Creep of adhesively-bonded FRP-strengthened steel structures at elevated temperatures

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Newcastle High Level Bridge (1849)
Strengthened in 2008

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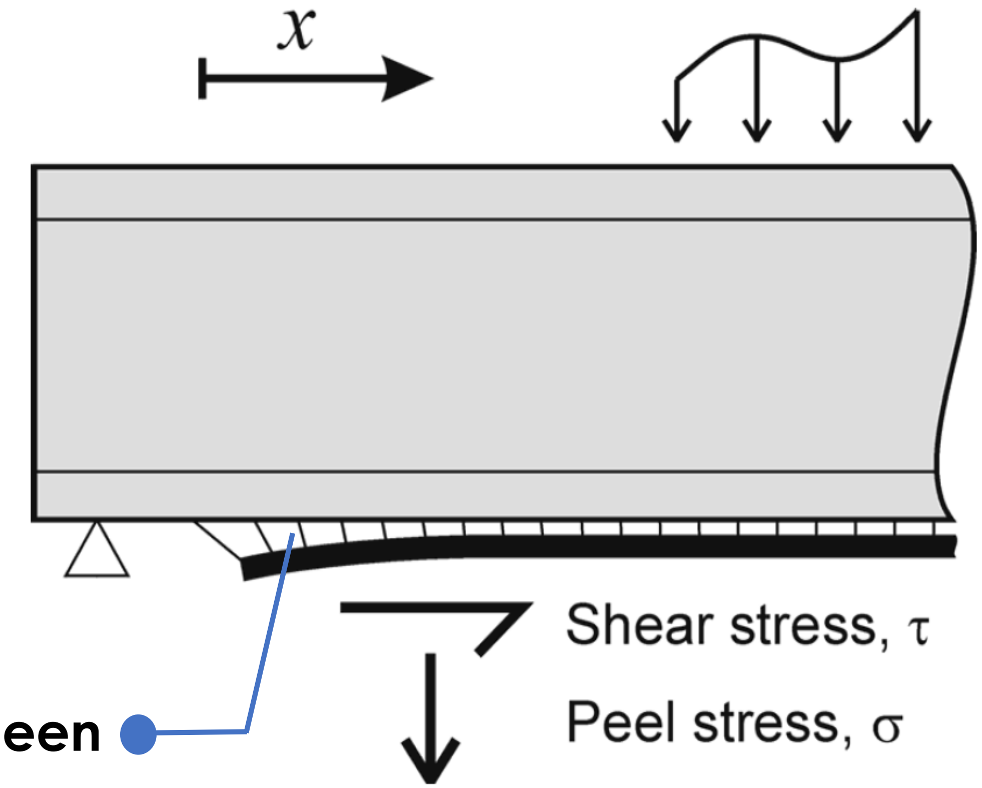
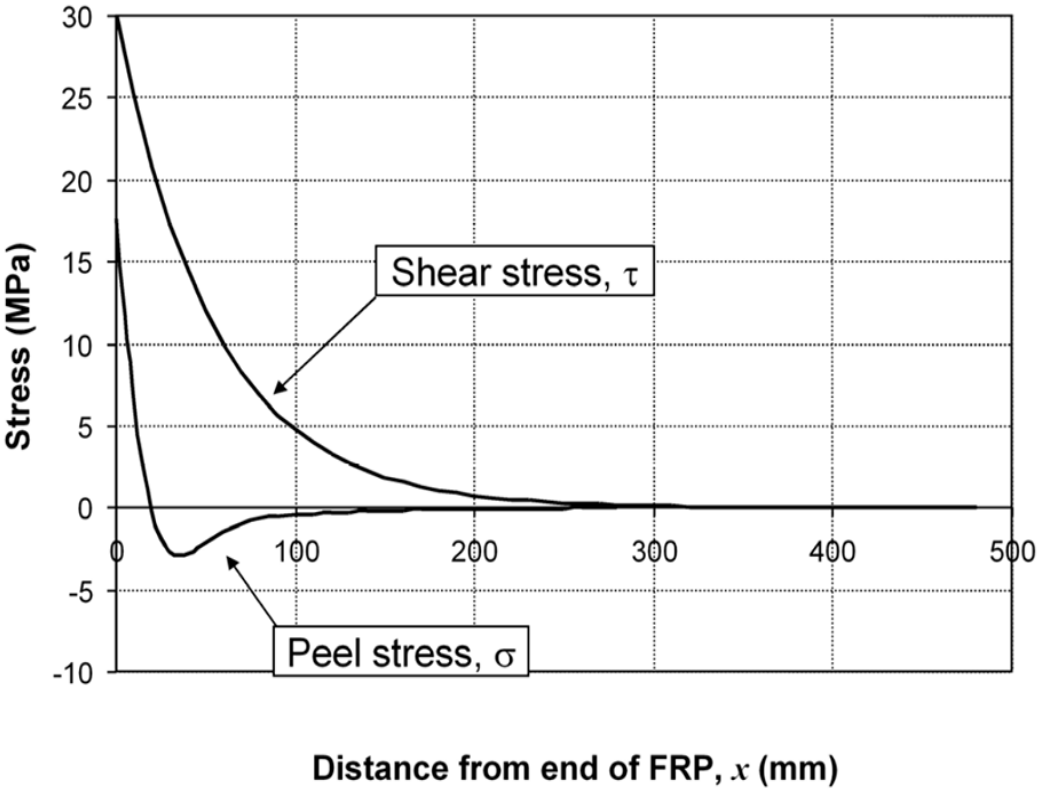
Bonded fibre reinforced polymers (FRPs) are now widely used in rehabilitating and strengthening existing structures. This bonded strengthening method relies upon the **structural adhesive** to transfer the load between the FRP plate and strengthened structure.

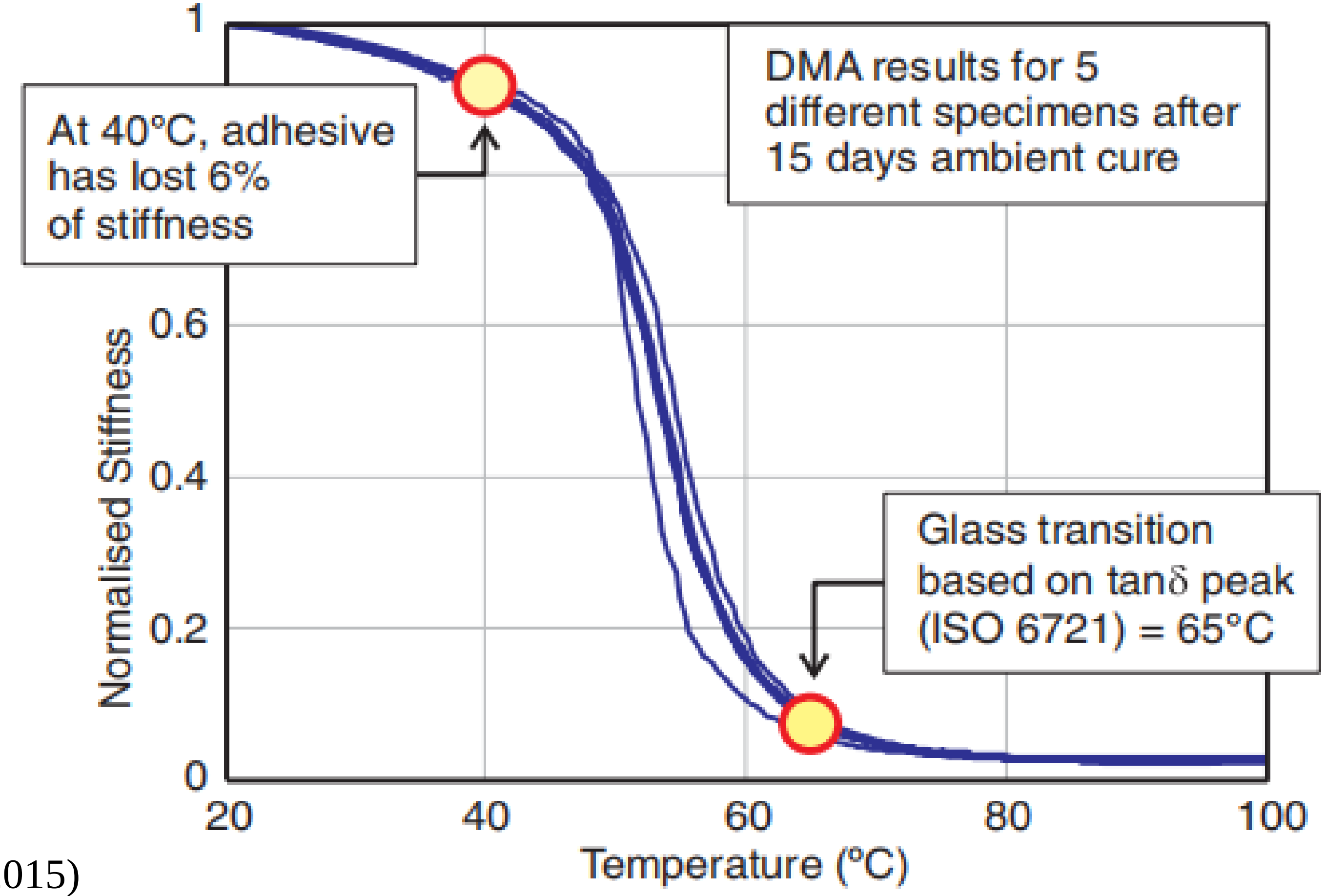


Elastic bond models have been used in design.



A viscoelastic model is required for FRP strengthening at elevated temperatures

Strengthen the Sauvie Island Bridge, USA (Mosallam *et al*. 2015)



At 40°C, adhesive has lost 6% of stiffness

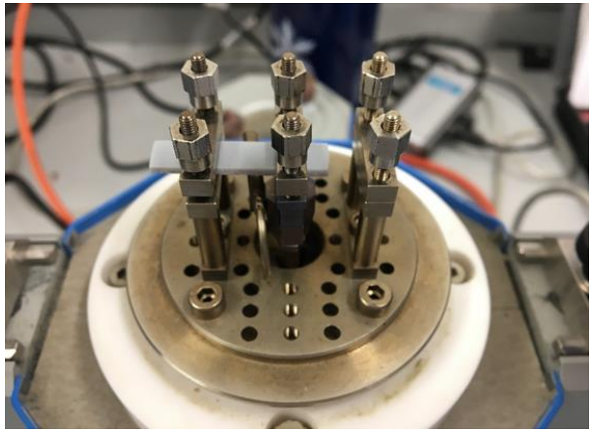
DMA results for 5 different specimens after 15 days ambient cure

Glass transition based on tanδ peak (ISO 6721) = 65°C

Investigates the effects of temperature-dependent viscoelastic creep behaviour on an adhesively-bonded, FRP-strengthened steel beam

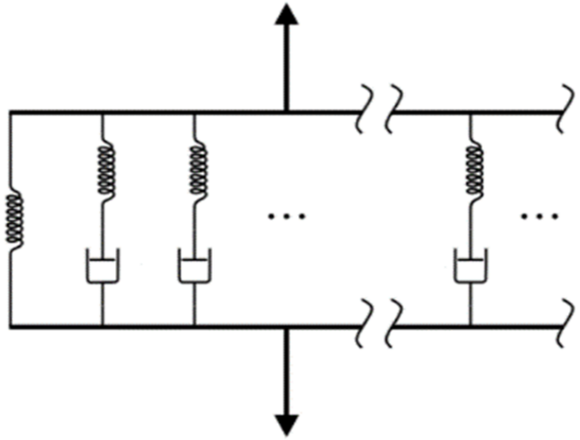
1. Experiment

Experimental characterisation of the adhesive



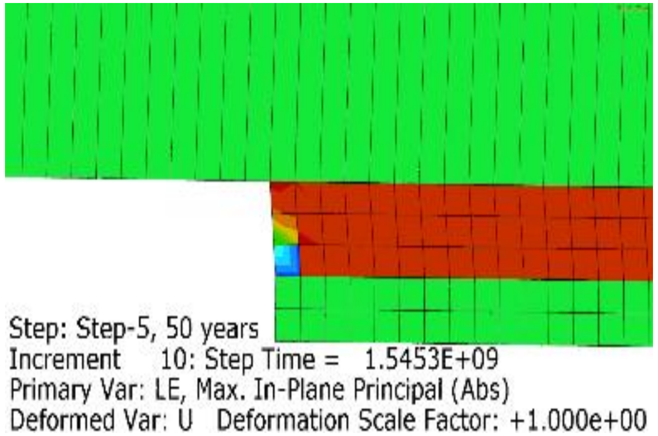
2. FE Model

A FE model of an FRP-strengthened steel beam



3. Analysis

Analytical study of the effect of adhesive creep at warm temperatures



```
Step: Step-5, 50 years
Increment    10: Step Time =    1.5453E+09
Primary Var: LE, Max. In-Plane Principal (Abs)
Deformed Var: U   Deformation Scale Factor: +1.000e+00
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Experimental Work

I. Glass transition behaviour

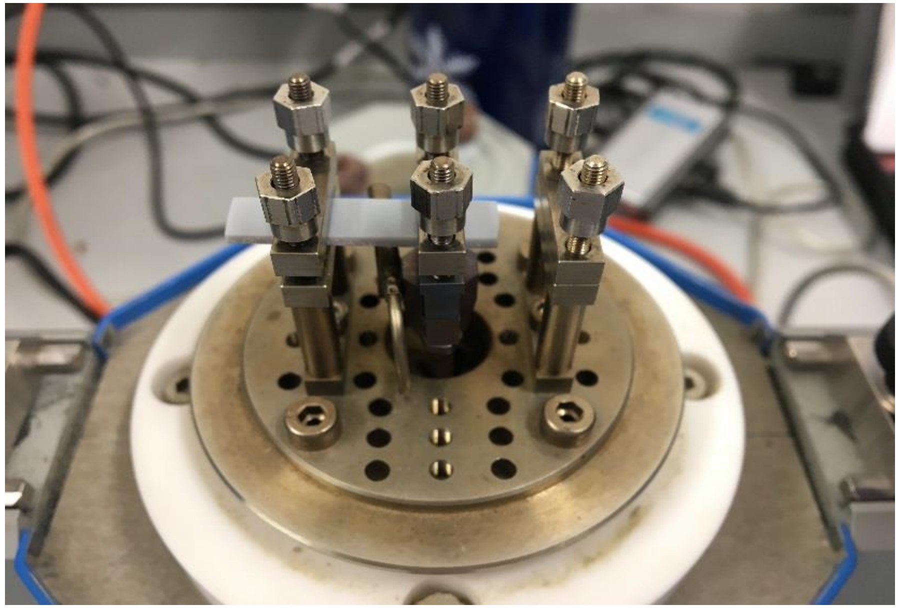
- Time/Temperature Scan
- 1 Hz, 0.05mm displacement
- 2°C/min from 25°C to 100°C

➡ The glass transition temperature (T_g)

II. Thermo-viscoelastic response

- Multi-frequency Scan
- 0.01 to 100 Hz (16 frequencies)
- 25°C to 135°C (interval T = 5°C)

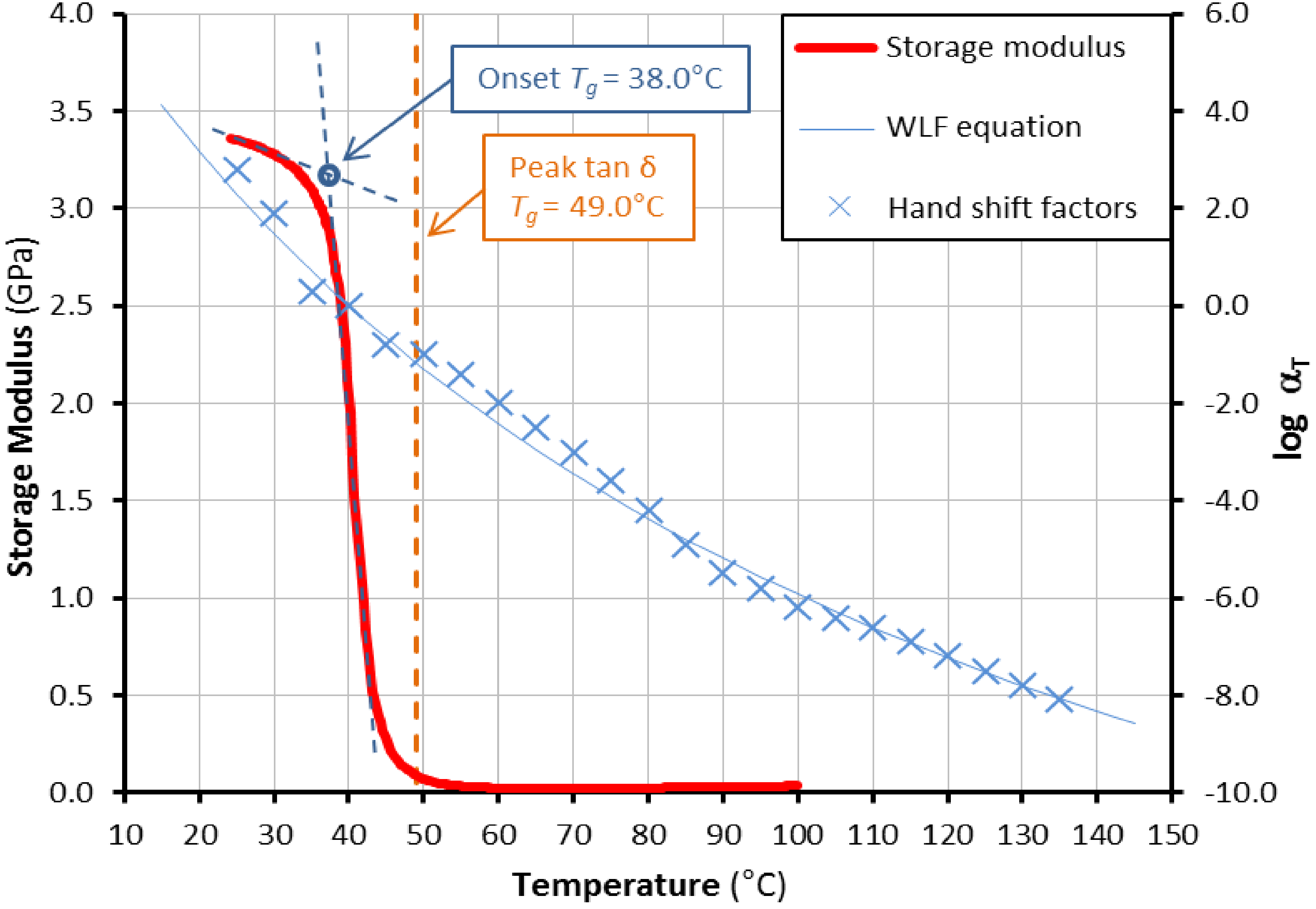
➡ The modulus master curve using Time-temperature superposition principle



Single cantilever configuration

- Equipment: dynamic mechanical analyser (DMA 800)
- Material: typical epoxy adhesive (Sikadur® 330)
- Sample size: nominally 33×7.5×1.3 mm
- Sample cure: 7 days at room temperature
- DMA configuration mode: single cantilever

I. Glass transition behaviour

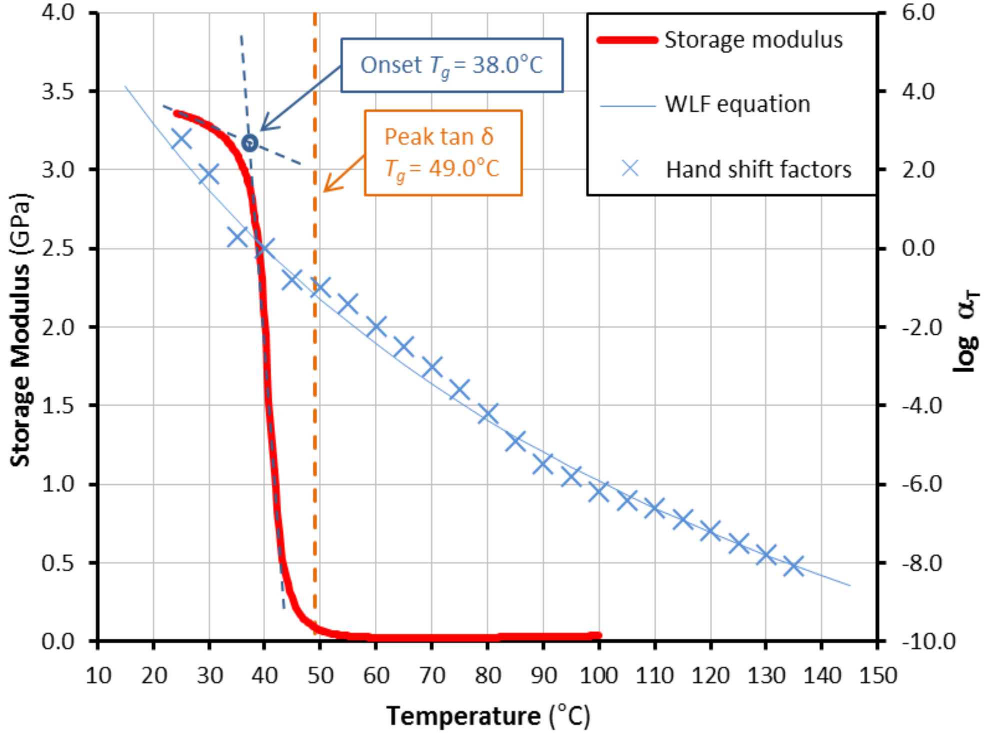


Experimental Work

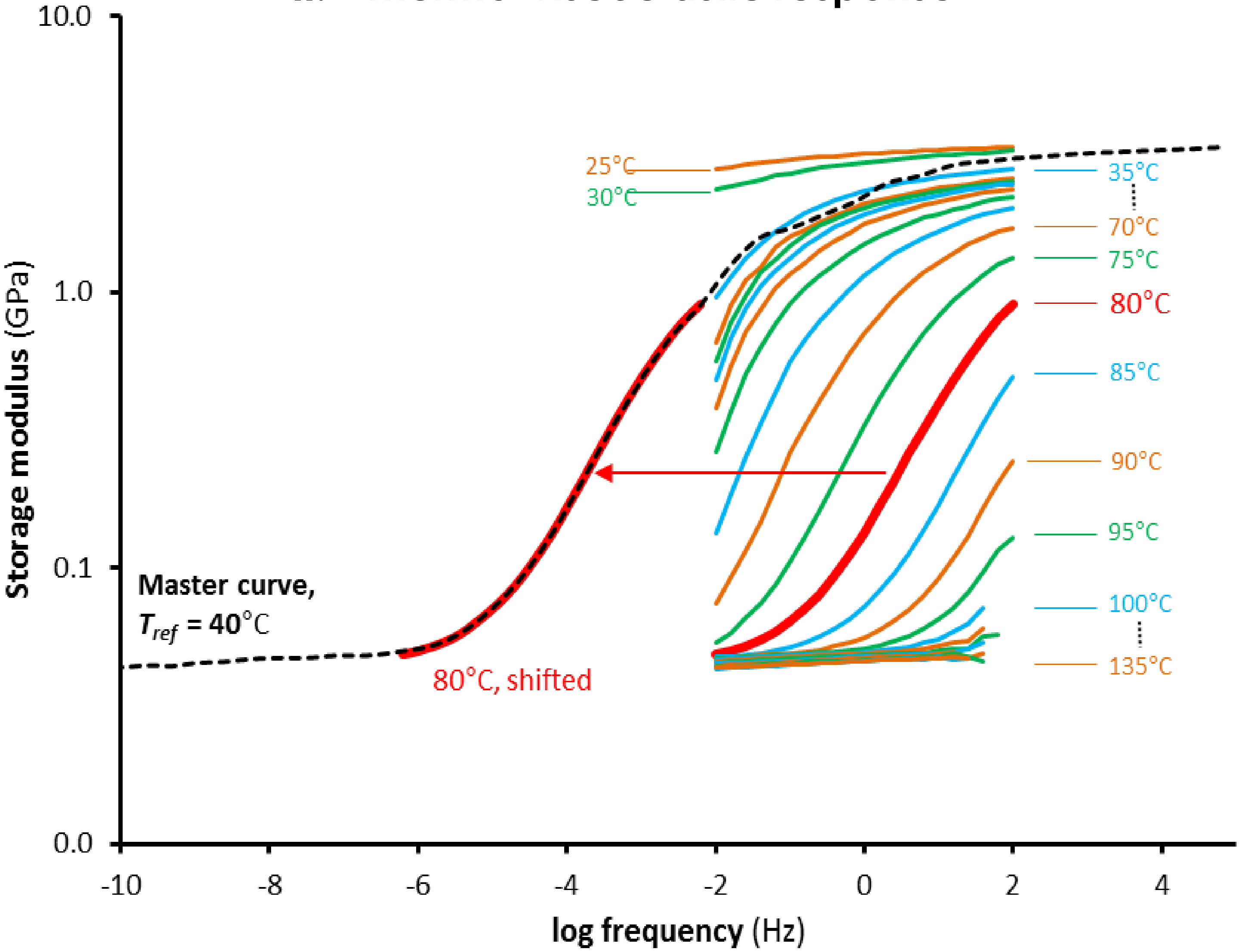
Time-temperature superposition principle (TTSP)
Williams-Landel-Ferry (WLF) equation:

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

T_{ref} = 40 °C, C_1 = 21.022 and C_2 = 152.64



II. Thermo-viscoelastic response



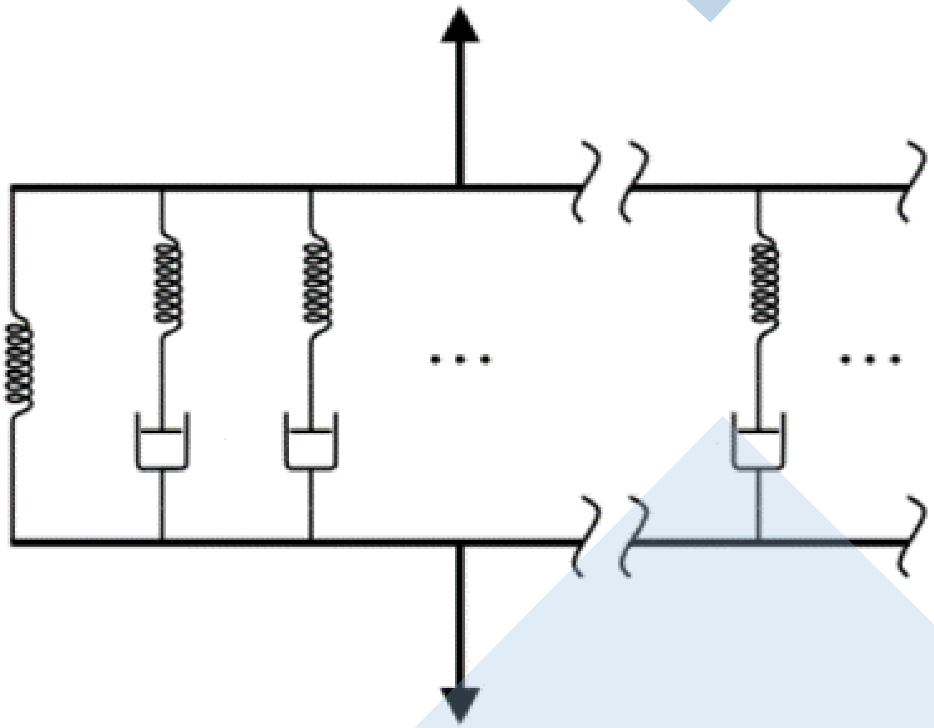
FE Model

The generalised Maxwell viscoelastic response (linear viscoelastic model) is expressed as a **Prony series** in frequency, for input into the **ABAQUS** finite element model.

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

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.

G_0 **= 1292.9MPa** determined from the T_g test.



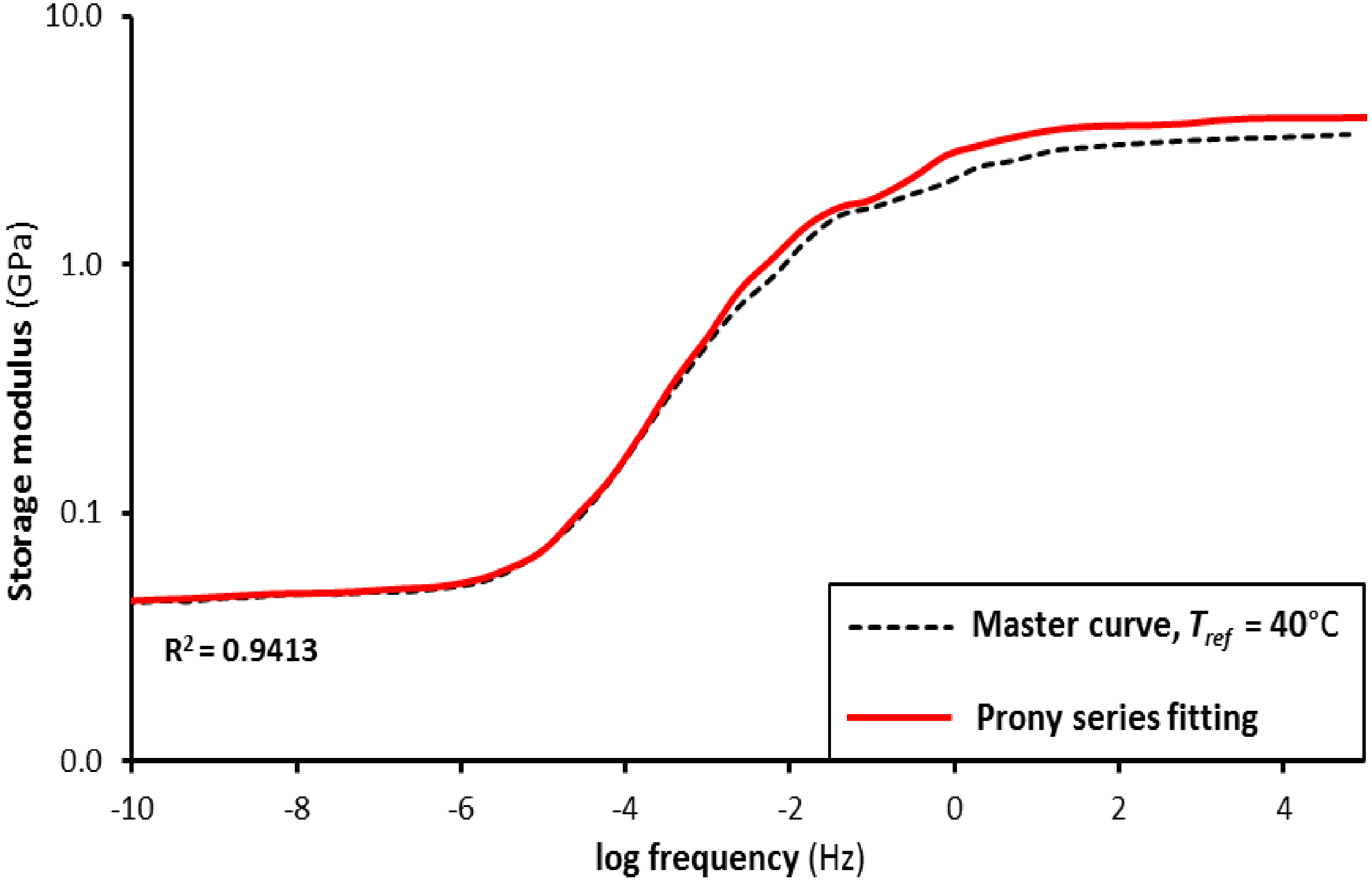
Generalized Maxwell model

The **bulk modulus** was assumed **not** to be temperature dependent, so that the corresponding bulk modulus parameters were taken as $k_i = 0$

Parameters in the adhesive Prony series

i	g_i	$\tau_i\,(s)$	i	g_i	$\tau_i\,(s)$
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		$\sum g_i = 0.98927$	

The Prony series parameters obtained by fitting with the master curve. The fitting is accurate enough to be used in further FE modelling, especially at **low frequency (long time)** range (≤ 100Hz).



Master curve for T_{ref} = 40°C versus Prony series fitting

2 FE Model

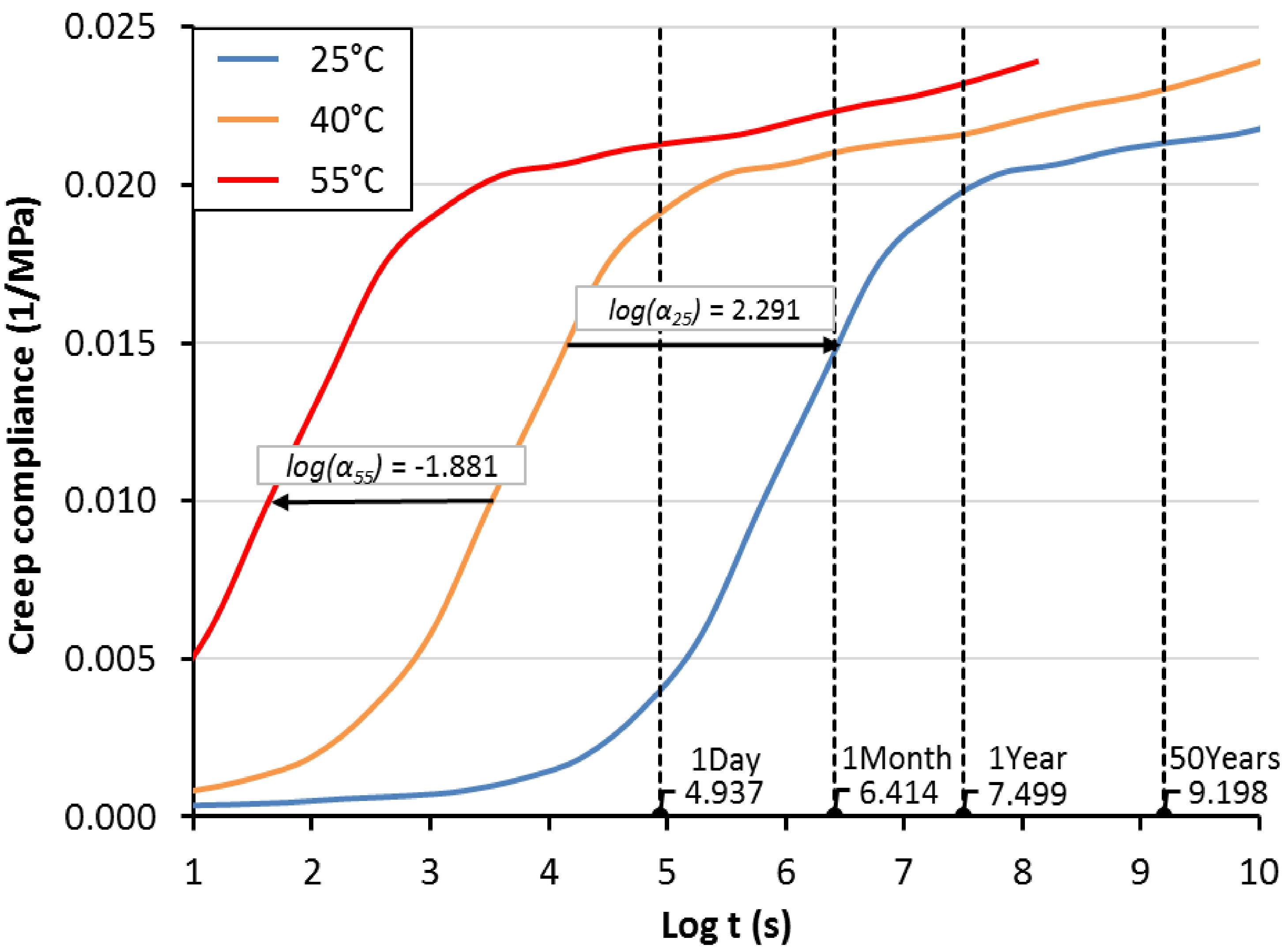
In ABAQUS, the **time-dependent** viscoelasticity of the adhesive was defined by time domain Prony series with the same parameters:

$$G'(t) = G_0\left[1 - \sum_{i=1}^{N} g_i\left(1 - e^{-t/\tau_i}\right)\right]$$

The **temperature-dependent** viscoelasticity was defined by the WLF equation:

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

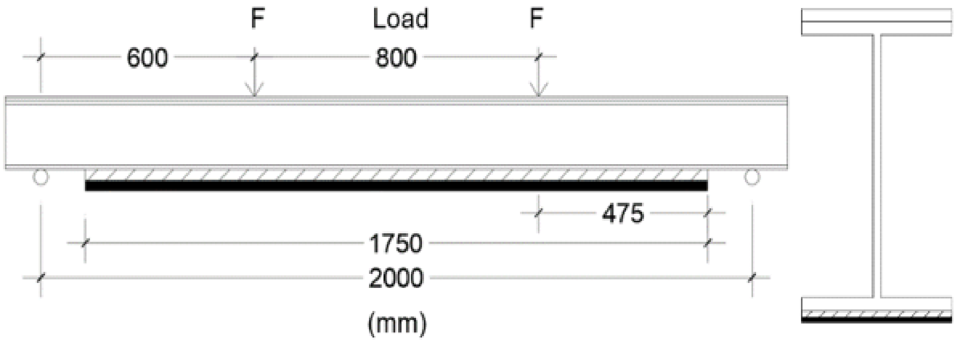
$T_{ref} = 40$ °C, $C_1 = 21.022$ and $C_2 = 152.64$



Creep compliance obtained for different temperatures

2

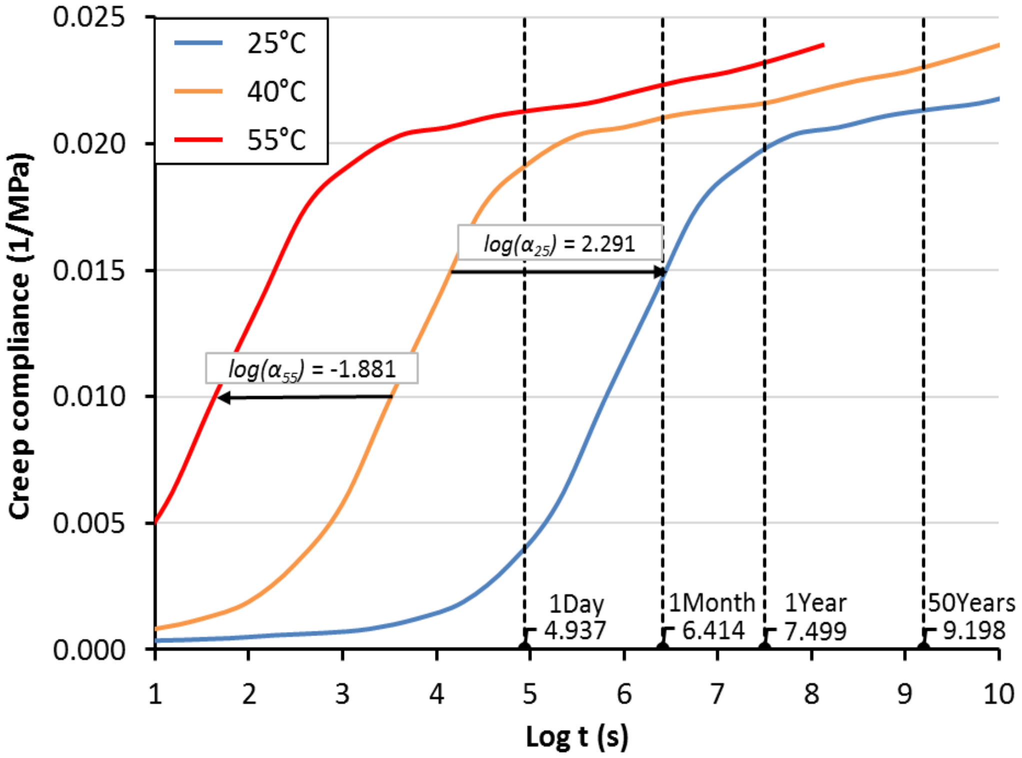
FE Model



Steel Plate (p)
E_p = 205GPa σ_y = 355MPa
t_p = 8 mm
Beam (b)
Steel, UKB 178×102×19
E_b = 205GPa σ_y = 355MPa
Adhesive (a)
t_a = 2 mm
Strengthening (s)
CFRP plate
E_s = 170GPa t_s = 1.4 mm

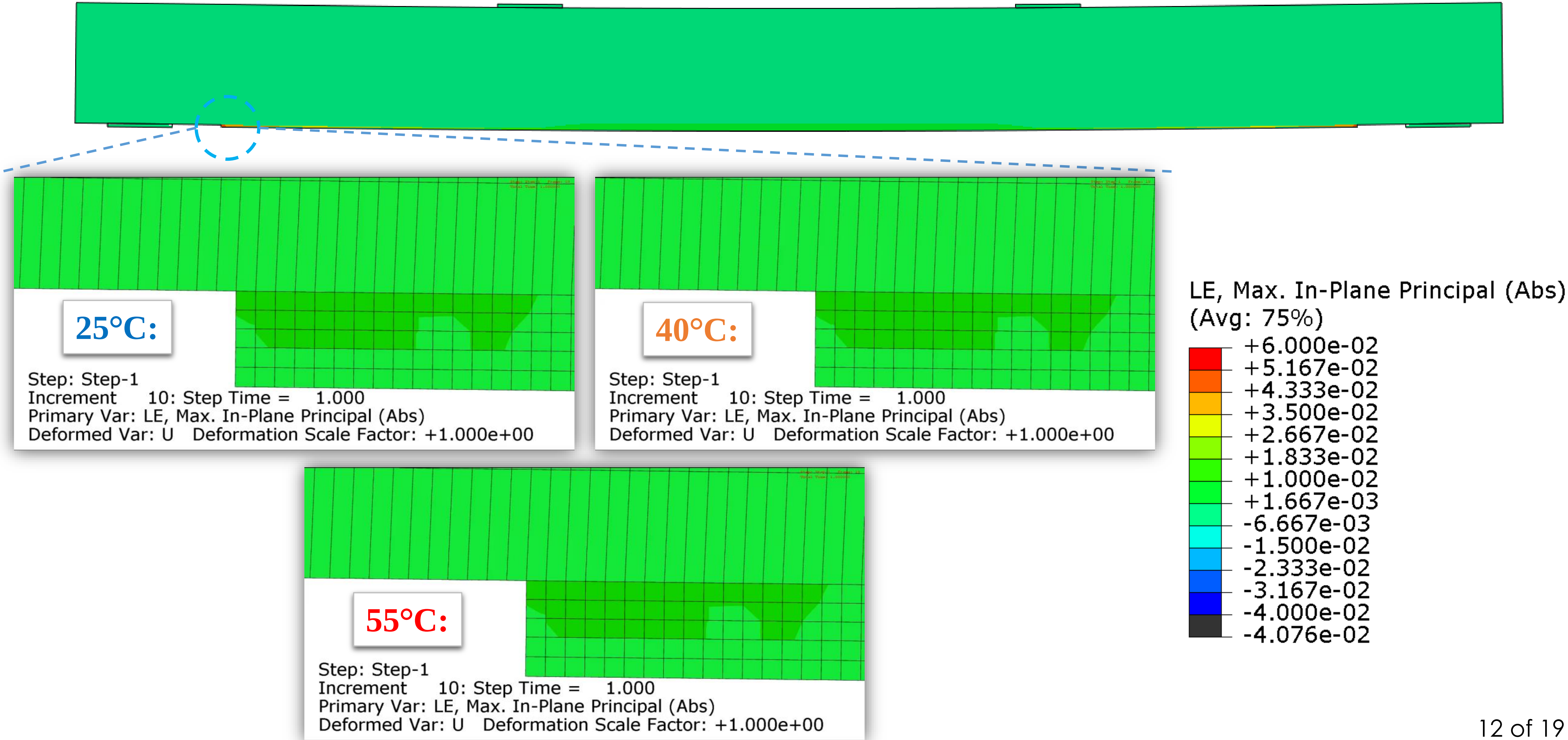
The geometry and material properties of the FE strengthened beam model

- The **thermo-viscoelastic** constitutive model.
- Thermal expansion is **not** included in this model.
- The **constant** temperature and load (with **F = 110kN**) were applied.



- **25°C** – around room temperature
- **40°C** – just above the Onset T_g (38°C)
- **55°C** – exceeds the Onset T_g (38°C)

ABAQUS model strain distribution



25°C:

```
Step: Step-1
Increment     10: Step Time =     1.000
Primary Var: LE, Max. In-Plane Principal (Abs)
Deformed Var: U   Deformation Scale Factor: +1.000e+00
```

40°C:

```
Step: Step-1
Increment     10: Step Time =     1.000
Primary Var: LE, Max. In-Plane Principal (Abs)
Deformed Var: U   Deformation Scale Factor: +1.000e+00
```

55°C:

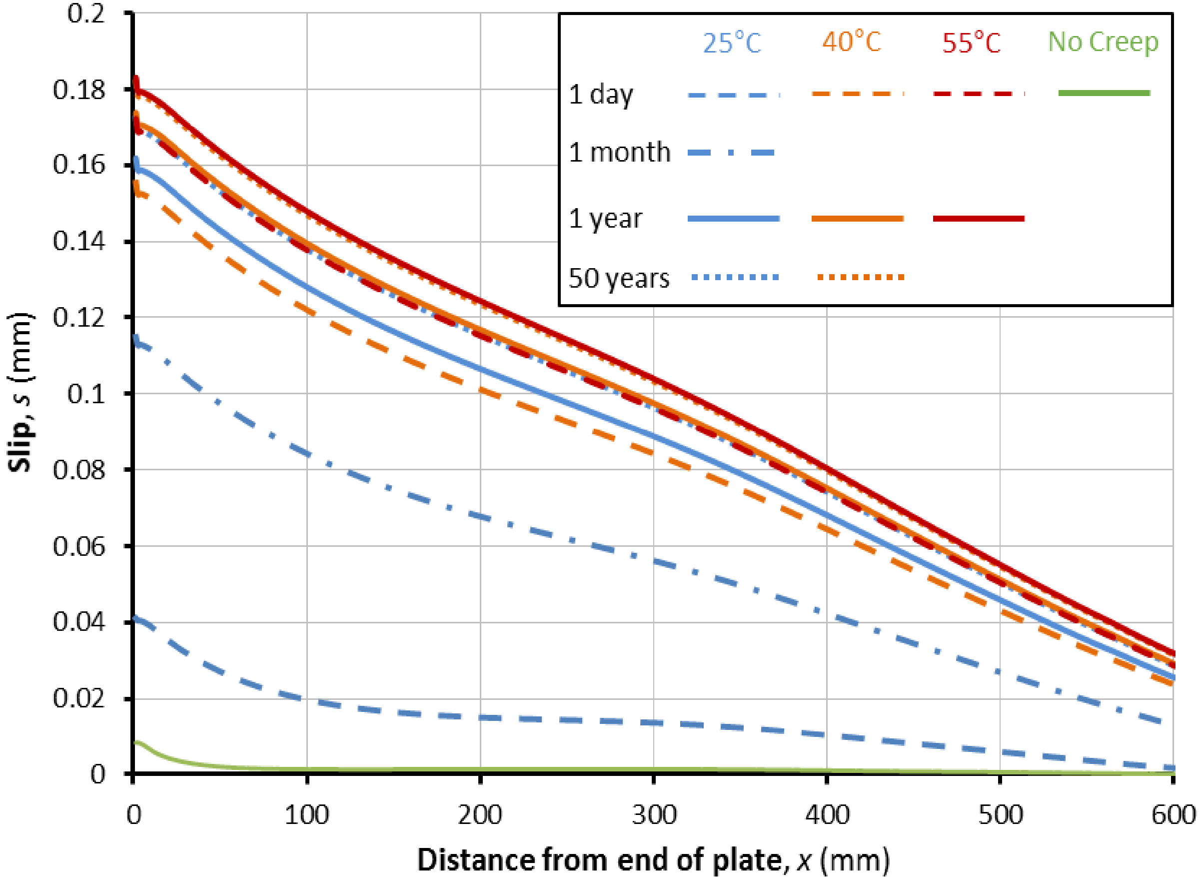
```
Step: Step-1
Increment     10: Step Time =     1.000
Primary Var: LE, Max. In-Plane Principal (Abs)
Deformed Var: U   Deformation Scale Factor: +1.000e+00
```

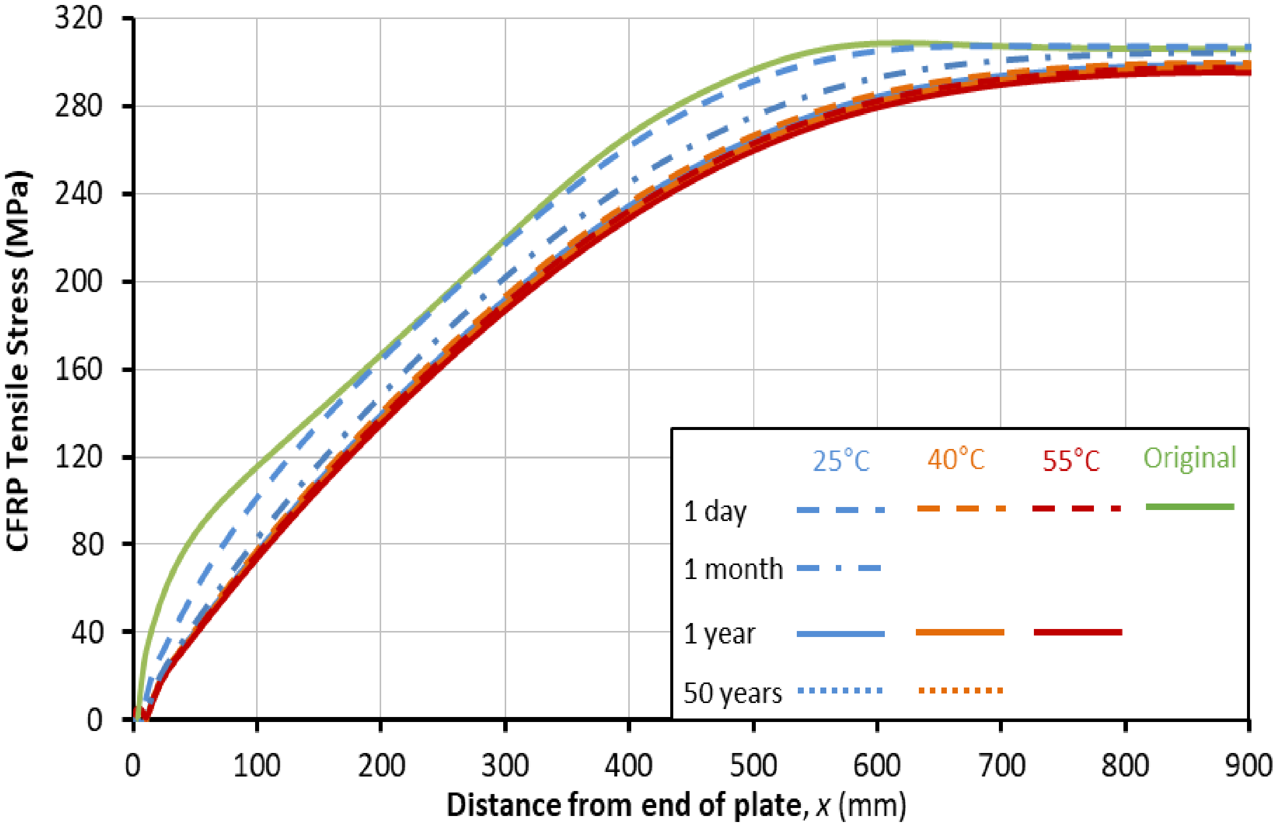
3

Analytical study

The **benchmark** case (no creep) is shown in green :

- Agrees with an elastic bond analysis.
- 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.





3

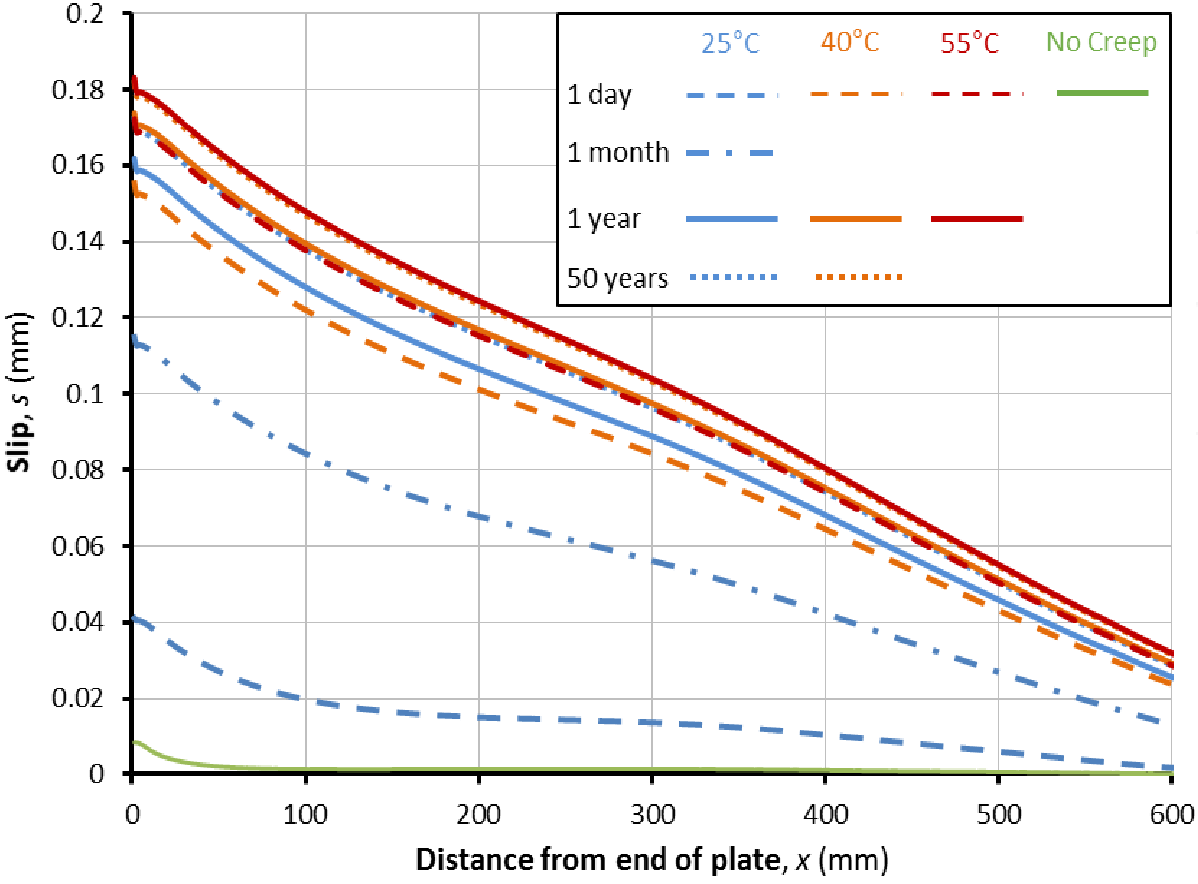
Analytical study

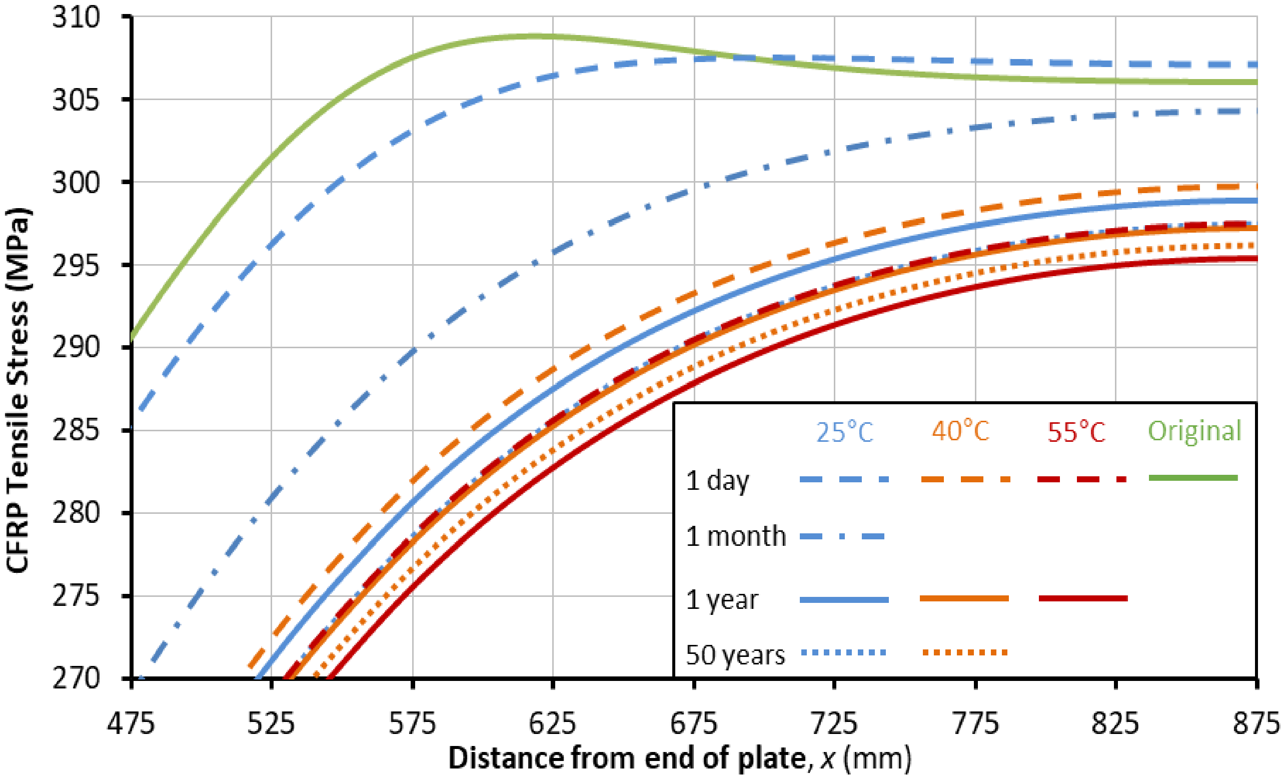
After 1 day at 25°C:

- The plate end slip increases from 0.01mm to 0.04mm.
- The axial stresses are redistributed along the beam.
- The load-carrying capacity of the beam is **not** affected.

After 1 month at 25°C:

- The plate end slip has increased to 0.12mm.
- The CFRP stress has dropped at the centre of the beam.
- The beam has to carry a **higher** proportion of the moment.





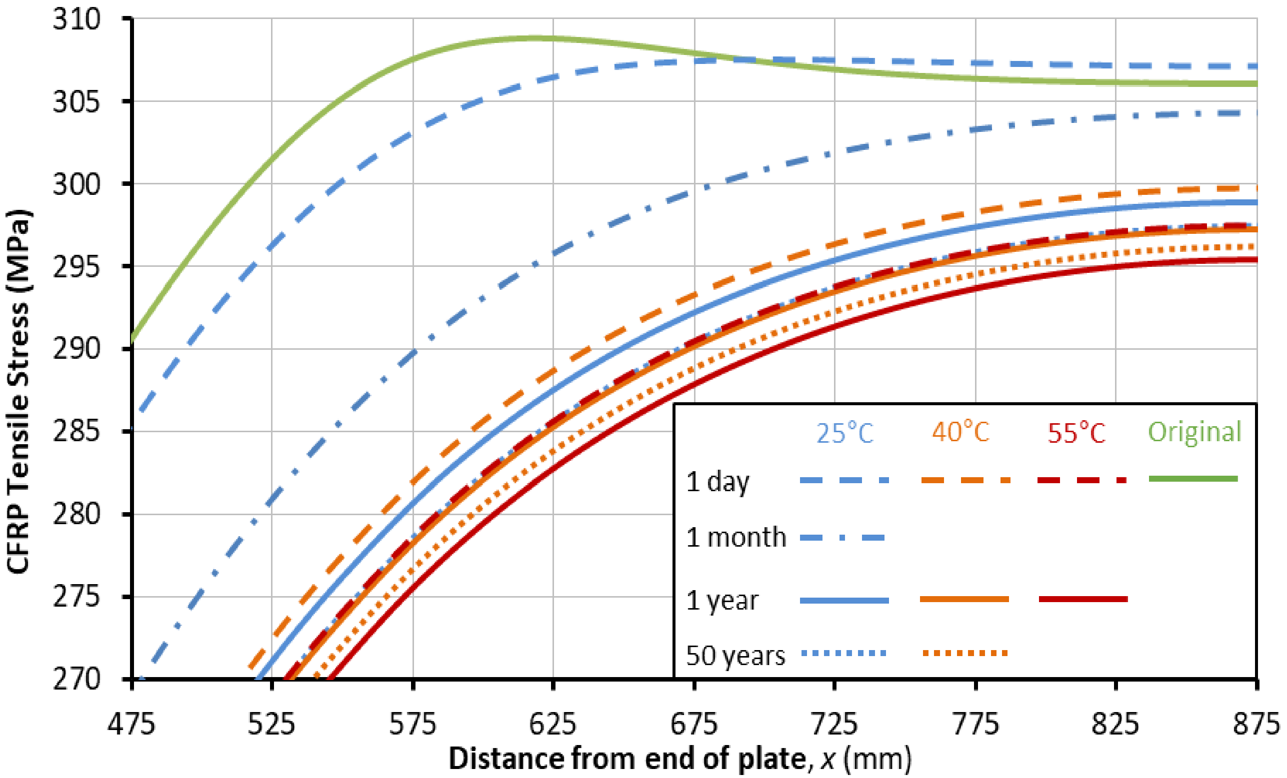
(Showing the central portion of the beam in greater detail)

3

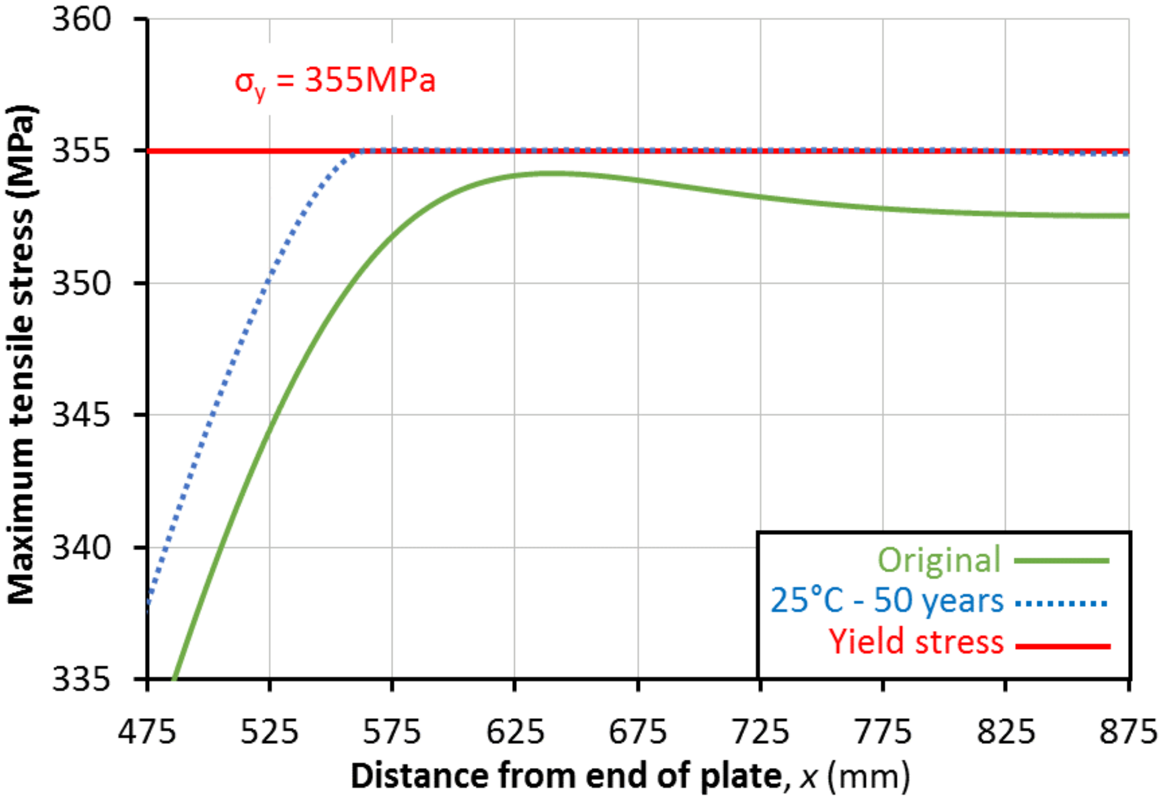
Analytical study

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.
- Consequently the strengthening is no longer able to contribute to carrying the additional continuous loads.



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

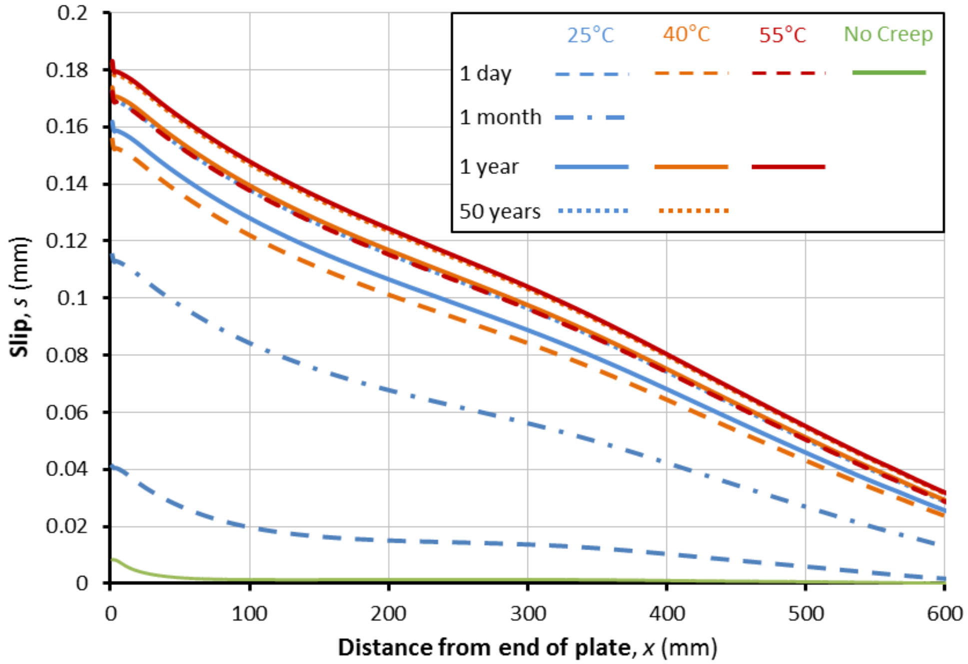


(Showing the central portion of the beam in greater detail)

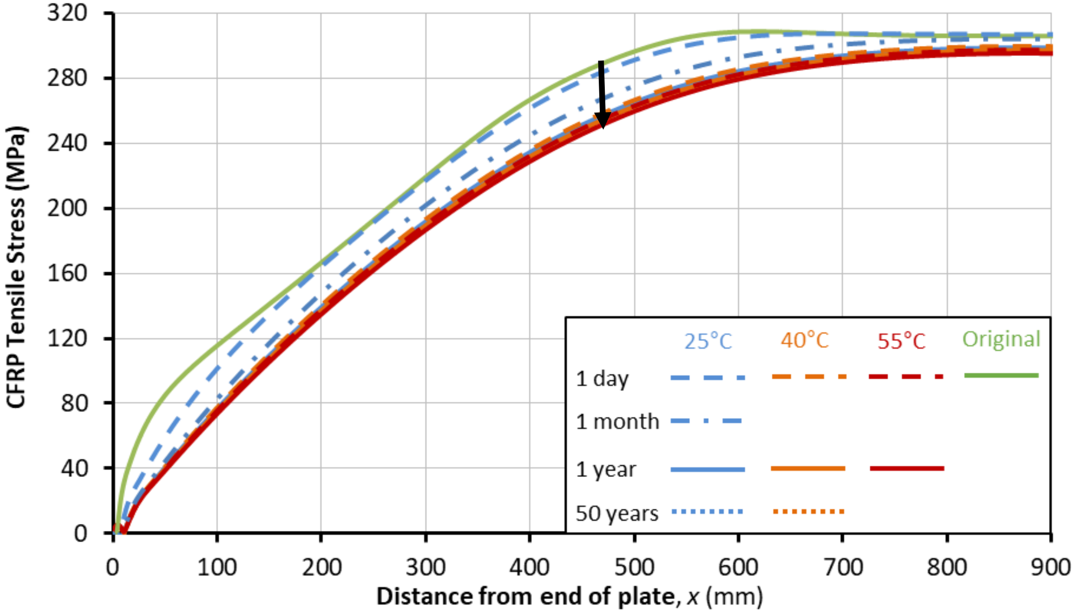
3 Analytical study

Similar behaviour is seen at **40°C** and **55°C**, but at higher creep rates.

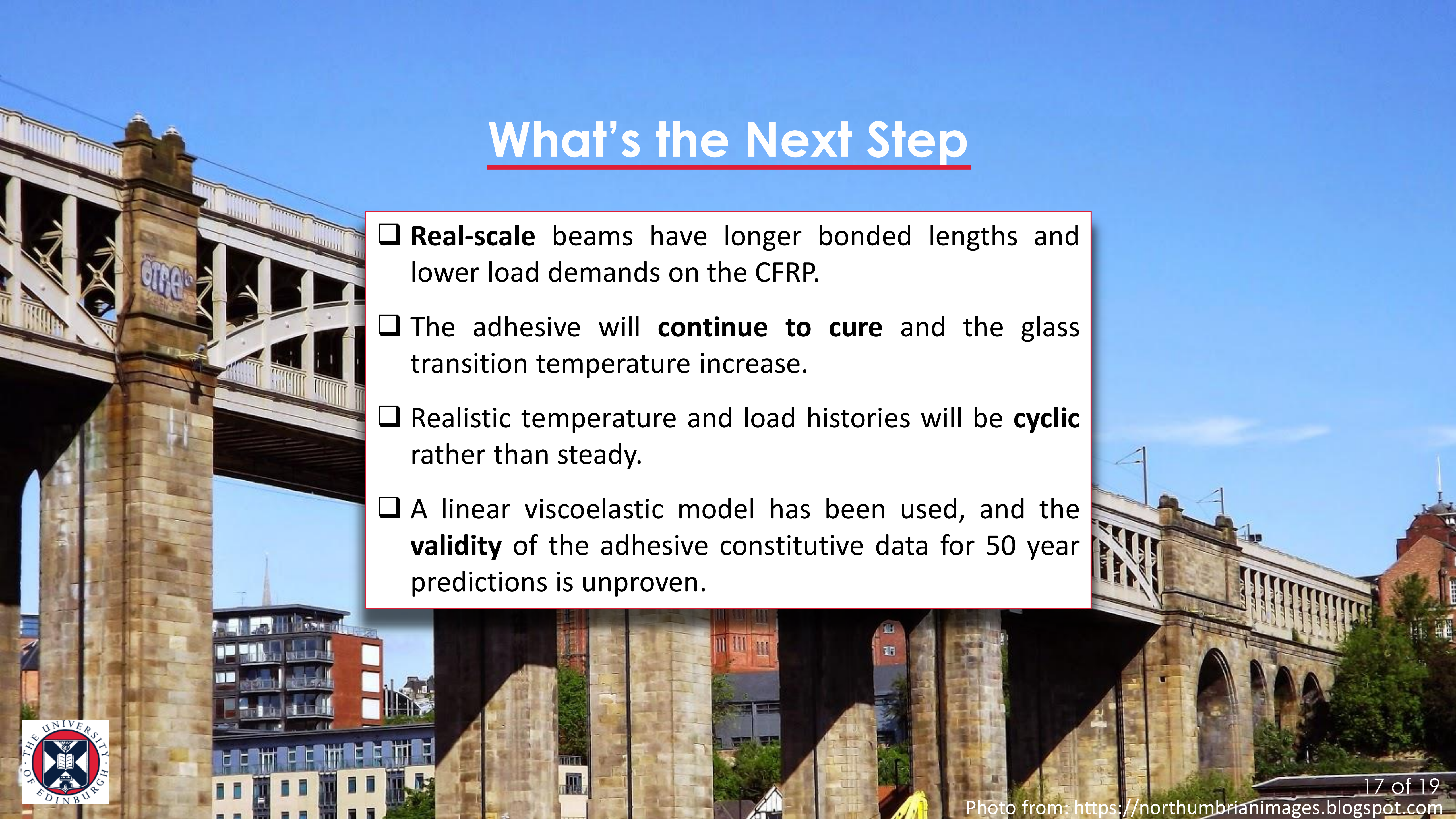
For example, a plate end slip of 0.17mm is seen after 50 years at 25°C, or 1 year at 40°C, or 1 day at 55°C.



This results in a reduction in the CFRP plate stress from **291MPa to 256MPa** at the loading point (x = 475mm).



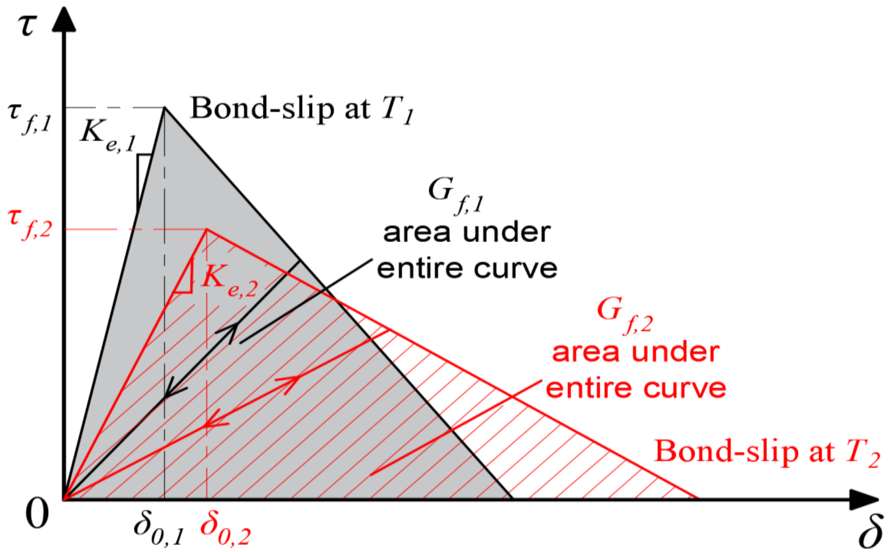
What’s the Next Step



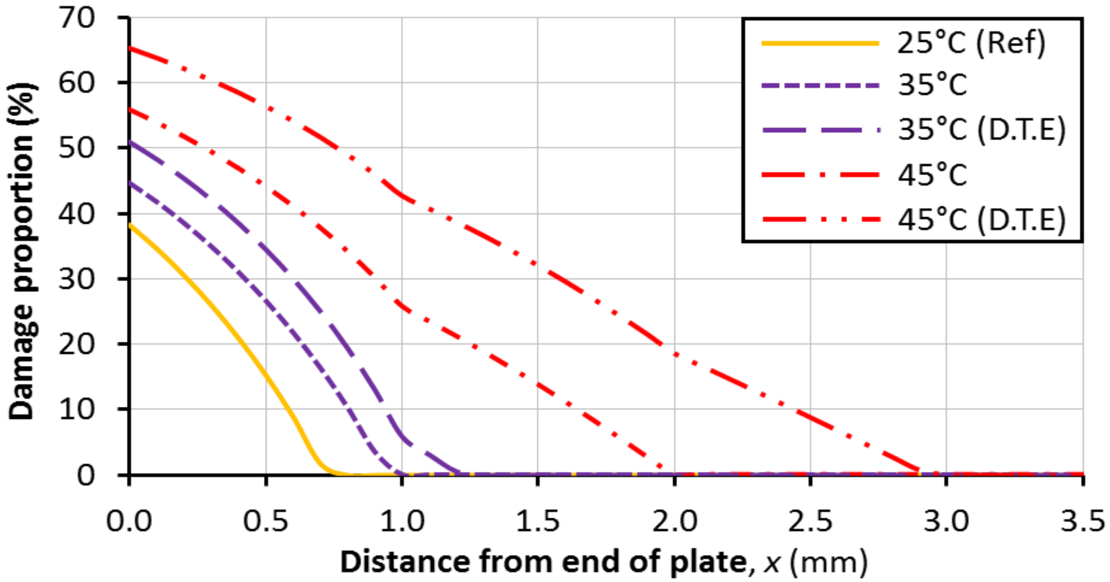
- ☐ **Real-scale** beams have longer bonded lengths and lower load demands on the CFRP.
- ☐ The adhesive will **continue to cure** and the glass transition temperature increase.
- ☐ Realistic temperature and load histories will be **cyclic** rather than steady.
- ☐ A linear viscoelastic model has been used, and the **validity** of the adhesive constitutive data for 50 year predictions is unproven.

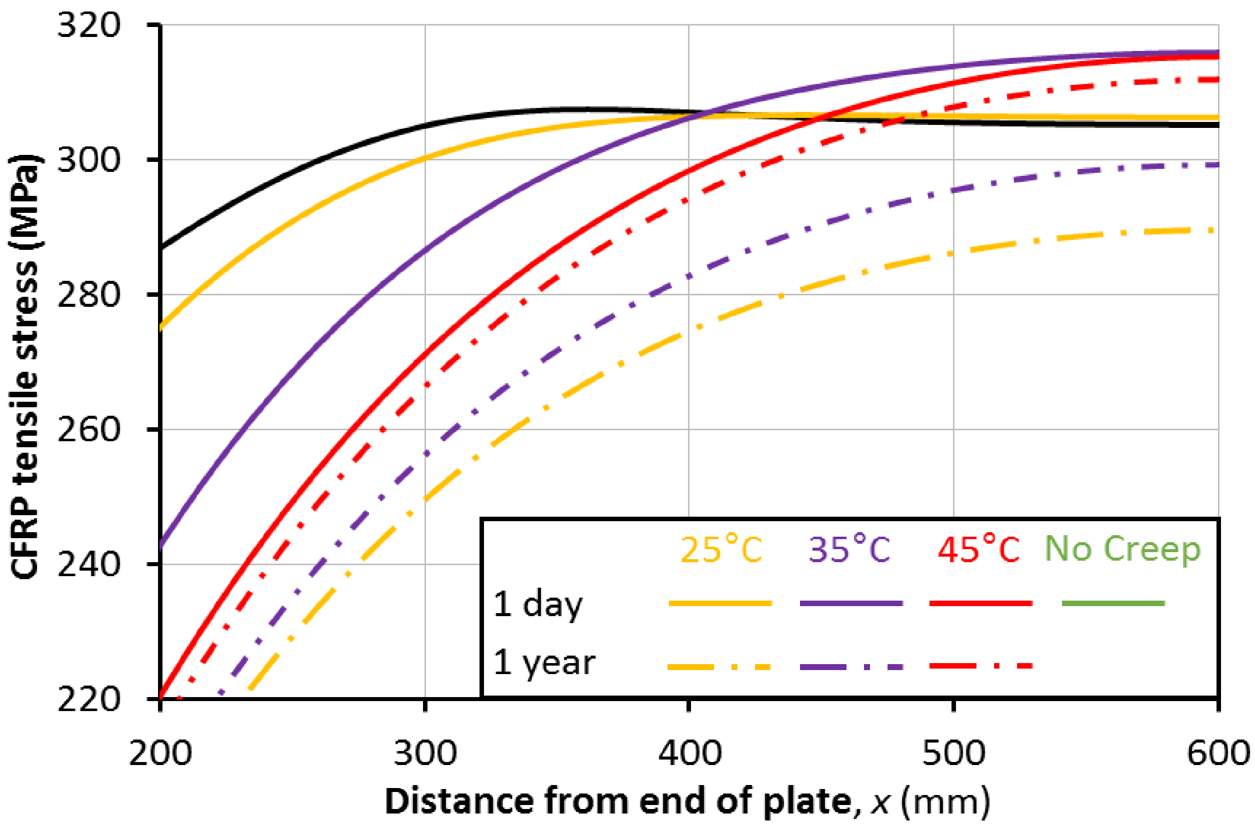
Photo from: https://northumbrianimages.blogspot.com

Add **Differential thermal expansion** and **a joint debonding criterion** into the FE model



Temperature dependent Bond-slip relation (Zhou *et al.* 2019)



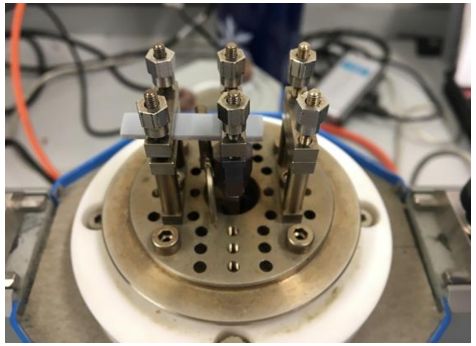


- Under warm temperatures, the damage may occur in the bonding joint.
- The D.T.E could enhance the CFRP plate stress, and maintain the effectiveness of strengthening to some extent.

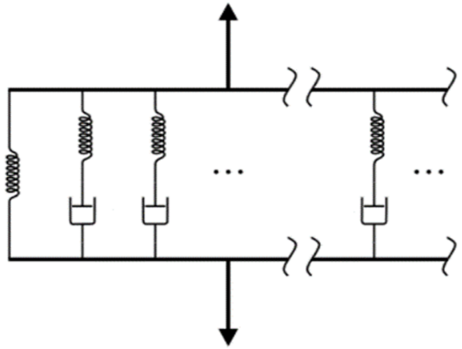
Conclusions

1) 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.
2) However, under increasing time and temperature, 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.

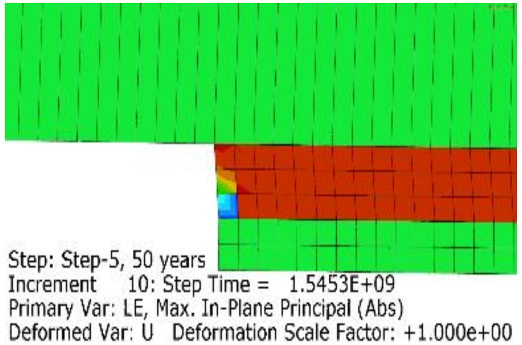
1. Experiment



2. FE Model



3. Analysis


Step: Step-5, 50 years
Increment 10: Step Time = 1.5453E+09
Primary Var: LE, Max. In-Plane Principal (Abs)
Deformed Var: U Deformation Scale Factor: +1.000e+00