Nonlinear creep of the adhesive bond in FRP-strengthened steel beams

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NONLINEAR CREEP OF THE ADHESIVE BOND IN FRP-STRENGTHENED STEEL BEAMS

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ABSTRACT
When fibre-reinforced polymer (FRP) plates are applied to strengthen steel beams, the strengthening relies upon the structural adhesive to transfer load between the FRP plate and the steel structure. When the ambient temperature approaches the glass transition temperature (T_g) of the adhesive; however, the adhesive becomes viscoelastic, which could have a significant effect upon its long-term service performance. This paper investigates the impact of nonlinear creep at elevated service temperatures upon bonded FRP-strengthened steel beams. It is an analytical study, based upon experimental characterisation of the adhesive. The adhesive nonlinear response was obtained using a dynamic mechanical analyser (DMA) multiple stress creep-recovery test. These results were incorporated into a nonlinear viscoelastic finite element model to predict the displacement across the adhesive joint caused by adhesive creep. The model provides an analysis of a strengthened steel beam's long-term behaviour at warm temperatures. The analytical results demonstrate that as the temperature rises and the viscoelasticity develops, increased slip occurs between the FRP plate and steel beam, which could reduce the effectiveness of the strengthening.

KEYWORDS
Bonded strengthening, structural adhesive, creep, nonlinear viscoelasticity.

INTRODUCTION
Elastic bond models are used to analyse the adhesive bond when designing FRP strengthening for steel structures (Cadei *et al.* 2004). However, the adhesive's service temperature can approach its glass transition T_g during its service life (Stratford and Bisby 2011). The structural adhesive becomes viscoelastic, and this can significant increase the creep rate and result in a reduction in the effectiveness of strengthening. The creep, however, also enables stress redistribution along the length of the strengthened FRP plate, which is potentially beneficial. Elastic bond models do not consider this complicated viscoelastic behaviour. Several studies have examined the simple linear viscoelastic creep behaviour of adhesive joints (Zhang and Wang 2011; Jiang *et al.* 2018; Wang *et al.* 2019). Majda and Skrodzewicz (2009) and Houhou *et al.* (2014) found that epoxy adhesives had nonlinear viscoelasticity through the experimental work, but they did not examine the impacts of this stress-dependent nonlinear creep on the behaviour of a strengthened beam. This paper examines a model for the structural adhesive that investigates the effects of nonlinear viscoelastic creep behaviour on an adhesively-bonded, FRP-strengthened steel beam. Whilst higher service temperatures are likely, this paper examines temperatures up to 45°C, to establish the behaviour of the strengthening at these "warm" temperatures.

NONLINEAR VISCOELASTIC MATERIAL MODELLING
The current modelling uses the nonlinear viscoelastic characterisation of Sikadur 30 adhesive carried out by Houhou *et al.* (2014). The results of their DMA multiple stress creep-recovery tests are shown in Figure 1 as creep compliance master curves (the coloured curves), where the creep compliance is the ratio of the time-dependent creep strain to the applied constant stress. One of the challenges in this study

is that is very difficult to characterise the adhesive at sufficiently long timescales at elevated temperatures, and for the present study Houhou *et al.*'s results have been extrapolated to allow this.

Houhou *et al.* (2014) used time-temperature superposition to determine the shift factors necessary to develop the master curves, yielding an Arrehenius equation described by the parameters Θ_0 and E_0 given in Table 1. They expressed the adhesive behaviour using the linear viscoelastic Burger's model, identifying with different parameters to describe the different stress levels (see Houhou *et al.* 2014).

For the current analysis, the parallel rheological framework (PRF) in the Abaqus finite element software was used to fit the experimental master curves, as is a nonlinear viscoelastic model that can be applied for any stress level. The fitted PRF curves are shown in black in Figure 1, and the corresponding nonlinear viscoelastic material parameters are summarised in Table 1. A PRF using one hyperelastic element and three viscous elements was used, with the *Yeoh* model selected to describe the hyperelasticity (Dassault Systèmes, 2014; Ropers *et al.* 2017):

$$U = \sum_{i=1}^{3} C_{i0} \, (\bar{I}_1 - 3)^i + \sum_{i=1}^{3} \frac{1}{D_i} (J^{el} - 1)^{2i} \tag{1}$$

where U is the strain energy per unit of reference volume, C_{i0} and D_i are material parameters, $\bar{I}_1$ is the first deviatoric strain invariant and J^{el} is the elastic volume ration. Each of the viscous strain elements contains a factor *SRatio* that determines its ratio to the total viscous creep strain, and all the three elements used the power-law strain hardening model (Dassault Systèmes, 2014; Ropers *et al.* 2017):

$$\dot{\bar{\varepsilon}}^{cr} = (A\tilde{q}^n[(m+1)\bar{\varepsilon}^{cr}]^m)^{\frac{1}{m+1}} \tag{2}$$

where $\dot{\bar{\varepsilon}}^{cr}$ is the equivalent creep strain rate, $\bar{\varepsilon}^{cr}$ is the equivalent strain, $\tilde{q}$ is the equivalent deviatoric Kirchhoff stress. A, n and m are material parameters.

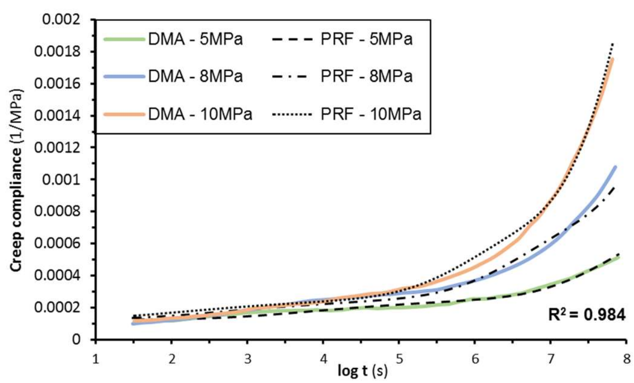

Figure 1. Nonlinear creep compliance master curves for a reference temperature of 25°C: test results versus PRF model fitting

Table 1. The parameters obtained for the adhesive PRF model

C_{10}	C_{20}	C_{30}	D_1	D_2	D_3
Yeoh parameters					
1026.51	2172.67	-270.076	1.039×10^{-5}	0	0
SRatio	*A*	*n*	*m*	Θ_0	E_0
Power-law strain hardening parameters				*Arrhenius form*	
0.03722	1.452×10^{-14}	9.144	-0.01209	25	610066.2
0.8105	5.243×10^{-15}	8.414	-1.399×10^{-5}	25	610066.2
0.1451	1.348×10^{-14}	7.482	-8.049×10^{-5}	25	610066.2

ANALYTICAL STUDY OF THE EFFECT OF ADHESIVE NONLINEAR CREEP

A study was conducted of how the nonlinear viscoelastic behaviour of the adhesive affects a benchmark CFRP-strengthened steel beam, shown in Figure 2. A short CFRP plate was used to give larger plate-end bond stresses and to allow the effect of creep to be studied, rather than as a realistic design scenario. Differential thermal expansion between the steel and the CFRP results in large bond stresses (Cadei *et* *al.* 2004); however, for this preliminary study differential thermal expansion is not included, so that the thermo-viscoelastic impacts could be isolated.

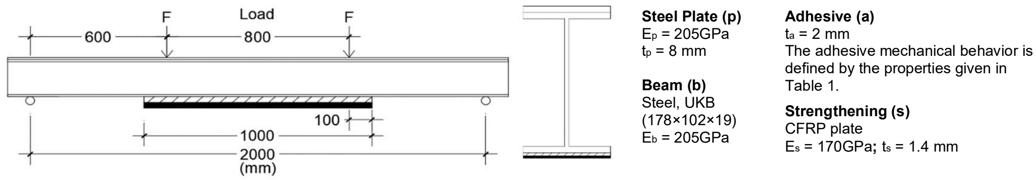

Figure 2. The geometry and material properties of the CFRP strengthened beam studied

The strengthened beam was modelled in 3D using Abaqus (Dassault Systèmes, 2014). A uniform temperature was applied to the beam and strengthening, and both the temperature and the applied load were held constant ($F = 110$kN). The behaviour of the adhesive was examined after different times.

Figure 3 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 4 plots the CFRP axial stress distribution along the end part of the plate. The benchmark case with no creep (in green) agrees with an elastic bond analysis.

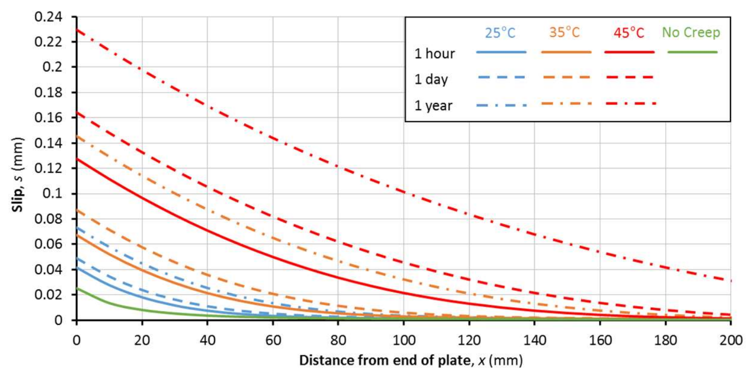

Figure 3. The slip distribution along the plate at various creep time and temperature conditions

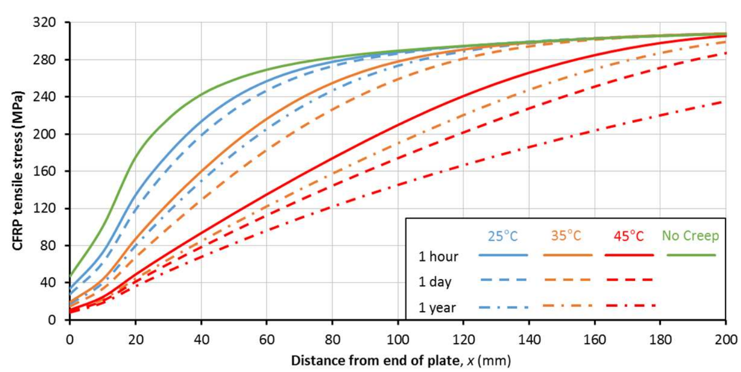

Figure 4. CFRP axial stress distributions at various creep time and temperature conditions

Introducing nonlinear 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 can be significant after 1 hour at 25°C. The plate end slip increases from approximately 0.025mm to 0.042mm. This results in the CFRP stress dropping at the end of the plate, and consequently in this region the steel beam is required to carry a higher proportion of the moment. At the centre of the beam, however, there is minimal change in the slip and CFRP axial stress, the adhesive shear stress is small, and the contribution of the CFRP plate to the moment capacity of the section is unchanged.

- After 1 day at 25°C, the plate end slip increases only slightly to 0.049mm, and the CFRP axial stress has not dropped significantly. This is in-part due to the initial stress redistribution at the end of the plate that reduces the adhesive stress and hence the nonlinear creep rate.
- After 1 year at 25°C, however, the slip has increased substantially to 0.073mm, and the CFRP axial stress has reduced significantly. Under the loading points (x = 100mm), the reduction in the CFRP plate stress means that the steel beam must carry more moment, and (although not shown here) the steel starts to yield. The strengthening consequently no longer meets its purpose.

Similar behaviour is seen at 35°C and 45°C, but at far higher creep rates. The results after 1 year at 35°C and 45°C rely on extrapolation of Houhou *et al*'s adhesive characterization, but the likely effect on the strengthened beam is nevertheless of interest. For example, after 1 year the plate end slip is around 0.073mm at 25°C, 0.145mm at 35°C, or 0.230mm at 45°C. This results in a significant reduction in the CFRP stress (from about 290MPa to 145MPa under the loading points, x = 100mm, at 45°C).

CONCLUSIONS

A parallel rheological framework (PRF) adhesive model has been used to characterise the nonlinear response of a typical epoxy adhesive used for FRP strengthening, and this has been used to model the effect of adhesive nonlinear viscoelasticity on the performance of a strengthened beam. This preliminary analytical work indicates that:

(1) Adhesive nonlinear viscoelasticity results in additional slip between the plate end 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 creep rate to reduce, and so long as the strengthening can make the necessary contribution to the section's moment capacity.

(2) At increased time and temperature, the slip increases, the CFRP stress reduces, and the strengthening may no longer contribute to the beam's moment capacity, resulting in the steel beam yielding.

The case modelled here was deliberately chosen to observe creep effects, and the limitations of this preliminary study should be recognised: (a) real-scale beams have longer bonded lengths and may place different load demands on the adhesive; (b) differential thermal expansion has not been examined but is known to be significant; (c) a joint debonding criteria has not been included, which is likely to be affected by temperature; (d) realistic temperature and load histories will be cyclic rather than steady state; and (e) additional adhesive constitutive data is needed at higher time-temperature combinations. These limitations are currently being studied as part of the project.

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