Creep of Adhesively-bonded FRP-strengthened Steel Structures at Elevated Temperatures

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ABSTRACT

Ambient cured epoxy adhesive is widely used for bonding fibre reinforced polymer (FRP) plates to structures. The present paper examines a typical strengthening adhesive to investigate the effect of adhesive thermo-viscoelasticity. The response of the adhesive was determined using a series of tests using the multi-frequency scanning mode of a dynamic mechanical analyser (DMA). The thermo-mechanical properties of the adhesive were then characterised using time-temperature superposition parameters and a Prony series representation for generalised Maxwell creep. The adhesive response was in turn used within a finite element model of steel beam strengthened using a bonded CFRP plate to exam the effect of creep in the adhesive at warm temperatures. The study found that thermo-viscoelastic creep of the adhesive bonding layer causes an increase in the slip between the FRP and the structure. Redistribution of the stresses along the beam can allow the plate to maintain its contribution to the moment capacity of the beam; however, as the temperature and time increases, the slip increases, and the CFRP becomes less effective, potentially resulting in failure of the strengthening system and yield of the steel beam.

KEYWORDS: Bonded strengthening, Structural adhesive; Creep; Thermo-viscoelasticity.

INTRODUCTION

Bonded fibre reinforced polymers (FRPs) are now widely used in rehabilitating and strengthening existing structures. This bonded strengthening method relies upon the structural adhesive to transfer the load between the FRP plate and strengthened structure. Bond models are used to analyse the behaviour of the adhesive layer at ambient temperature and are currently used in design [1]. However, when the temperature approaches the adhesive glass transition temperature (T_g), the adhesive will become soft and show viscoelasticity, and causes the adhesive's stiffness and strength to decrease dramatically. The creep rate also increases rapidly, which could cause a significant reduction in the effectiveness of strengthening during long-term service [2]; however, it is also possible that this creep could enable stress redistribution along the length of the plate, which is potentially beneficial. A typical epoxy-based adhesive used for FRP strengthening purposes has a T_g of around 40°C to 70°C, temperatures which structures may see in service through solar heating or other means.

Using an elastic model to analyse the adhesive behaviour during the service of a strengthened structure could therefore be insufficient, and a viscoelastic constitutive model may be required. Several studies have been conducted examining the viscoelastic creep behaviour of FRP to concrete adhesive joints, but these do not examine temperatures effects [3,4,5]. FRP to steel joints could be more likely exposed to elevated temperatures, but these have received less attention. Sahin and Dawood [6] conducted experimental analysing the elevated temperatures effects upon CFRP strengthened steel beams, but this was based upon an elastic model and did not consider creep. Stratford and Bisby [2] developed a simple elasto-plastic strengthened beam model and demonstrated that warm temperatures could result in a runaway debonding failure of the FRP-steel adhesive connection. However, they also did not consider creep, and recommended that a better viscoelastic model be built to examine the long-term service performance in depth. Therefore, this project examines a model for the structural adhesive that investigates the effects of temperature-dependent viscoelastic creep behaviour on an adhesively-bonded, FRP-strengthened steel beam.

EXPERIMENTAL CHARACTERISATION OF THE ADHESIVE

An ambient cure structural adhesive for FRP strengthening was used in this study (Sikadur 330). A dynamic mechanical analyser (DMA8000) was used to characterize the viscoelasticity of the adhesive at warm temperatures. Rectangular adhesive samples (nominally 33 × 7.5 × 1.3mm) were cast and cured for 7 days at room temperature. DMA was first used to obtain the glass transition response of the adhesive using a single cantilever configuration, sinusoidal displacement, and a 2°C/min temperature ramp (similar to a study that preceded this work [7]). The resulting change in elastic storage modulus is shown in red in Figure 1, showing the reduction in stiffness at warm temperatures. This response is usually reported as a single glass transition temperature (T_g) for which there are numerous different definitions, two of which are shown in the figure [7].

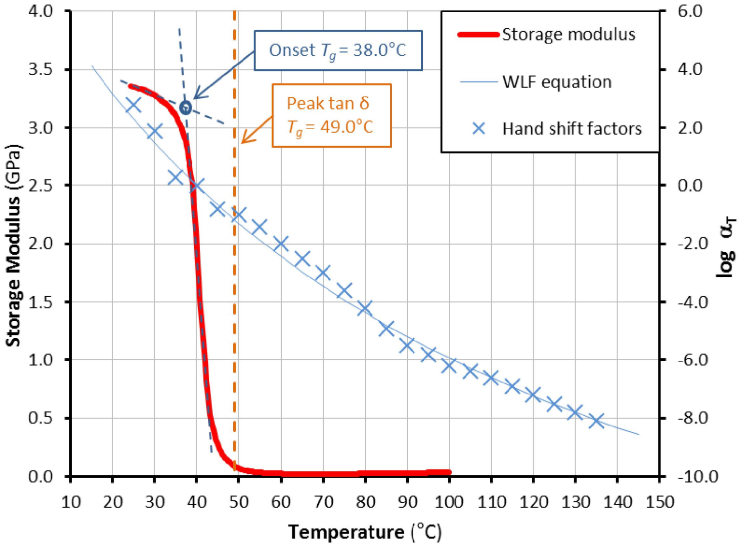


Figure 1. Glass transition response of the adhesive, together with the hand shift factors compared with WLF law prediction

The second stage of the experimental work was used to characterise the adhesive viscoelastic response, by developing a generalised Maxwell model suitable for use in finite element modelling.

Adhesive samples were subjected to multifrequency strain scans (0.01 to 100Hz) at temperatures from 25°C to 135°C. The response at each temperature is shown in Figure 2. Time-temperature superposition was then used to build the master curve shown in Figure 2, using the Williams-Landel-Ferry (WLF) equation [3,8,9]:

$$log(\alpha_T) = \frac{-C_1(T - T_{ref})}{C_2 + (T - T_{ref})} \quad (1)$$

The master curve uses a reference temperature T_{ref} = 40°C, being the nearest temperature to T_g (onset) = 38°C. The hand shift factors (α_T) are shown as blue crosses in Figure 1, and curve fitting the WLF equation gave the constant values as C_1 = 21.022 and C_2 = 152.64. The generalised Maxwell viscoelastic response (which is a linear viscoelastic model) is expressed as a Prony series in frequency, for input into the Abaqus finite element model [8,9]:

$$G'(\omega) = G_0\left[1 - \sum_{i=1}^{N} g_i\right] + G_0 \sum_{i=1}^{N} \frac{g_i \tau_i^2 \omega^2}{1 + \tau_i^2 \omega^2} \quad (2)$$

where $G'(\omega)$ is the frequency-dependent shear modulus, N is the number of terms in the Prony series, and ω is the angular frequency. The initial shear modulus, G_0 = 1292.9MPa, was determined from the initial elastic modulus from the T_g test (Figure 1). Table 1 summarises the Prony series parameters obtained from the master curve in Figure 2. In this study, the bulk modulus was assumed not to be temperature dependent, so that the corresponding bulk modulus parameters were taken as k_i = 0 [10].

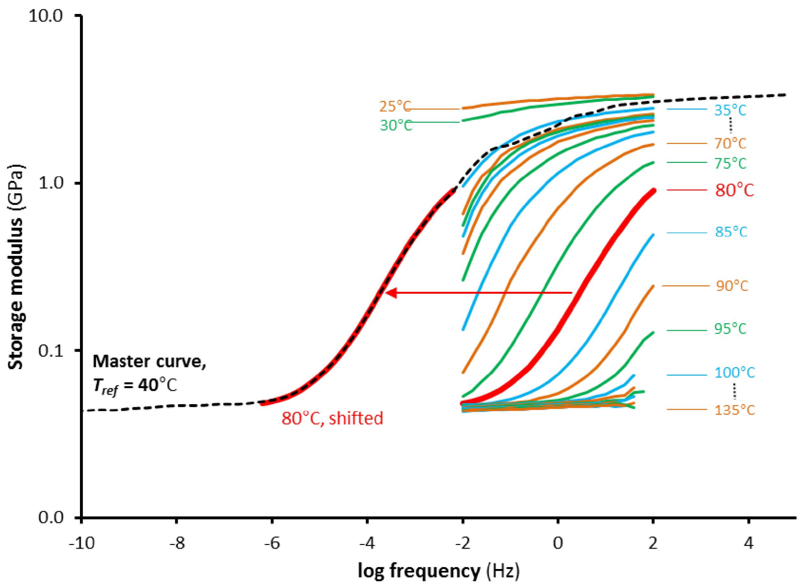


Figure 2. Master curve and the unshifted storage modulus data for T_{ref} = 40°C

Table 1. Parameters in the adhesive Prony series

i	g_i	τ_i (s)	i	g_i	τ_i (s)
1	0.00069	4.1×10^9	8	0.15106	92
2	0.00014	5.0×10^8	9	0.20782	12
3	0.00057	8.2×10^7	10	0.30753	0.41
4	0.00062	1.9×10^6	11	0.11247	3.9×10^{-2}
5	0.00293	6.4×10^4	12	0.05713	9.3×10^{-3}
6	0.01594	6.6×10^3	13	0.06955	1.4×10^{-4}
7	0.06282	7.1×10^2		$\sum g_i$ = 0.98927	

ANALYTICAL STUDY OF THE EFFECT OF ADHESIVE CREEP AT WARM TEMPERATURES

A finite element (FE) model of an FRP-strengthened steel beam was used to conduct a preliminary study of how the thermo-viscoelastic behaviour of the adhesive affects the strengthening system. This examines the lab-scale CFRP-strengthened beam shown in Figure 3, based upon the beam in Stratford and Bisby [2], with a top steel plate added to alleviate premature compression failure.

The thermo-viscoelastic constitutive model developed above was used to describe the adhesive. This was input into the Abaqus FE software using the WLF (T_{ref}, C_1, C_2) and Prony series parameters (Table 1). Abaqus automatically converts the frequency domain Prony series to time domain using a Fourier transform [8,9,11].

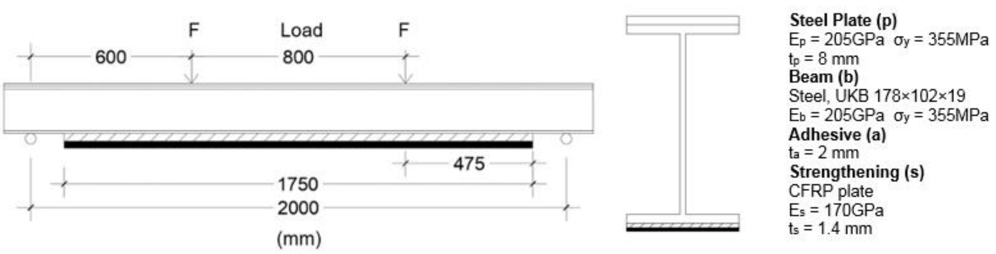


Figure 3. The geometry and material properties of the FE strengthened beam model

Thermal expansion is not included in this model. In reality, differential thermal expansion is important [1,2], but for this preliminary study we deliberately chose to isolate the thermo-viscoelastic effects. The additional implications of differential thermal expansion will be reported in a subsequent paper.

The temperature and the applied load were held constant (with F = 110kN), and the behaviour of the adhesive examined after different time periods. Figure 4 plots the distribution of relative slip between the CFRP plate and the soffit of the steel beam (the shear deformation of the adhesive), after being subjected to different temperatures and time periods. Figure 5 plots the CFRP axial stress distribution along the beam (a) for half of the beam and (b) a detailed view close to the centre of the beam.

The benchmark case with no creep is shown in green in both plots. This agrees with an elastic bond analysis. As expected, the CFRP axial stress is broadly constant between the loading points and increases linearly in the shear span. Close to the plate end there is a local increase in slip and reduction in the axial stress in the CFRP.

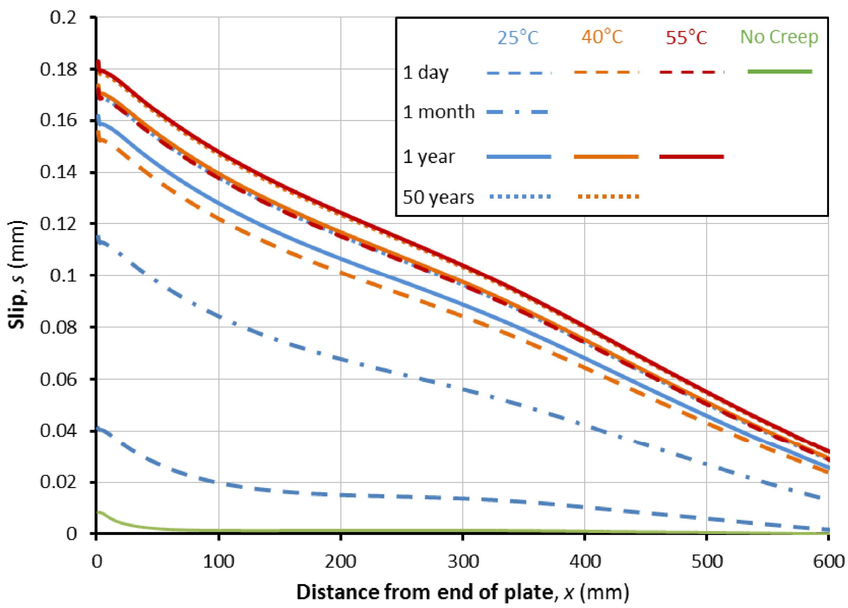
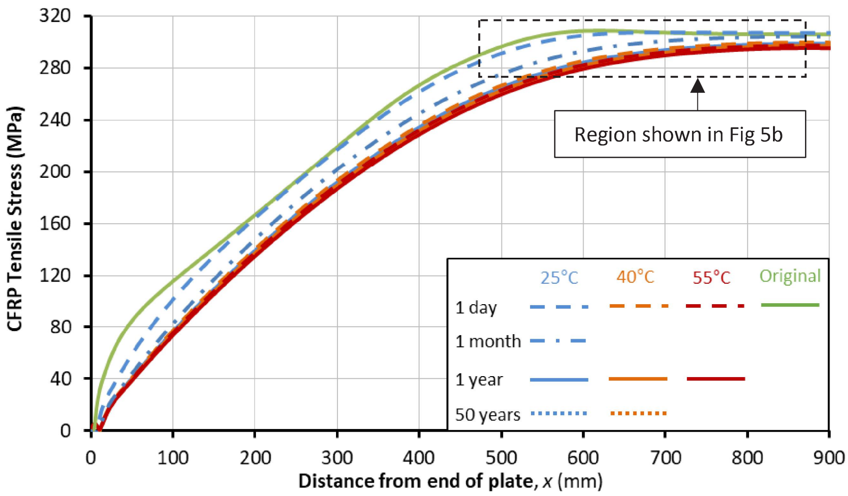


Figure 4. The plate-end slip distribution at various creep time and temperature conditions

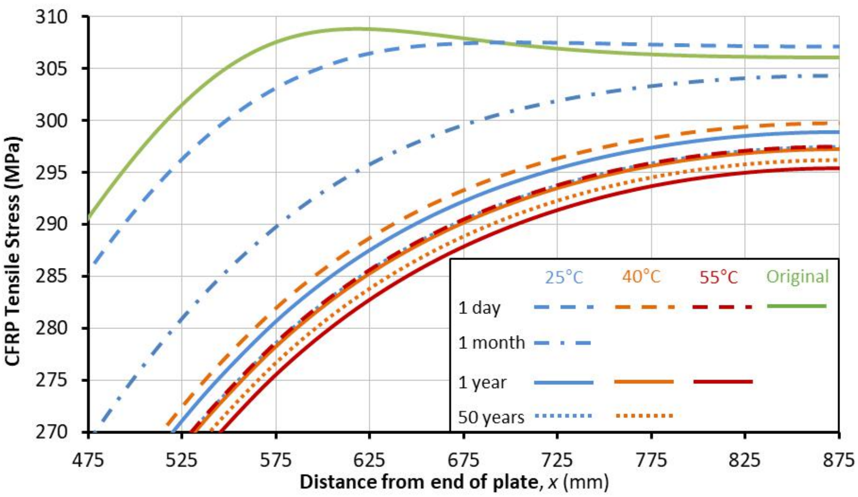
Introducing viscoelasticity into the adhesive model results in significant increases in the slip deformation, accompanied by redistribution of the CFRP axial stress along the beam.

- The model predicts that the effects of creep are significant after 1 day at 25°C. The plate end slip increases from 0.01mm to 0.04mm; however, this does not affect the load-carrying capacity of the beam because the axial stresses are redistributed along the beam, and the plate stress is unaffected in the central portion of the beam.
- After 1 month at 25°C, however, the plate end slip has increased substantially to 0.12mm, and there are greater slips at the centre of the beam. This results in the CFRP stress dropping, and consequently the steel beam is required to carry a higher proportion of the moment.
- After 1 year and 50 years at 25°C, the slip increases further, and the CFRP axial stress reduces. The steel beam must carry more moment, starts to yield under the loading points (although not shown here) and consequently the strengthening is no longer able to contribute to carrying the additional continuous loads.

Similar behaviour is seen at 40°C and 55°C, but at higher creep rates. For example, a plate end slip of 0.17mm is seen after 50 years at 25°C, or 1 year at 40°C, or 1 day at 55°C. This results in a reduction in the CFRP plate stress from 291MPa to 256MPa at the loading point (x = 475mm).



a) Showing half the length of the symmetric beam



b) Showing the central portion of the beam in greater detail

Figure 5. CFRP axial stress distributions at various creep time and temperature conditions

CONCLUSIONS

DMA tests have been used to characterise a typical epoxy adhesive used for FRP bonded strengthening, and this has been used to model the effect of adhesive thermo-viscoelasticity on the performance of the strengthened beam. This preliminary analytical work indicates that:

- Adhesive viscoelasticity results in additional slip between the plate and the soffit of the beam. This slip may not be significant if redistribution of the adhesive and CFRP plate stresses can occur along the beam, allowing the strengthening to provide the required increase in moment capacity.
- Under increasing time and temperature, however, the slip will become too large, the CFRP stress will reduce, and the strengthening will no longer fulfil its purpose of increasing the moment capacity, and the steel beam will yield.

The case modelled in this preliminary study was deliberately chosen to observe creep effects, and the limitations of this study must be recognised:

- Real-scale beams have longer bonded lengths and lower load demands on the CFRP.
- Differential thermal expansion has not been examined but is known to be significant.
- A joint debonding criteria has not been included, and this is likely to be affected by temperature.
- The adhesive will continue to cure and the glass transition temperature increase [7].
- Realistic temperature and load histories will be cyclic rather than steady.
- A linear viscoelastic model has been used, and the validity of the adhesive constitutive data for 50 year predictions is unproven.

In future work, the model will be improved to consider the above limitations and reported in a subsequent paper.

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