understanding of the properties of adhesives under more difficult conditions that may lead to issues in predicting the design strength of composite elements. This paper presents a series of experimental tests to investigate the adhesive properties under both medium temperature (25 and 40°C) and cyclic loading, with adhesives cured under two curing temperatures. All specimens and tests were developed according to ASTM-D638. The results showed significant effects of temperature on the tensile strength and fatigue life of adhesives, as measured by monitoring the number of cycles until failure; the number of cycles was increased by 8 times for two types of structural adhesives cured under high temperature and tested under normal temperatures of 25°C.

1. Introduction

Many pieces of infrastructure were constructed during the first half of 20th century, including both concrete and steel structures; however, such structures deteriorate over time, and for vital structures such as bridges, this raises the need for them to be strengthened to sustain their applied loads. Structural deterioration takes place with all types of structures over time, irrespective of the construction type and materials used, which leads to reduction of strength and stiffness of structural members. In addition to structural deterioration, however, many structures were originally designed for loads lower than the current loads. Thus, the maintenance, restoration and development of structural components to meet current needs is a common problem facing many authorities. Structural strengthening is described as the process of upgrading the structural system of an existing construction to improve performance with respect to the existing loading conditions or to increase the strength of the structural components to meet new loading conditions. Strengthening with Carbon Fibre Reinforced Polymers (CFRP) is one of the strengthening methods now being adopted by structural engineers, but although this technique is now widely used, there is still a lack of information about bond behaviour between CFRP and the adjacent layers. This is troubling, as the bond between CFRP and steel is critical, and debonding failure is the dominant failure in steel-FRP systems, although not in concrete-FRP structures [1-10]. Previous studies have focussed on the bond properties between CFRP and steel members under different types of loadings and severe environmental conditions. However, when designing the CFRP-steel joints under specific loading and environmental conditions, it is essential to understand the behaviour of each component under each set of conditions. Recent studies have thus focused on the engineering properties of CFRP and adhesive under different loading conditions [11-13], finding that the tensile strength and longitudinal ultimate strain increase significantly under a medium strain rate of 50 s⁻¹, while the current study focusses on evaluating adhesive behaviour under fatigue loading associated with different temperatures. The effect of curing temperature is also studied in this paper in order to evaluate the effect of curing temperature on the fatigue properties of structural adhesives. A total of 48 samples were prepared for two types of adhesives, which were then tested at two different temperatures.
2. Experimental programme

Two types of adhesives were used in this study that are mainly used for structural strengthening applications. The manufacturer’s properties for these adhesives are shown in Table 1:

| Adhesive   | Ultimate Tensile strength (MPa) | Elastic modulus (MPa) |
|------------|---------------------------------|-----------------------|
| Adhesive-A | 32                              | 1900                  |
| Adhesive-B | >14                             | 7100                  |

Teflon moulds with a standard groove were manufactured for this project for casting the specimens, as shown in Figure 1; these were designed based on ASTM-D638.

2.1 Specimen Preparation
The epoxy samples were prepared and mixed according to the manufacturer’s instructions in each case. Each adhesive type has two parts, part-A and part-B, and the mix ratios used in the experiment were measured by weight to be 100:40 PartA:PartB and 2:1 PartA:PartB for adhesive A and adhesive B, respectively. The adhesives were mixed thoroughly and then poured into the Teflon moulds, then each adhesive was pressed a few times to expel any voids within the sample. Samples were then left for curing: for Adhesive-A, 12 samples were cured at 23 °C for 7 days and 12 samples were cured at 50 °C for 4 hours, while for adhesive-B, 12 samples were cured at 23 °C for 7 days and 12 samples were cured at 40 °C for 4 hours. The curing temperatures were selected based on the manufacturer’s specifications for each type of adhesive. The temperature in each case was controlled by storing the samples in a chamber and fixing the room temperature of the chamber.

2.2 Testing Procedure
In order to apply fatigue loading parameters, sets of three adhesive samples were tested under direct tensile force to find the ultimate tensile strength; a constant speed and displacement of 1mm/min was applied until each sample failed. These tensile tests were carried out according to ASTM-D638.
frequency, defined as the number of load cycles, per second was set to 4Hz, while the minimum and maximum applied stresses were set to be 10% to 40% of the ultimate tensile strength of the adhesive according to the manufacturer’s properties. In addition, as temperature may affect composite structures, particularly with regard to the chemical bond between FRP materials and structural elements, the effect of temperature was also studied. An increase in temperature was thus associated with the fatigue loading to represent actual loading states of composite structures. Two temperatures were used in this study, 25°C 40°C. These temperatures were chosen to represent average room temperature in Melbourne and the maximum temperature in Melbourne during peak summer season. To apply the different load cases, an Instron machine with a built-in chamber was utilised for all tests, as seen in Figure 2.

Figure 2: INSTRON machine with built-in chamber

To ensure that the samples were heated to the temperature of the chamber, a thermocouple was attached to each specimen to compare the sample and chamber temperatures, as shown in Figure 3.
3. Experimental Results

The experimental results for the two adhesive types are presented in this section for both static and dynamic testing and for the two testing temperature degrees.

3.1 Static tests

The specimens were tested under ambient temperatures and static loading to derive the ultimate tensile strength. The following table shows the results obtained for the two types of adhesives.

| Ultimate tensile strength (MPa) | S1   | S2   | S3   | Average |
|--------------------------------|------|------|------|---------|
| Type-A                        | 20.3 | 22.6 | 20.0 | 21.0    |
| Type-B                        | 22.9 | 22.0 | 23.2 | 22.7    |

The average stress strain curves for the two adhesive types are shown in Figure 4. It is clear that adhesive type-A is much more ductile than adhesive type-B, with a failure strain of 0.065 compared to 0.014 for the latter.

![Figure 4: Stress-strain curves for the two adhesives: a) type-A adhesive; b) type-B adhesive](image-url)
3.2 Fatigue tests

Based on the quasi-static tensile tests of the adhesive samples, 10 to 40% of the ultimate load was applied as the minimum and maximum applied fatigue load and the frequency was set to be 4Hz. A stress range, $\Delta\sigma$, was thus calculated as shown in Table 3:

| Type   | Ultimate strength (Mpa) | 10% of the ultimate stress (MPa) | 40% of the ultimate stress (MPa) | Stress range $\Delta\sigma$ (MPa) |
|--------|-------------------------|----------------------------------|----------------------------------|----------------------------------|
| Type-A | 21                      | 2.1                              | 8.4                              | 6.3                              |
| Type-B | 22.7                    | 2.3                              | 9.1                              | 6.8                              |

As mentioned, the two types of adhesives were cured under two conditions and then tested under the above stresses at two different temperatures (25 and 40 °C). Table 4 shows the total number of fatigue cycles for both adhesives; the values in this table are the average values calculated from testing six specimens, with outliers omitted from the calculations.

| Curing Temperature °C | Testing Temperature °C | No. of cycles x10³ |
|-----------------------|------------------------|---------------------|
| Adhesive type-A       | 25                     | 240                 |
|                       | 50                     | 2000                |
| Adhesive type-B       | 25                     | 70                  |
|                       | 40                     | 623                 |

(a)
Figure 5 shows the behaviour of the structural adhesives under two testing temperatures. For samples tested under 25°C, the number of cycles went from $0.24 \times 10^6$ to $2.0 \times 10^6$ cycles when cured under 50°C for adhesive-A, and from $0.07 \times 10^6$ to $623 \times 10^6$ cycles for adhesive-B. However, both adhesives performed poorly when tested under 40°C which indicates exceedance of the glass transition temperature ($T_g$) for both adhesives. The failure mode for all samples tested under both temperatures was marked by breakage near the gripping area, as shown in Figure 6. The fatigue behaviour of the adhesives samples cured under high temperatures indicates a promising development in the area of FRP strengthening structures that may benefit FRP strengthening of steel structures that develop fatigue issues. Several observations can be derived from the results: the accelerated curing of adhesives has no effects on the ultimate tensile and shear strength of epoxy, as observed by various other studies [14, 15]. However, the accelerated curing of structural adhesives does significantly increase their fatigue life which may improve the fatigue performance of structures.
4. Conclusion
The fatigue performance of two types of structural adhesives were studied in this paper. All adhesive samples were made in accordance to ASTM-D638 and cured in accordance to the manufacturer’s guidelines under normal temperatures (25 °C) and or high temperatures (40 °C or 50 °C). Samples were then subjected to cyclic loading under two testing temperatures, 25 °C and 40 °C, to represent the effects of actual environmental conditions for composite bridge girders. The results showed a significant effect of curing temperature on service fatigue life, as the number of cycles increased by more than 8 times for both adhesives when cured under high temperatures and tested under normal temperature (25 °C). There was only an insignificant effect of curing temperature when testing was performed under high temperatures, however, though both adhesives performed similarly under those conditions.

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