Experimental study on the creep behaviour of GFRP pultruded beams

Simone LONI[1], Ioannis STEFANOU[2], Paolo S. VALVO[1]

[1]*Department of Civil and Industrial Engineering, University of Pisa - Italy*
E-mail: *simoneloni@msn.com, p.valvo@ing.unipi.it*

[2]*Université Paris-Est, Laboratoire Navier, CNRS, ENPC, IFSTTAR - France*
E-mail: *ioannis.stefanou@enpc.fr*

Keywords: Pultruded beams, fibre reinforced polymer composites, creep, Time-Temperature-Stress Superposition Principle, Findley's law.

SUMMARY. The objective of the paper is to explore the validity of the Time-Temperature-Stress Superposition Principle (TTSSP) to describe the creep behaviour of glass fibre reinforced polymer (GFRP) pultruded beams. For this purpose, an experimental programme, including both short- and long-term creep tests, has been carried out. A total of twenty pultruded GFRP beams have been tested in a 4-point bending scheme. Tests have been conducted at controlled room temperature (26°C, 32°C, 41°C) and prescribed percentage of the ultimate load (26%, 35%, 45%). Findley's law has been used to interpret the results of the short-term experiments. Then, the TTSSP has been applied to build a master curve, usable to predict the results of long-term experiments. The results demonstrate the extent of validity of the TTSSP for predicting the creep behaviour of GFRP composites, at least for the material used and the duration of the tests.

1 INTRODUCTION

Glass Fibre Reinforced Polymer (GFRP) composites are widely used in the aerospace and automotive industries. More recently, GFRP composites have also found several applications in civil engineering. GFRP composites have considerable advantages for structural applications mainly due to their high strength to weight ratio. On the other hand, some weak points limit their applicability: heterogeneity, anisotropy, durability, and creep. Creep is mainly attributed to the viscosity of the polymer matrix and to the gradual damage of the reinforcing fibres over time.

Significant experimental research has been focused on the characterisation of the creep behaviour of composite materials [1,2]. The time scale of the phenomenon in real structures is of the order of some decades. Nevertheless, the creep models mostly found in the literature are based on simple extrapolation of short-term experimental data. A more accurate prediction of the long-term behaviour of viscous materials can be obtained by means of the Time-Temperature-Stress Superposition Principle (TTSSP) [3]. The TTSSP is an extension of the Time-Temperature Superposition Principle (TTSP), initially proposed to characterise the long-term behaviour of various viscoelastic materials [4]. The TTSSP has been successfully used in the past for predicting the long-term behaviour of polymers. However, its validity for GFRP composites is not evident.

This work includes a series of nine short-term (24 hours) and one long-term (40 days) 4-point bending tests on pultruded GFRP composite beams. Creep deflection data have been acquired at the mid-span section and at the load application points. Because of the 4-point bending scheme, the beam segment included between applied loads is under bending moment only ("pure bending state"). The remaining segments of the beam, included between the load application points and the supports, are subjected to combined shear force and bending moment ("shear-bending state").

The paper follows the following structure. In Sections 2 and 3 the material tested and experimental setup are presented, respectively. Then, in Section 4 the experimental programme is described in detail. In Section 5 the TTSSP is applied and the validity of this principle is explored by juxtaposing the creep behaviour of the long-term experiment (40 days) with the prediction of the creep behaviour (master curves) obtained by the TTSSP. Finally, the deflections in pure bending and shear-bending states are compared in order to assess the effect of shear forces.

2 MATERIALS

The material tested is a GFRP composite made of glass fibres soaked in an epoxy resin matrix The selected glass fibres combine the excellent mechanical and electrical properties of traditional E glasses with the acid corrosion resistance of E-CR glass. The resin is an epoxy novolac-based resin designed to provide exceptional thermal and chemical resistance properties at higher temperatures. The volume fractions of the fibres and matrix are about 65% and 22%, respectively. The material tensile strength, evaluated through preliminary bending tests, is about 663 MPa.

The specimens are pultruded beams having rectangular cross section, 40 mm x 16 mm, and 1000 mm length (Fig. 1).

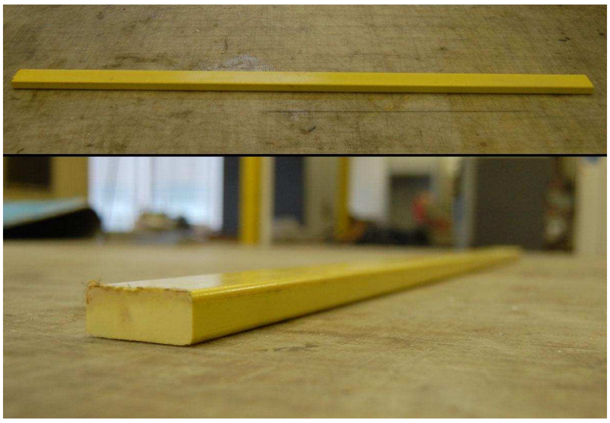

Figure 1: The specimen.

3 EXPERIMENTAL SETUP

The creep tests have been carried out using a 4-point bending scheme (Fig. 2), where two vertical loads of intensity *F* are applied at the thirds of the 600 mm total span. The experimental setup was designed according to the *European Standard EN ISO 14125:1988* [5].

The tests have been carried out on a specific custom made apparatus (Fig. 3). The metallic frame of the apparatus is made of standard steel U-profiles. The supports of the specimens are made of cylindrical tubes of 48 mm diameter. Twelve experiments can be simultaneously tested in the apparatus. The span of the specimens may be either 600 mm or 800 mm. The load is applied though levers which allow to multiply the applied weight by a factor of 7.

In the tests performed, each lever was loaded at its end by metallic plates of known weight (mass ≈ 4 kg). The loads were applied to the beams through hangers, which connected the specimens and the levers. The weight of the metallic plates before the loading was carried by hydraulic pistons. The values of the applied forces did not exceed ±1% of the target load level during each test and the hydraulic pistons made possible to smoothly apply the loads in 5 seconds.

Specific care has been taken in order to reduce as much as possible the friction at the movable parts of the apparatus and at the supports of the specimens (use of bearings and lubricant). It can be shown that the second order effects related to large deflections, the residual friction at the supports, and the self-weight of the specimens have negligible effects on the test results.

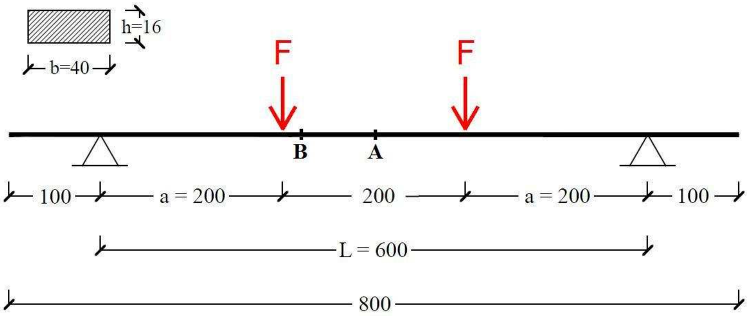

Figure 2: Schematic representation of the experimental setup.

The temperature was monitored by sensors installed in the room and close to the specimens. Three heaters, several infra-red sensors and a moisture sensor were installed in the experimental room. The variation of temperature during each test was maintained within ±2% and the average temperature did not exceed ±1% of the target temperature. This variation conforms to relevant experimental standards. Each specimen was left at the target temperature for at least 1 hour before the load application in order to assure an homogeneous temperature field.


Figure 3: Creep apparatus.

For each beam, two displacement transducers were placed at the mid-span section and at 80 mm from the mid-span section (Fig. 2, points A and B, respectively). The accuracy of such transducers was higher than 0.01 mm and the errors did not exceed ±1%. The experimental data were recorded through a computer data acquisition system by the software *LABView*.

The maximum stress was calculated by Navier's classic theory, with the bending moment M_{MAX} evaluated considering the effective span after the deformation (exact contact point).

4 EXPERIMENTAL PROGRAMME

We assume that the creep behaviour of the tested beams in the short term can be characterised through Findley's law [1]. Hence, by excluding the deflection due to elastic deformation, we have

$$\delta_c(\sigma, T, t) = m(\sigma, T) \cdot t^{n(\sigma, T)}, \tag{1}$$

where δ_c is the creep deflection, m is the amplitude of transient creep deflection, n is the time exponent, σ is the stress, T is the temperature, and t is the time.

According to the Time-Temperature-Stress Superposition Principle, each Findley short-term curve (Eq. 1) can be shifted horizontally and vertically in order to describe the evolution creep deflections at a reference stress state, σ_R, and temperature, T_R. Thus, considering the time exponent n to be stress-temperature independent, Findley's law (Eq. 1) becomes [4]

$$\delta_c(\sigma, T, t) = a_v \left[m(\sigma_R, T_R) \cdot \left(\frac{t}{a_h} \right)^{n(\sigma_R, T_R)} \right]. \tag{2}$$

The vertical shift, a_v, os equal to one because the elastic deflection is not considered, while the horizontal shift, a_h, is given by

$$a_h = \left[\frac{m(\sigma, T)}{m(\sigma_R, T_R)} \right]^{\frac{1}{n(\sigma_R, T_R)}} = \left[\frac{m(\sigma, T)}{m_R} \right]^{\frac{1}{n_R}}, \tag{3}$$

where m_R and n_R are the parameter values at the reference conditions. In a log-log diagram of creep deflections versus time, the short-term curves are shifted by –log(a_h). By performing several short-term tests in various (σ, T) states, we obtain the master curve, which describes the creep deflection in the long term.

N. Test	***T* (°C)**	***F* (N)**	***σ* (MPa)**
1	26	1450	170.1 [≈ 26%]
2	26	1994	231.8 [≈ 35%]
3	26	2589	300.3 [≈ 45%]
4	32	1450	170.1 [≈ 26%]
5	32	1994	231.8 [≈ 35%]
6	32	2589	300.3 [≈ 45%]
7	41	1450	170.1 [≈ 26%]
8	41	1994	231.8 [≈ 35%]
9	41	2589	300.3 [≈ 45%]

Table 1: Master plan.

The tests have been carried out at three room temperatures (26°C, 32°C, and 41°C) and three load levels (26%, 35%, and 45% of the ultimate load) (Tab. 1). For each test condition, two specimens have been tested. The duration of the short-term creep tests was 24 hours. The reference conditions chosen were 26°C and 26% of the ultimate load. Indeed, in civil engineering applications, FRP composite materials are usually designed for comparable stress levels. Moreover, 26°C can be considered as an average environmental temperature in many building sites. In order to investigate the validity of the derived master curve, two specimens were tested under the reference conditions for 40 days.

5 RESULTS AND DISCUSSION

According Findley's law, the creep deflections in pure bending and shear-bending states are

$$\delta_{c,i}(t) = m_i \cdot t^{n_i}, \tag{4}$$

where the subscript $i = PB$ and $i = SB$ denote the parameter values in pure bending and shear-bending states, respectively. It must be pointed out that the creep deflections in the pure-bending state [$\delta_{c,PB} = \delta_c(A) - \delta_c(B)$] are related to the mid-span deflection of an equivalent beam of length 160 mm subjected to two bending moments at both ends. Conversely, the creep deflections in the shear-bending state [$\delta_{c,SB} = \delta_c(A)$] are related to the mid-span deflection (point A) of the experimental setup (Fig. 2). In order to evaluate the values of Findley's parameters m_i and n_i, the previous equation is plotted as a straight line in bi-logarithmic scale:

$$\log \delta_{c,i}(t) = \log m_i + n_i \cdot \log t. \tag{5}$$

The values of m_i and n_i are determined by interpolation technique, neglecting the first minutes of the experimental data. It should be mentioned that a logarithmic fit of the experimental data would be better than Findley's power law fitting. However, Findley's law is simpler and handier for the shifting of the short-term experimental data. In the frame of a power law fit, in log-log plot the creep data are adapted by a bi-linear curve (Fig. 4). Yet, only the second straight line, which starts after about 30 minutes in each experiment, is considered here in for the shifting of the curves as it describes better the secondary creep stage. The R-squared value of the linear regression of the totality of the experimental data is about $R^2 = 0.92$, corresponding to a quite good fit.

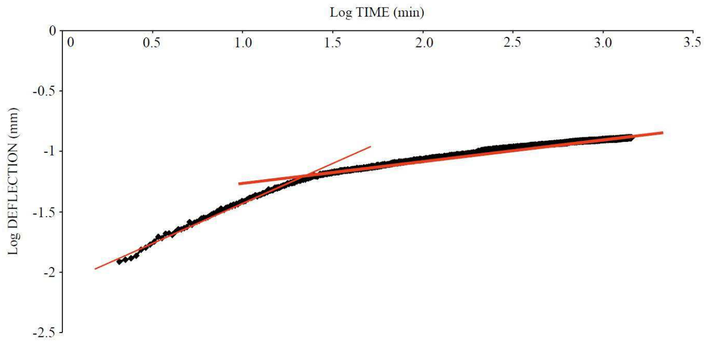

Figure 4: Bi-linear curve in bi-logarithmic plot.

For each test condition, the average values of the parameters m_i and n_i between the two specimens were calculated in order to obtain the average and characteristic short-term creep curves that are used in the following to derive the master curve. Henceforward, the parameters m_i, n_i and the relative short-term creep curves refer to the average values for each (σ, T) pair.

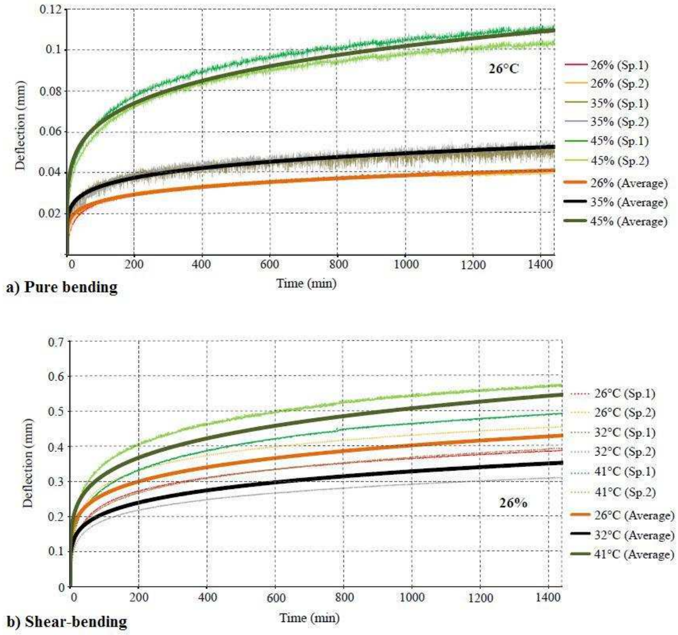

Figure 5: Creep curves of GFRP pultruded beams.

At the same temperature, the creep deformations increase with increasing stress levels in both pure bending and shear-bending states (Fig. 5a). Nevertheless, the creep deflections at the same stress level, do not seem to depend strongly on the temperature at least for the lowest stress levels (Fig. 5b). A reason for this phenomenon can be the low temperature levels with respect to the heat distortion temperature (145°C) of the resin matrix, which do not produce temperature dependence of the creep behaviour except for the highest stress level.

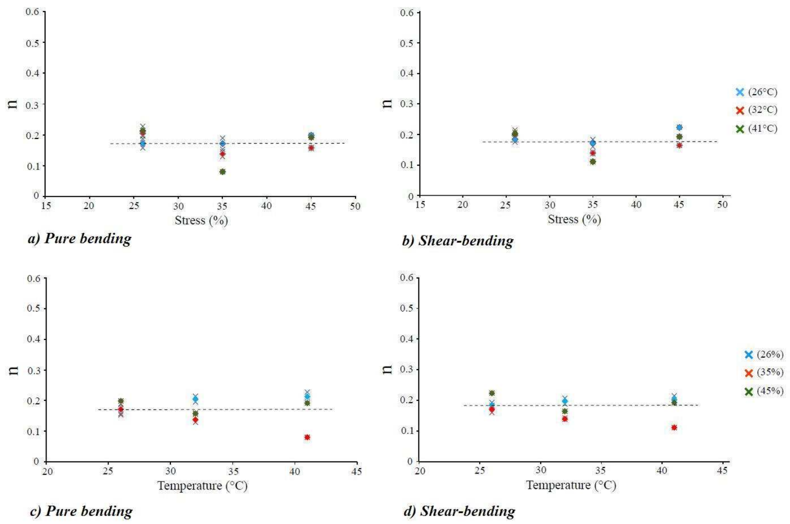

Figure 6: Variation of the time exponent *n* as a function of the stress and temperature levels.

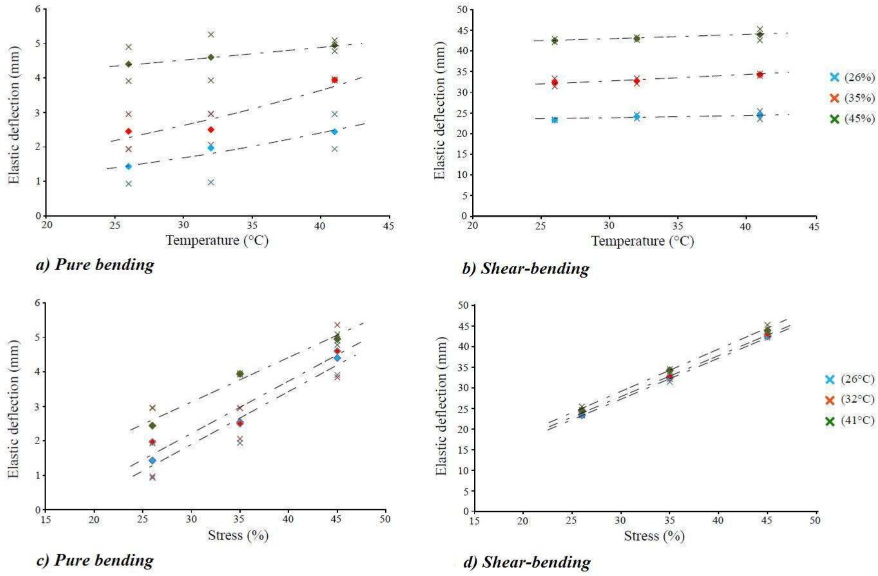

Figure 8: Variation of the elastic deflection as a function of the stress and temperature levels.

In pure bending and shear-bending states, the time exponent n_i remains almost constant with the stress levels (Fig. 6a-6b) as confirmed in [6,7] for axial stress states and in [8] for bending stress state of pultruded beams. The parameter n_i can be also considered to be temperature independent in both stress states (Fig. 6c-6d). The temperature independence of the parameters n_i agrees with the findings of [7]. On the contrary, in [6] the parameter n_i seems to be temperature dependent, which can be justified by the fact that the temperatures test therein were not far from the glass transition temperature. As shown in [6], Findley parameter m_i is a function of both stress and temperature. Furthermore, the value of m_{i} increases with increasing temperature and stress levels (Fig. 7). Likewise, the elastic deflection $\delta_{0,i}$ depends on both the stress and temperature (Fig. 8). Figure 9 presents the stress percentage (with respect to the material tensile strength) versus creep deflection of the short-term experiments at two time instances (12 and 24 hours). A nonlinear viscoelastic behaviour is observed for stress levels above 35% of the ultimate load.

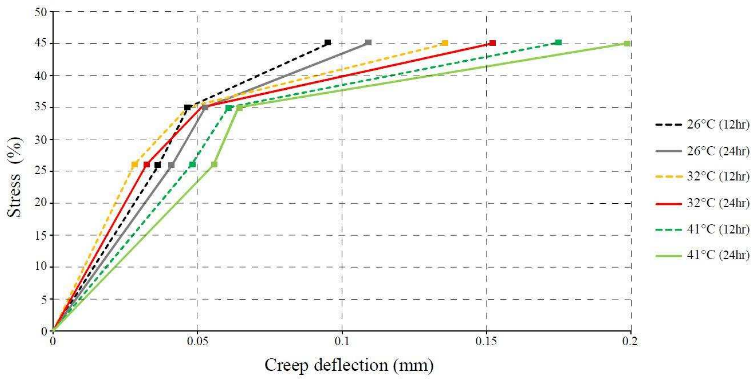

Figure 9: Stress percentage-creep deflection plot at different temperature levels and values of elapsed time for pure bending state.

	Pure bending				Shear-bending			
Test conditions	$\delta_{0,PB}$ (mm)	m_{PB}	n_{PB}	$a_{h,PB}$	$\delta_{0,SB}$ (mm)	m_{SB}	n_{SB}	$a_{h,SB}$
26% / 26°C	1.43	0.0118	0.172	**1**	23.32	0.113	0.184	**1**
26% / 32°C	1.97	0.00727	0.205	**-**	24.11	0.0843	0.197	**-**
26% / 41°C	2.44	0.0118	0.213	**1**	24.47	0.126	0.202	**0.55**
35% / 26°C	2.45	0.01514	0.1716	**0.23**	32.38	0.173	0.171	**0.099**
35% / 32°C	2.50	0.01883	0.138	**0.066**	32.74	0.225	0.139	**0.024**
35% / 41°C	3.94	0.03568	0.0806	**0.0016**	34.24	0.3613	0.111	**0.002**
45% / 26°C	4.40	0.0258	0.199	**0.011**	42.50	0.223	0.238	**0.017**
45% / 32°C	4.60	0.0482	0.158	**0.0003**	42.96	0.1642	0.401	**0.0010**
45% / 41°C	4.95	0.04912	0.192	**0.00025**	43.92	0.1925	0.472	**0.00042**

Table 2: Values of $\delta_{0,i}$, m_i, n_i and $a_{h,i}$.

The master curves, obtained through the horizontal shift factors shown in Tab. 2 and the present acceleration procedure, indicate a prediction of creep behaviour of about 11 years for pure bending state and about 6.5 years for shear-bending state. In Figure 10 we present the calculated master curves for pure and shear-bending. The master curves were obtained by interpolation of the nine short-term curves after having being shifted with the above mentioned shift factors.

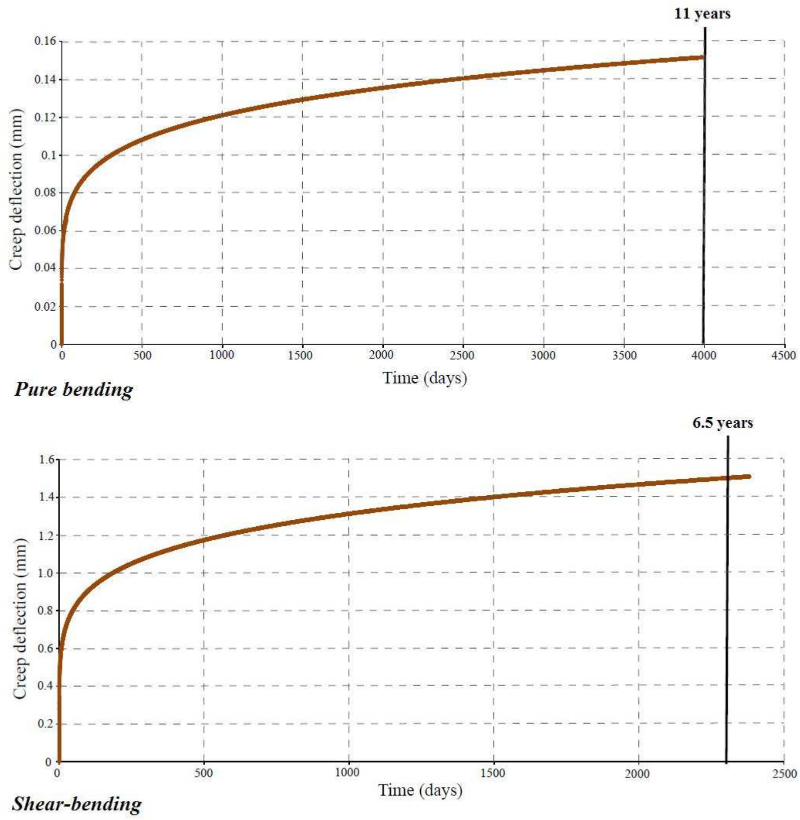

Figure 10: The master curves of creep deflection of 26°C and 26% of ultimate load.

In Fig. 11, we compare a) the experimental data in long term for 40 days, b) the master curve derived by TTSSP and c) the long-term curve by extrapolating the short-term creep data of 24 hours. The comparison points out an overall good agreement between the theoretical prediction by TTSSP and the long-term experimental data. However, the creep curve by extrapolation of short-term data (1 day) is quite misleading as it results to an overestimation of the creep deflections of about 12% in pure bending state and 13.5% in shear-bending state for the period of 40 days. This is a quite important remark for drafting standards and building codes as most of the empirical laws that are proposed in literature are based on extrapolation of short-term data (of the order of some months) to long-term behaviour (several decades). Clearly, the extrapolation of the short-term results is not an accurate method because the mechanisms of creep may evolve and change in time and/or because tertiary creep might be triggered. This holds also for the present study which investigated the applicability of TTSSP. It should be emphasised that the comparison performed herein and the good overall agreement of the TTSSP prediction with the long-term experimental results is limited to 40 days only. On the other hand, nothing guarantees that the system will remain in the secondary creep stage and that it won't become unstable (tertiary creep-failure). Such aspects should be the subject of further investigation and validation.

Finally, in the frame of Euler-Bernoulli beam theory (slender beams), the creep modulus in pure bending, E_{PB}, and shear-bending, E_{SB}, have been compared. The ratio between the aforementioned creep moduli versus time demonstrates the decrease of the creep modulus (increase of creep deformations) in the presence of shear forces. However, the effect of shear forces seems rather limited (about 1.5% after 40 days).

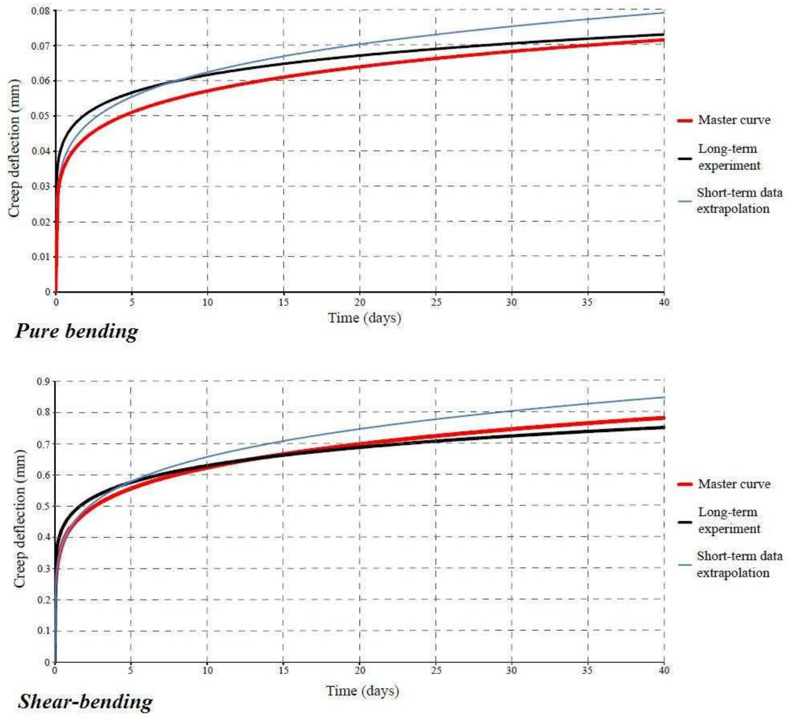

Figure 11: Comparison between experimental data in long term for 40 days, theoretical master curve and the long-term curve by extrapolation of short-term data for 1 day.

6 CONCLUSIONS

A total of twenty GFRP pultruded beams with epoxy matrix have been tested for 24 hours in 4-point bending experiments at controlled room temperature (26°C, 32°C, 41°C) and prescribed percentage of the ultimate load (26%, 35%, 45%). In order to evaluate the effects of shear forces, we have distinguished the creep responses of the segments of the beam subjected to bending moment only (pure bending) and combined shear and bending moment (shear-bending).

The creep responses of the tested GFRP pultruded beams are quite well fitted by Findley's power law. The Findley's law time exponent n_i turns out to be independent of temperature and stress. On the contrary, the parameter m_i depends on both temperature and stress. The trends of the parameters m_i and n_i are in agreement with previous experimental tests present in the literature [6,7,8], even though the materials tested here are not the same.

By applying the TTSSP, the master curves for the pure bending and shear-bending states have been determined for a reference state of 26°C and 26% of the ultimate load. The acceleration procedure indicates a prediction of the creep behaviour of about 11 years for the pure bending state and more than 6.5 years for the shear-bending state, based on the 24-hour tests.

In order to explore the validity of the TTSSP, a long-term experiment has been carried out at reference conditions for 40 days and juxtaposed with the theoretical master curve. The comparison shows an overall good agreement at least for the period of 40 days. Moreover, the master curve predicts better the viscoelastic behaviour in the long term compared to the simple extrapolation of the 24-hour short-term test data. Nevertheless, for a reliable application of the TTSSP in the framework of proposing new guidelines for creep prediction, further experimental results should be obtained on different materials and conditions.

Lastly, we observe that the effects of shear forces on the creep behaviour has been rather limited (about 1.5% reduction of the creep modulus after 40 days).

References

[1] Findley, W.N., "Creep characteristics of plastics", in *Symposium on Plastics*, American Society for Testing and Materials, Philadelphia, PA, 118–134 (1944).

[2] Schapery, R.A., "On the characterization of nonlinear viscoelastic materials", *Polymer Engineering & Science*, **9**(4), 295–310 (1969).

[3] Leaderman, H., "Elastic and creep properties of filamentous materials and other high polymers", *The Textile Foundation*, Washington, DC (1943).

[4] Griffith, W.I., "The accelerated characterization of viscoelastic composite materials", PhD Thesis in Mechanical Engineering, Virginia Polytechnic Institute, Blacksburg, VA (1980).

[5] EN ISO 14125:1998, *Fibre-reinforced plastic composite – Determination of flexural properties*.

[6] Yen, S.-C. and Williamson, F.L., "Accelerated characterization of creep response of an off-axis composite material", *Composite Science and Technology*, **38**(2), 103–118 (1990).

[7] Ma, C.C.M., Tai, N.H., Wu, S.H., Lin, S.H., Wu, J.F. and Lin, J.M., "Creep behavior of carbon-fiber-reinforced polyetheretherketone (PEEK) $[\pm 45]_{4s}$ laminated composites", *Composites Part B: Engineering*, **28**(4), 407–417 (1997).

[8] Sá, M.F., Gomes, A.M., Correia, J.R. and Silvestre, N., "Creep behavior of pultruded GFRP elements – Part 1: Literature review and experimental study", *Composite Structures*, **93**(10), 2450–2459 (2011).

[9] Loni, S., *Experimental and theoretical study on the creep behavior of GFRP pultruded beams*, MSc Thesis in Civil Engineering, University of Pisa, Pisa, Italy (2013).