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This paper first presents a state-of-the-art review about the viscoelastic time-dependent – creep behavior of fibre reinforced polymer (FRP) materials in general, and pultruded glass fibre reinforced polymers (GFRPs) in particular, at different element scales. The literature review aims at pointing out the present gaps regarding the understanding of this phenomenon and guiding the future developments lines for the application of pultruded GFRP in civil infrastructure, including bridges and buildings. The paper then presents results of experimental investigations carried out on pultruded GFRP material made of polyester and E-glass fibres at two different scales: (i) laminate and (ii) full-scale profile. The test programme included (i) flexural creep tests on 8 mm thick small-scale specimens with a span of 160 mm, subjected to sustained loads corresponding to stress levels ranging from 20% to 80% of their ultimate stress; and (ii) a flexural creep test on an I-profile (150 × 75 × 8 mm) with a span of 1800 mm, subjected to a constant load of 1/3 of its ultimate load. The deflections and axial strains over time, measured in laboratory environmental conditions, were recorded for time durations up to 1600 h. The results obtained confirm an important effect of the creep phenomenon on pultruded GFRP profiles, with small-scale specimens having failed for load levels as low as 50% of the ultimate stress; in addition, the creepocity measured on both types of elements was quite significant after the first hours, even for an average load level of 30%. Subsequently, the experimental results were used for material characterisation by means of empirical and phenomenological formulations (Part 2).
1. Introduction

Pultruded glass fibre reinforced polymer (GFRP) profiles have great potential as construction materials due to a number of advantages that include lightness, strength, easy and rapid installation, improved durability under aggressive environments, good thermal and acoustic insulation and electromagnetic transparency [1]. Currently, there are several examples of the structural application of GFRP profiles in the construction of buildings and bridges, in both new construction and rehabilitation [2–5]. However, the high initial costs and the susceptibility to creep phenomena constitute major and legitimate concerns associated with the use of these materials in construction – the latter are also driven by the limited age (10–25 years) of most of these applications, since a service life of at least 50 years is normally required for most civil engineering structures.

The polymeric nature of the matrix of GFRP profiles is responsible for their susceptibility to creep. Over the last years, several studies have addressed the time-dependent mechanical behavior of FRP composites [3], yet, only few of them were carried out on the flexural creep behavior of GFRP structural elements subjected to bending. The purpose of this paper is to study in further depth the flexural creep behavior of pultruded GFRP profiles used in civil engineering structural applications, contributing with additional information on this important aspect of their behavior. The first part of this paper provides a brief state-of-the-art review of previous research related to the viscoelastic behavior of FRP composites in general, and pultruded GFRP profiles in particular. The main goal of this literature review is to provide an update of the most relevant research carried out during the past two decades on the creep behavior of pultruded GFRP elements, including those subjected to bending at different material scales. The second part of this paper describes an experimental study about the creep behavior of pultruded GFRP elements in bending: creep tests were carried out at two material scales – laminates and beam profiles – in order to investigate the viscoelastic nature of the GFRP material at a linear creep regime.

2. Literature review – Creep phenomenon

Most of the research on the time-dependent behavior of FRP materials has been performed in the military and aerospace industries, and addressed the viscoelastic behavior of laminated composites [6], most of them manufactured using processes other than pultrusion. Those industries present significant additional differences compared to civil engineering applications with regard to the load level in service conditions, the types of laminated material, the fibre architectures, the environmental conditions and the design procedures [5].

This section presents and discusses the most relevant studies on the creep behavior of pultruded GFRP composites, specifically targeted for civil engineering infrastructure applications – these studies focus both on the experimental characterisation of the material and the development of analytical formulations. The literature review gives particular attention to flexural and compression loading, which was adopted in most studies performed about the creep phenomenon on pultruded composites at full-size elements (with uni and bidirectional structural behavior). It is worth mentioning that most investigations referred here were published after 1995, when an extensive review was presented by Scott et al. [3].

2.1. Flexural loading

Daniali [7] analyzed the influence of the resin nature (polyester and vinylester), the temperature (at room and at 54 °C) and the geometry of T-shaped GFRP pultruded beams (solid and with cavity webs) on their short- and long-term flexural behavior. The beams were tested in bending, in a two-span setup, subjected to uniformly distributed loads. Failure of the solid web lintels occurred due to lateral-torsional buckling and failure of the cavity web lintels was triggered by buckling and cracking of the web. As expected, the ultimate loads decreased with the increase of temperature, and for the profiles made of polyester such variation was more relevant for the solid web lintels (38%) than for those with cavity webs (28%). Such relative difference was lower for the vinylester lintels. Creep tests were carried out at the two above mentioned temperatures with both types of T-lintels loaded to 50% of their respective ultimate load, over periods of 5000 and 10,000 h, for solid and cavity web members, respectively. For the solid web lintels, the results indicated a creepicity (rate of creep deflection) that was almost twice in the polyester reinforced lintels than in their vinylester counterparts. The creep deflection of both cavity web lintels remained very similar after 10,000 h of testing (around 17.5% of their static deformations). At elevated temperature, another set of creep tests was conducted for load levels of 50%, 60%, and 80% of the beams ultimate load. In general, the vinylester composite beams proved to have a much better long-term serviceability performance when compared with their polyester counterparts. For instance, for a load level of 80% (at 54 °C), failure of the polyester lintels occurred in less than 10 h, while the vinylester lintels failed after more than 50 h. In both cases the author reported larger creep deflections compared to those measured at room conditions. It was concluded that under sustained loading conditions polyester beams suffer greater reductions in strength, stiffness, behave worse and are less predictable than vinylester beams, particularly at high temperatures.

Experiments performed by Bank and Mosallam [8] examined the short-term failure behavior and the long-term creep response of pultruded GFRP wide flange sections (E-glass/vinylester resin), namely a full-scale frame structure assembled from one beam and two columns with the following plane geometry – 1800 mm high by 2700 mm wide. During 10,000 h, the frame was loaded to a constant load of 70 kN in 4-point bending, about 1/4 of its static failure load. The short-term test results showed linear-elastic behavior until some critical section after which irreversible damage to the frame led to nonlinear response. After several loading/unloading cycles, once the ultimate failure of the portal frame was achieved, the connections between the columns and the traverse beam were the first points to fail, which was followed by the rupture of the compression flange of the beam. The results of creep tests revealed a greater creepicity over the first 2000 h, after which the creep rate remained nearly constant. For instance, the girder midspan deflection increased 12.8% after 3500 h and approximately 22% over the total test duration. A theoretical empirical model, namely Findley’s power law [9], was employed to predict viscoelastic stiffness in a shear-deformable beam theory. In others words, this pioneer study was one of the first attempting
to provide practical formulae for the time-dependent full-scale longitudinal flexural modulus and full-scale shear modulus, regarding the fulfillment of service limit states (SLS) requirements for civil infrastructure applications. The authors reported a decrease of 35% and 46% in those moduli over a 10-year sustained loading. The predictive models were in good agreement with creep deformation data from short-term creep tests (3500 h), and thus were suggested to be used to describe the long-term viscoelastic response of GFRP structures.

In another important research, reported in [10] by Mottram, the short- and long-term structural stiffness properties of entirely pultruded GFRP beam assemblies were studied. The beam assemblies (2 units) were produced from coupling one pair of I-sections in-between outer flat GFRP plates, using a 0.5 mm thick layer of adhesive. Each beam, with a length of 735 mm, had a closed-section with nominal dimensions of 76 × 50 mm joining two I-profiles (76 × 38 × 6.25 mm) and two 6 mm thick flat sheets. An assembled beam was tested under quasi static 3-point bending in a span of 700 mm. The author attributed the short-term stiffness reduction (of nearly 10%) when compared with the stiffness capacity of the original pultruded sections (which was obtained using linear elastic beam theory and a rigid adhesive) to the adhesively bonded connection system of the assembly. Although creep tests had been conducted only for 24 h (at normal room conditions), according to Mottram the creep behavior was similar to that referred in [8]. Likewise, expressions for the time-dependent viscoelastic moduli (tensile and shear creep format) were achieved based on Findley’s law model. These moduli were then coupled into Timoshenko’s beam theory to estimate the creep deflection over time, as well as to predict the above-cited viscoelastic properties, using the data recorded from the “accelerated” long-term test. The midspan creep-to-initial deflection ratio of an assembled (bonded) beam had an increase of 25%, 60% and 100% after 1 week, 12 months and 10 years, respectively.

Barpanda and Raju [11] evaluated the effect of hybridization on the creep and stress relaxation characteristics of pultruded composite (E-glass–graphite/epoxy hybrid composite). The authors tested a set of small-coupons subjected to a combination of static and dynamic bending load conditions, at temperatures of 60 °C–140 °C for a load duration of 1/2 h and a recovery duration of 1/4 h. Due to the very short-term duration of the tests, they applied a Time–Temperature Superposition Principle (TTSP) to predict the long-term response of the hybrid composite. As an important conclusion, the authors noted the dependence of the flexural creep compliance and relaxation modulus on the fibre type and architecture configuration of the hybrid composite.

The long-term creep viscoelastic properties of two different types of polymeric materials were reported by Bradley et al. [12]. They examined the effect of the curing conditions and compared the creep response of post-cured neat and glass-reinforced polyester and vinylster. The experimental programme included flexural creep tests on coupons for a period of 10,000 h at room conditions. The results of experimental data were used to model the creep response based on Findley’s power law. It was shown that the increase in the time and/or temperature of curing led to a decrease in the parameter n. In other words, the creep performance of the specimens improved with the temperature and duration of resin curing, which provided more complete cross-linkings in the polymers. Exponent n and creep phenomenon in the polyester coupons were higher than in the vinylster coupons. Finally, the influence of including the reinforcement in both types of samples was also studied – while the n exponent did not vary significantly with the fibre reinforcement, the magnitude of creep decreased significantly.

Concerning E-glass reinforced polymer composites, also produced by pultrusion, Abdel-Magid et al. [13] studied the long-term creep behavior and creep–rupture flexural properties of two types of GFRP – polyurethane (PU) and epoxy (EP) – composites. 3-Point bending creep tests were performed on both material systems at room temperature and at 50 °C. While the composite systems showed similar short-term flexural properties, those were notably different at long-term. For instance, the PU composite exhibited tertiary creep–rupture in a few hours under 75% and 57% of its flexural strength, respectively at room temperature and at 50 °C. On the other hand, for the same temperature conditions the EP composite showed higher resistance compared to the PU composite even for higher loading levels. The authors pointed out the effects of the shear properties of the polymeric matrix and the fibre/matrix interface strength on creep-rupture ultimate strength. The bending test proved to be a reasonable method to obtain the creep-rupture properties of composites; however, as noted by the authors, the bending test may not be the best due its susceptibility to shear deformation in the polymeric material.

One of the first studies to include the influence of the viscosity effect due to shear deformation in the prediction of long-term displacements was published by Shao and Shammugam [14]. The authors explicitly used a power law expression for deflection creep type to investigate the time-dependent flexural creep behavior of pultruded composite sheet piling. Two panels made of polyester reinforced with E-glass rovings and mats were tested under 3-point bending in a span of 6100 mm. In each panel the applied load corresponded to 25% and 50% of the maximum load. Three types of creep response (displacements, axial tensile and shear strains) were monitored over a time period of 1 year. For the load levels at stake, the authors analysed the time-dependent axial tensile and shear deformations based on the assumption of the simplified Findley’s model. Accordingly, the time-dependent tensile and shear moduli were used to predict creep deflections using Timoshenko’s beam theory, these were compared to experimental data and results were then fitted by Findley’s model. A good agreement was obtained between the time exponents in the empirical models of the three different mechanical parameters (axial tensile, shear and deflection creep), allowing the authors to determine the creep deflections based on Timoshenko’s beam equation, that resemble the Findley’s power law by using averaged viscoelastic parameters. As an important conclusion, it is worth mentioning the contribution of shear creep on the long-term deflection, whose magnitude to the total creep deflection tripled up to 1 year when compared to its effect on the total instantaneous static displacement. Moreover, the expressions obtained for the time-dependent tensile and shear moduli indicated reductions of viscoelastic stiffnesses after 30 years of 68% and 36%, respectively, compared to the corresponding elastic values. Over the same period, the creep deflection increased 50%.

2.2. Compression loading

With regard to compressive loading, Spencer [15] carried out creep tests at room temperature on unidirectional glass/epoxy pultruded rods (6.35 mm of diameter and 19.0 mm of length), loaded to 30% of their material ultimate strength. The author concluded that for a test duration of 840 h the small percentage variation of the axial strain (0.4‰) had a negligible effect on the dimensional stability of the rod. This conclusion was supported by the mean axial strain prediction over 10 years based on the experimental data, which allowed determining the viscoelastic effects on the pultruded rod under compressive loading.

An extended experimental work on the creep behavior of pultruded FRP column angles was presented by McClure and Mohamadi [16]. Creep tests were carried out on two series of test members, with different element scales, both composed of isophthalic polyester resin reinforced with mats and rovings of E-
glass fibres: (i) angle stubs with cross-section dimensions of 50.8 × 50.8 × 6.4 mm, 152.4 mm long and (ii) small-coupons 31.75 mm long, 12.7 mm wide and 6.35 mm thick, taken from the strong leg of the angle stubs. Each type of element was loaded to approximately 45% of its respective short-term failure load (local buckling stress for angle stubs and ultimate stress for small-specimens), for a time duration of 2500 h in creep and 250 h in creep recovery, in normal laboratory conditions. Before unloading the average creep-to-initial elastic strains ratio was 14.4% in the stubs and 13.8% in the coupons, with about half of such increase having occurred in the first 24 h. At the end of the recovery stage, an average of 67% and 54% of the creep strain was recovered in the stubs and coupons, respectively. Findley’s power law was used to estimate the creep deformation of both element types, with a good agreement being achieved between the experimental data and the estimated results over the entire test duration. The authors noted a substantial difference on the average value of the n exponent from the power law obtained from the stub and coupon tests (0.170 and 0.254, respectively). No clear explanation for this variation was provided by the authors, although it was recognised that the applied stress in the small-coupons was 3.3 times higher than in the angles (each one with different absolute values). One of the main conclusions pointed out by the authors was that there is no real benefit in testing full-sized pultruded sections over small-specimen tests, taking into account the good correlation of the predictions between both data scale results.

Scott and Zureick [17] conducted experimental and analytical investigations on the compression creep of a pultruded E-glass/ vinyl ester composite. Only small-scale coupons with geometric dimensions of 102 × 102 × 6.35 mm were subjected to longitudinal compressive loads, at three stress levels (20%, 40% and 60% of the short-term ultimate compressive stress), for a time duration up to 10,000 h. Using the test data measured over 1 year, the experimental results were successfully fitted to a practical power law expression. For applied-to-ultimate stress ratios of 20%, 40% and 60% the strain creepacity was in average 12.75%, 13.07% and 12.20%, respectively, after 5000 h of test duration. Moreover a straightforward design formula was proposed to predict the time-dependent longitudinal modulus, on the basis of the parameters obtained from an approximated power law model, and it provided an excellent agreement when compared to the exact (higher order) expression – the authors evaluated relative differences lower than 4%. In addition, they estimated the reduction of viscoelastic stiffness to be as much as 20% after 75 years.

Dutta and Hui [18] performed a study about the tension and compression behavior of glass–fibre reinforced polyester composite material under sustained loads (60–80% of ultimate stress) at three temperature levels (25 °C, 50 °C and 80 °C). The test material consisted of GFRP plates with a nominal thickness of 6.35 mm. At room temperature the creep test was carried out during 1/2 h and at elevated temperatures tests were run until failure of the coupons, which typically occurred within 1 h after applying the load. The researchers applied a Findley’s law approach to fit experimental data, in which a semi-empirical model coupled in a time–temperature superposition model allowed predicting the time-to-failure. In this study, the parameters of Findley’s model were replaced with functions of time and temperature ratios, and the proposed expression matched very well with many characterisation creep curves published in the literature.

Choi and Yuan [19] investigated the time-dependent deformation of pultruded GFRP composite columns under axial-compressive loading tested under laboratory conditions, with controlled and constant temperature and relative humidity. Opened- and closed-cross section columns were experimentally examined (WF and box shapes) with dimensions of 102 × 102 × 6.4 mm and a length of 1200 mm. The results of the experiments compared well with predictions from empirical Findley’s law model, for time duration up to 2500 h. According to the authors, the total compressive creep strains were found to increase on average by 30% and 50% of their initial elastic deformations in the first hour and day, respectively. Compressive viscoelastic modulus was obtained as a function of time, based on Findley’s linearisation theory, showing accurate estimates for the range of stress levels applied in their investigation (20–50% of the short-term ultimate compressive strength). The time-dependent compressive elastic modulus was evaluated on GFRP columns at several years elapsed from the sustained axial load application – the authors estimated a reduction of about 30% of the initial value at 50 years.

2.3. Summary

Table 1 summarises and compares the above mentioned studies in a chronological order with respect to the types of loading, test duration, material constitution, element scale. Regarding the type of loading, it can be seen that almost no studies are reported in the literature about the creep response in tension of pultruded GFRP components, e.g., as tensile tendon, bar, cable, etc.

Other recent studies have been conducted on the creep behavior of pultruded GFRP, mainly under compressive loading combined with other effects, such as the influence of creep on the structural stability, at normal and/or elevated service temperatures [20,21]. In columns, sustained axial loads at elevated service temperatures (up to 65.5 °C) can significantly reduce the longitudinal stiffness and trigger nonlinear elastic lateral deflection and ultimately to buckling failure. When combined with fire loading conditions, the compression creep behavior has been characterised by laminated theories including phenomenon of the thermo-viscoelasticity nonlinearity during glass transition [22].

In brief, although several studies were carried out on the creep behavior of GFRP composites, there have only been a few experimental studies on the flexural creep of pultruded GFRP members. Moreover, most experimental tests performed in bending have focused on small-coupons or relatively short specimens, instead of full-sized structural elements, and for short-durations of testing. In this context, the aim of the present study, divided in two parts, is to contribute for engineering creep characterisation of pultruded GFRP composites required for bridge and building infrastructure applications under long-term sustained loads, corresponding to typical service conditions.

3. Experimental programme

The pultruded GFRP profile used in the experimental programme was produced by TopGlass and consists of an I-section with the following nominal dimensions: height – 150 mm, width – 75 mm, equal web and flange thickness – 8 mm. The pultruded profile is made of an isophthalic polyester matrix reinforced by alternate layers of E-glass rovings and mats. The first part of the experimental programme aimed at evaluating the time-independent static properties of the pultruded GFRP profile and comprised mechanical tests on small-scale GFRP coupons (laminates) and full-scale beam elements. In the second part of the experimental programme creep tests were carried out at those two element scales, and the load levels were defined based on the values of the ultimate stress determined in the first part of the test programme.

3.1. Static tests

3.1.1. Laminated material – Specimens tested

At the laminate scale level, the mechanical characterisation of the pultruded GFRP material was achieved through different types
of tests performed on small-coupons cut from the web and flanges of the I-section profile, namely tensile, compressive, flexural and interlaminar shear tests (cf. Fig. 1). Burn-off tests were also carried out to determine the inorganic content by weight of the GFRP material – all tests were performed according to standards [23–28].

3.1.2. Structural beam elements

At the structural element scale, the flexural behavior of the I-section pultruded profile was characterised by testing two beams (IS-1 and IS-2) under 4-point bending in a span of 1800 mm. Fig. 2 shows the experimental setup adopted in the beam quasi-static test – simply supported beam model. The test setup included the following elements: a closed steel loading frame; a metallic distribution H-profile; an Enerpac hydraulic jack with a load capacity of 200 kN and a stroke of 155 mm; TML displacement transducers with a stroke of 50 mm and precision of 0.01 mm; strain gauges placed in the web and flanges at different cross-sections; beam support system materialised by steel rollers (50 mm diameter) placed in-between steel plates. In order to prevent lateral displacements, both beams were laterally restrained at midspan section with a transverse bracing system and beam IS-1 was also restrained at the support sections, as detailed in Fig. 2b – lateral restraint was provided by steel angle sections (50x50/C2x30/C2x6 mm) positioned throughout the entire height of the profile.

All flexural tests were carried out under a load controlled speed rate of approximately 0.15 kN/s. The beams were first subjected to two loading-unloading cycles, in which they were loaded up to approximately half of the estimated failure loads. Subsequently, the beams were monotonically loaded until failure. The applied load, the deflections at midspan and at the loaded sections as well as axial strains were measured and registered in a PC using an HBM data acquisition system with 100 channels.

Table 1

<table>
<thead>
<tr>
<th>Authors</th>
<th>Material pultruded</th>
<th>Element scale</th>
<th>Loading type</th>
<th>Test duration</th>
<th>Observations (analysis)</th>
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<tr>
<td>Spence (1990)</td>
<td>Glass/epoxy</td>
<td>Short-rod</td>
<td>Compression</td>
<td>840 h</td>
<td>Long-term deformation and viscoelastic effects on dimensional stability</td>
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<td>Daniali (1991)</td>
<td>Glass/poly-vinylester</td>
<td>Beam-lintel T</td>
<td>Flexural</td>
<td>10,000 h</td>
<td>Influence of resin, temperature, geometry of T-shaped beam on long-term creep</td>
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<td>Bank and Mosallam (1992)</td>
<td>Glass/vinylester</td>
<td>Full-size frame H</td>
<td>Flexural</td>
<td>3500–10,000 h</td>
<td>Modelling $E(t)$ and $G(t)$ moduli using tensile and shear creep-strain data</td>
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<td>Mottram (1993)</td>
<td>Glass/polyester</td>
<td>Beam assembly II</td>
<td>Flexural</td>
<td>24 h</td>
<td>Creep behavior similar to reference in [8] creep moduli and creep deflection (overall)</td>
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<td>McClure and Mohammad (1995)</td>
<td>Glass/polyester</td>
<td>Prismatic coupon short stub I</td>
<td>Compression</td>
<td>2500 h</td>
<td>Evaluation of creep deformation at two scales (exact and simplified power law)</td>
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<tr>
<td>Scott and Zureick (1998)</td>
<td>Glass/vinylester</td>
<td>Prismatic coupon</td>
<td>Compression</td>
<td>10,000 h</td>
<td>Findley's linearised model up to 0.6ηu design formula $E(t)$ for stiffness at t</td>
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<td>Barpanda and Raju (1999)</td>
<td>Glass-graphite/epoxy</td>
<td>Small-coupon</td>
<td>Flexural</td>
<td>30 min</td>
<td>Hybridization effect on creep and stress relaxation characteristics applying TTSP</td>
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<td>Bradley et al. (1998)</td>
<td>Neat and glass/poly-vinylester</td>
<td>Small-coupon</td>
<td>Flexural</td>
<td>10,000 h</td>
<td>Effect of curing conditions and comparison of creep response: neat polymer vs. GFRP</td>
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<tr>
<td>Choi and Yuan (2003)</td>
<td>Glass/polyester</td>
<td>Long column H long square tubular column</td>
<td>Compression</td>
<td>2500 h</td>
<td>Evaluation of time-dependent deformation; prediction of compressive modulus at t</td>
</tr>
<tr>
<td>Shao and Shanmugam (2004)</td>
<td>Glass/polyester</td>
<td>Sheet piling U</td>
<td>Flexural</td>
<td>9000 h</td>
<td>Time-dependent behavior for three types of creep: tensile, shear and deflection (coupling)</td>
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</tbody>
</table>

Fig. 1. (a) Interlaminar shear, (b) compressive, (c) flexural, and (d) tensile tests.
3.2. Creep tests

A set of coupon specimens, extracted from the original profile, were tested in 3-point bending and a full-section profile was tested in 4-point bending, in order to characterise the long-term mechanical and structural behavior of the GFRP pultruded material at two different scales – laminated material (small-scale specimens) and beam (structural element), respectively. All tests were carried out during a period of approximately two months. This experimental work was conducted in the laboratories of IST, under normal laboratory environmental exposure, with small temperature and humidity variations.

3.2.1. Laminated material – Specimens tested

As for the determination of elastic properties, the long-term characterisation of an orthotropic material, in particular in what concerns creep, involves obtaining the viscoelastic properties of the material when subjected to multiple solicitations and in different directions [6]. This viscoelastic characterisation can be performed based on derivations of the theoretical formulation of the classical laminate theory (CLT) [29], coupled with physical empirical models, numerical methods [3,4,30] or, as an alternative, through experimental tests.

The latter approach was adopted in the present study – flexural tests were carried out in the principal direction of the reinforcement (longitudinal, L), according to test standard ISO 899-2 [31]. Two sets of seven small-scale coupons – 240 mm long, 15 mm wide and 8 mm thick – taken from the laminated plates (flanges and web) that constitute the I-profile were tested. The simply supported specimens were tested under 3-point bending during 1200 h. Specimens were tested for different load levels, corresponding to maximum stresses ranging from 20% to 80% (110–440 MPa) of the material’s ultimate flexural stress (cf. Table 2, global av.).

The span-to-thickness ratio of the specimens’ cross-section adopted (160/8 – 20) was sufficiently high to prevent tertiary creep failure by interlaminar shear and, in addition, to minimise the effect of shear deformation. Specimens were labelled using a reference that consists of a combination of one letter and one number – the letters refer to the part of the profile, where the laminate was extracted (W – web; F – flange), while the numbers refer to the different load levels, defined as a percentage of the GFRP material’s ultimate flexural stress (20–80%). As an example, specimen F-40 stands for a laminate extracted from the flange subjected to a load level of 40%.

The sustained loading system was materialised through the suspension of metallic pieces, previously grouped to ensure the predefined load level. To this end, two pairs of steel frames were positioned in parallel to each other – their relative distance (160 mm) defined the test span. These frames were connected at their base by a transverse beam, which guaranteed the stability of the assembly. Fig. 3 shows details of the test setup used in these experiments: (a) top beams of a pair of frames, used to support the test specimens; (b) threaded rod between frame columns for adjusting and setting the previous distance, increasing the stiffness of the system and avoiding deflections of the main frames; and (c) ø12 oval metal ties, used to suspend the metal weights.

The measurement of deflections in the load application section was achieved using analogous displacement transducers of TML (stroke between 10 and 50 mm and precision between 0.001 and 0.01 mm) – their pistons were centred in the upper zone of the ties’ latches, in which a slight indentation had been previously performed by drilling. This procedure prevented slippage between the cylindrical surface of the anchor and the measurement devices during the load application process.

In addition, all specimens were instrumented with electrical strain gauges of Vishay, which were attached to the bottom surface of the specimens at their midspan section. The axial deformations were monitored using a data logger from VishayEllis – the strains recording was done manually by direct reading of the values displayed on the data logger LCD screen. The data acquisition program roughly followed the time spans defined in ISO 899-2 for non-automated registration: 1, 3, 6, 12 and 30 min; 1, 2, 5, 10, 20, 50, 100, 200, 500, 1000, etc. h. The specimens were loaded sequentially – the load application process, which involved applying several weights, took place relatively quickly (during 1–5 s).

3.2.2. Structural beam element

The time-dependent creep tests were carried out on an I-section GFRP profile (beam IC-3), subjected to bending, simply supported and without any lateral constraints. The beam was loaded in a 4-point bending setup – the two transverse loads were applied symmetrically, at approximately thirds of the 1800 mm span. As re-

Table 2

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<td>Web</td>
<td>σu/Fmax (MPa)</td>
<td>418.1 ± 11.6%</td>
<td>538.8 ± 6.7%</td>
<td>460.7 ± 4.3%</td>
<td>129.6 ± 4.2%</td>
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<td>E (GPa)</td>
<td>25.1 ± 7.4%</td>
<td>25.0 ± 4.5%</td>
<td>28.4 ± 21.8%</td>
<td>7.7 ± 26.8%</td>
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<td>Flange</td>
<td>σu/Fmax (MPa)</td>
<td>431.4 ± 10.8%</td>
<td>560.3 ± 5.0%</td>
<td>438.6 ± 7.6%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>E (GPa)</td>
<td>246.6 ± 4.6%</td>
<td>257.7 ± 4.5%</td>
<td>27.2 ± 16.2%</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Global</td>
<td>σu/Fmax (MPa)</td>
<td>424.8 ± 10.8%</td>
<td>550.0 ± 6.0%</td>
<td>450.0 ± 6.5%</td>
<td>129.6 ± 4.2%</td>
<td>39.4 ± 6.5%</td>
</tr>
<tr>
<td>E (GPa)</td>
<td>24.9 ± 6.0%</td>
<td>25.3 ± 4.6%</td>
<td>27.8 ± 19.0%</td>
<td>7.7 ± 26.8%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>c_u [%]</td>
<td>17.3 ± 13.8%</td>
<td>24.4 ± 8.3%</td>
<td>27.6 ± 10.8%</td>
<td>31.2 ± 9.7%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Inorganic content [%]</td>
<td>Calcination [ISO 1172]</td>
<td>Web – 61.1</td>
<td>Flange – 62.8</td>
<td>Global – 61.9 ± 1.7%</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
ferred, the test configuration adopted was similar to that used in failure tests conducted earlier by the first author [4], and fulfilled recommendations drawn in test standard EN 13706 [32]. This flexural test aimed at evaluating the creep behavior of the beam element under a constant load of 22.8 kN, which corresponds to 33% of the beam’s IS-1 ultimate load (as can be seen ahead in Fig. 4), for a time duration of 1600 h. Unlike the previous experiments, to the authors’ best knowledge, there are no test standards that define the creep properties to be determined in the specification of real scale pultruded profiles.

The experimental setup adopted in the beam creep test had included the following elements: closed metal loading frame; H-profile used for load distribution; Enerpac hydraulic jack (load capacity of 50 kN and stroke of 75 mm); support system materialised by steel rollers (50 mm diameter) placed in-between steel plates; unit of automatic control of hydraulic pressure; valve, manometer and hand pump hydraulic pressure, the latter to rectify a possible leak in the circuit and consequent pressure reduction.

The beam was instrumented with several electrical strain gauges, similar to those applied in the small-scale coupon experiments, and an analogue displacement transducer of TML placed at midspan (stroke of 50 mm and precision of 0.01 mm). The strain gauges were fixed in predefined positions of the web and flanges of the profile, in order to assess a complete state of deformation. The strains were registered using the same data logger used on the small-scale specimen tests. Axial strains and deflections were measured and registered each hour during the first day and each day (at approximately the same hour) in the remaining of the test. Finally, after 2 months, the beam was also monitored during unloading – here, measurements were made for a period of approximately 150 h.

4. Experimental results and discussion

4.1. Time-independent elastic properties

4.1.1. Laminated material

Table 2 lists the short-term mechanical properties (average ± standard deviation) obtained in these tests, for both the web and flange specimens tested in the longitudinal and transverse directions, according to the relevant normative standards. The main results are presented for the different types of loading by their respective ultimate stress/interlaminar shear strength ($\sigma_u/F_{Isb}$), elastic modulus ($E$), strain at failure ($e_u$) and inorganic content (% by weight).

As expected, the material behaved fully or almost fully linearly elastic up to failure, and the web and flange coupons exhibited very similar behavior, i.e. relative differences were clearly within the statistical scatter. In general, these results are consistent with material properties obtained by others authors [5], who used similar pultruded GFRP material and tested analogous laminated coupons.

4.1.2. Structural beam element

Fig. 4 plots the load-midspan deflection curves ($F-\delta$ curves) of the beams tested, together with the respective maximum longitudinal flexural stress in the flanges ($\sigma_{fu,L}$) and maximum transverse compressive stress in the web ($\sigma_{cu,T}$). These theoretical values, obtained from simple beam theory calculations, are in good agreement with the failure modes observed. In Fig. 4 an additional curve is plotted that corresponds to the creep test of beam IC-3 which, as already mentioned, was similar to beams IS-1 and IS-2 but had no lateral restriction and was loaded only up to about 1/3 of IS-1 beam’s ultimate load (22.8 kN). For all beams, the proportional limit was used to calculate the initial elastic modulus, known as — "apparent" full-scale longitudinal flexural modulus ($E_{ap}$), which is also presented in Fig. 4.

For all beams, the load–displacement curves are completely linear (until failure in the case of beams IS-1 and IS-2). Furthermore, in the loading–unloading cycles, beams IS-1 and IS-2 presented an elastic behavior. Such linear-elastic behavior is typically exhibited by GFRP beams up to failure [4,5,33,34].

Fig. 5 illustrates the failure modes of beam IS-1. Failure of this test beam occurred due to the combined effects of web crippling and crushing under the applied load, followed by the development
of longitudinal cracks in the web-top flange junction. In addition, the top flange experienced pseudo local buckling with flange and web-top flange separation in the same critical area under one of the applied point loads. On the other hand, the failure of beam IS-2 was due to symmetrical lateral-torsional instability with almost pure torsional buckling around the midspan section.

It is worth mentioning that different test setups caused significant differences on the ultimate load values as well as on their respective failure modes – w.r.t. the instability or resistance at ultimate limit states (ULS). These tests showed the importance of local (restrained condition) and global (unrestrained condition) instability phenomena, even in relatively non-slender beams ~31.2 (by radius of gyration) or ~12.0 (span-to-height ratio). The lateral restriction conditions proved to have a major influence on the ultimate/buckling failure loads, which varied from 68.6 kN (beam IS-1) to 38.2 kN (beam IS-2), the latter being about 50% of the former.

In addition to the above mentioned “apparent” modulus, the “effective” full-scale longitudinal flexural and shear moduli ($E_{\text{full}}$ and $G_{\text{full}}$) of the GFRP profile were also determined. Those effective elastic constants were determined by carrying out several full-scale flexural tests and then performing linear regression analysis of the slope of load-deflection curves for spans varying from 600 to 1800 mm. This method is suggested in EN 13706 standard (2002) [32] and was first proposed by Bank [35]. Based on these tests the following “effective” values of the time-independent elastic proprieties were obtained: $E_{\text{full}} = 36.2$ GPa and $G_{\text{full}} = 2.5$ GPa. As expected these values are different from those obtained in small-scale coupon tests. Such difference basically stems from the material inhomogeneity and/or orthotropy of both the GFRP laminates and the overall cross-section.

4.2. Time-dependent viscoelastic properties

4.2.1. Laminated material

Fig. 6 plots the total creep deflection as a function of time for specimens extracted from the flange (results obtained for web coupons were roughly similar), subjected to a load level range corresponding to 20–60% of $\sigma_{\text{fu,L}}$. Fig. 7 plots strain measurements of web specimens and shows also the corresponding “theoretical” strains, calculated based on cinematic relationships using the deflection measurements. The difference between those deformation values is relatively small, up to 3%, confirming the negligible shear deformation in these small scale elements.

Due to a deficiency in the data logger, detected during the tests, strain gauge measurements of some specimens were not valid. It is also worth mentioning that the displacement transducers used in specimens subjected to 20% of $\sigma_{\text{fu,L}}$ stopped providing measurements after about 270 h.

Regarding specimens subjected to higher load levels, as an example, Fig. 8 illustrates in detail the percentage increase of creep deflection $\delta$ (%) as function of time of specimens F-70 and W-80 – these failed approximately after only 3 h and 5 min, respectively. In addition, Fig. 9 shows the failure of coupon F-80, due to tensile rupture in bending of the bottom fibres, after 30 min.

This first series of tests showed the importance of the time-dependent effect at the laminated scale of the pultruded GFRP material. In these tests, the behavior of the material crossed the three stages of the creep phenomenon. In fact, in both types of specimens (web/flange), failure occurred in stage III, for load levels corresponding to 50% of $\sigma_{\text{fu,L}}$ or higher, with rupture times depending on the load level, varying between a few minutes (80% of $\sigma_{\text{fu,L}}$), 1/2–24 h (60–70% of $\sigma_{\text{fu,L}}$) and 2–27 days (50% of $\sigma_{\text{fu,L}}$).

After 1220 h, the deformations in the web specimens increased in general around 10% when compared to their initial elastic values.
such difference corresponded to variations of the vertical deflections and axial strains of about 0.31 mm and 0.30 ‰, respectively. It is worth mentioning that the creep deformation rates exhibited by flange specimens were lower than those of the web. As an example, the percentage variation of the deflection was 3–5% for flange coupons, while it was higher than 7% for those of the web. This aspect is discussed in further detail in second part of this paper.

4.2.2. Structural beam element

Fig. 10 shows the evolution of midspan deflection of the beam during the load cycle of the creep test – the curve presented is expressed in terms of percentage increase of creep deflection. The recovery deformation during the unloading cycle is illustrated in Fig. 11 in terms of “theoretical” axial strain (linear elasticity theory), after the total creep deformation experienced by the profile. As for some small-scale coupons, axial strain measurements of the beam were not valid.

The beam test showed the characteristic creep behavior of the material, with an evolution of deformation that was very similar to that measured in the tests of small-scale specimens, especially those of the flange. In relation to its initial value, the deflection increased 4%, 8%, and 12% at the end of the first day, week and month, respectively. At the end of the test, after 1600 h, the deformation achieved a maximum increase of 15%.

After unloading, the profile exhibited an immediate recovery of deformation (86% of the precedent deformation) – this variation was almost coincident with the instantaneous component of deformation of the loading cycle. This immediately recovered deformation was followed by a quite significant deformation recovery, particularly taking into account the short period of time during which unloading measurements were made – a deformation decrease in the order of 96% was measured for a strain variation of 2.56 ‰. It is expected that the last measurement recorded does not deviate much more from the value associated with unrecoverable deformation. It can be concluded that, within the previously acquired creep deformation, 9–10% of the recovery deformation is due to delayed elasticity phenomenon, while an expected residual margin, between 2% and 4%, is irreversible – permanent deformation.

The experimental programme carried out showed a rapid variation of the midspan deflection during the testing period, especially during the initial instants (in first 24 h). The fact that the results obtained for both types of test scale (laminates and full-profile) were consistent (as attested by analytical modelling described in Part 2 of the current paper), suggests that it is possible to use the results obtained for the pultruded GFRP small-scale material in the prediction of creep deformations of GFRP structural profiles.

Fig. 8. Creep deflection δ (%) over time of specimens F-70 and W-80.

Fig. 9. Failure of specimen F-80, after 30 min. (tensile rupture in bending of the bottom fibres).

Fig. 10. Creep deflection curve at load cycle.

Fig. 11. Total creep and recovery deformation curves.
5. Conclusions
This paper presented a study about the creep behavior of GFRP pultruded profiles. A brief review was first presented concerning the main previous experimental studies and analytical formulations about the creep response of GFRP materials, most of which subjected to flexural loads. The second part of the paper reported results of an experimental work on the flexural creep behavior of pultruded GFRP elements at two different element scales (laminate and beam) subjected to bending for approximately two months. The following main conclusions are drawn from this study:

1. Mechanical and structural viscoelastic full-characterisation of pultruded GFRP composites is required for bridge and building applications, in which the structural elements are subjected to long-term sustained loads (at serviceability levels). However, previous research on the creep behavior of FRP composites carried out during the latest years includes only a few experimental studies on the flexural creep of pultruded GFRP members. Furthermore, most of the tests reported in the literature have focused on small-scale coupons or relatively short specimens; large structural full-sized elements were rarely tested, and only for short durations.

2. The experimental study presented herein showed rapid evolutions of the deformations during the testing periods, especially in the first instants (24 h), with the creepocity exhibited by flange specimens being lower than that of web specimens. Small-scale tests showed the importance of nonlinear tertiary creep, which was noted by the premature failure of specimens loaded at 50% of their ultimate strength. Therefore, results of these tests confirmed the importance of avoiding higher load levels in the design of GFRP pultruded structures.

3. The beam test showed a characteristic creep behavior of the material, with a creep deformation that was very similar to that observed in the tests of small-scale coupons, especially those of the flange. At the end of the test, after 1600 h, the deformation achieved a maximum increase of 15%. The creep recovery was very significant.

4. The experimental results obtained in this study, namely the consistency observed in both types of material scale, suggest that it is possible to use results from small-scale coupons to predict the creep deformation of structural profiles.

Finally, just two words to mention that the flexural creep response of GFRP pultruded beams studied in this work have also been investigated by means of analytical investigations, in which the accuracy of existing formulae was assessed. The results of these analytical investigations, as well as their comparison with the experimental strain and deflection measurements, are reported in a companion paper (Part 2) [36].

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References
[20] Benett EA. Influence of creep on the stability of pultruded E-glass/polyester composite columns at elevated service temperatures. MSc Thesis in Civil Engineering. School of Civil Engineering, Georgia Institute of Technology; Atlanta; GA; 2005.
[21] Smith KJ. Compression creep of a pultruded E-glass/polyester composite at elevated service temperatures. MSc Thesis in Civil Engineering. School of Civil Engineering, Georgia Institute of Technology, Atlanta, GA; 2005.