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Timber-Timber-Composite (TTC) beam long-term behaviour. Full scale experimental campaign and simplified analytical model

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ABSTRACT

The variability of the physical and mechanical properties of wood requires that the analysis of its long-term behavior take into account all the factors capable of modifying these properties. The environmental conditions of humidity and temperature are factors that alter these properties, conditioning long-term behavior, a situation that is especially decisive in the case of structural elements in bending. The design standards establish simple corrective factors based on the type of environmental exposure that allow creep deformation to be estimated in a final stage from an initial instantaneous deformation value. A new analytical model is proposed that allows estimating the behavior at any stage from the knowledge of the environmental conditions to which the structural element has been subjected. The model is applied to different elements in various environments, from camera control situations to outdoor situations of 3-year seasonal cycles. In all cases, the precision of the model and the simplicity of its use are verified due to the basic factors on which it is based.

1. Introduction

Wood nature and the variability of its physical and mechanical properties determine limitations in the design process of structural elements. It is not an inert material compared to the environment, and the sensitivity that it is present during its growth stage to climatic conditions or actions is also present in its behaviour as a structural material [1]. Taking into account its main mechanical properties, the design of timber elements, especially beam and floors, is often conditioned by serviceability requirements [2]. Considering that these properties are not constant over time, it is possible to conclude that the study of the long-term behaviour of these elements becomes a fundamental matter.

Creep evolution implies a non-linear behaviour of the structural element when permanent load is applied, with special importance in visco-elastic materials as wood. The modification of the physic and mechanical properties of wood in relation to moisture content (MC) in dependence with the environmental conditions, temperature (T) and humidity (H), stablish that these considerations add to the load-time history (t), setting the basic parameters in a long-term behaviour evaluation.

Creep as a time-dependent progressive inelastic deformation behaviour, was described by Findely et al. [3] in terms of three consecutive stages. (Fig. 1). An initial stage or primary creep, where the strain rate is relatively high, but a decreasing rate. A second stage or secondary creep, where the strain rate is reduced to a minimum and becomes fairly constant. The tertiary stage or tertiary creep corresponds with the final stage, with a rapidly increasing rate, leading to the material failure.

From these considerations it is common to assume the presence of three type of creep behaviour [4]. A time-dependent creep (visco-elastic), that in the particular case of wood is linked especially to temperature and moisture content. This consideration of transient moisture content changes, determines a second type, known as mechano-sorptive creep. In addition to these two processes there is a third phenomenon, known as pseudo-creep, present in continued moisture cycling conditions. The conjunction of these three phenomena makes the evaluation of the long-term behaviour of timber members very complex. Although the first two creep processes can be considered irreversible as long as the load condition is maintained, the pseudo-creep process it has been shown as a phenomenon of certain reversibility. Holtzer et al. [5] expressed the complexity of the process and the adequacy of a methodology that in any case, must consider the visco-elatic stress–strain relationship (timber constitutive law) and the effect of the timber moisture content with respect to the environmental temperature and

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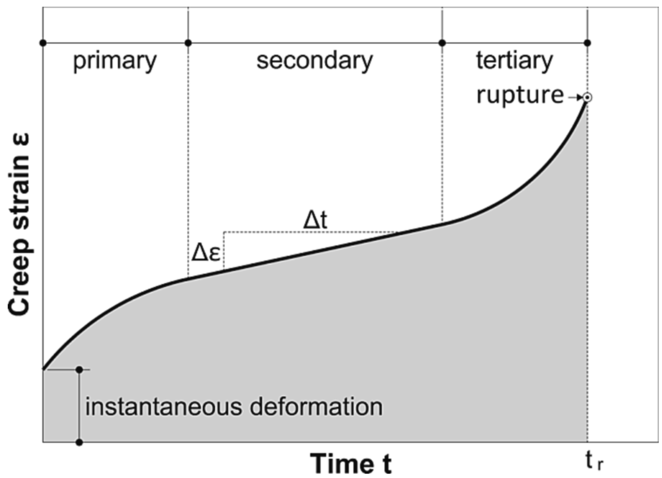

Fig. 1. Creep Stages.

humidity variation. In any case, it is considered that under variable temperature and moisture content, the time-dependent behaviour of wood is a complex process, especially when cyclic variations occur, and the approach to its knowledge and the development of predictive proposals has followed several parallel lines.

When creep develops within the primary and secondary stages, many equations has been proposed to model the response from different starting points. The use of a power law with three parameters (empirical constants) for constant environmental conditions and constant-load histories is complemented by mechanical models expressed as a series of Kelvin chains [6]. Due to the aforementioned difficulties and the variety of factors that affects the behaviour, there is no conclusive method for predicting creep behaviour in structures, and its modelling and prediction are not yet standardized.

From the previously consideration of the interaction phenomenon (mechanosorption) presented by Armstrong and Kingston [7], many constitutive models have been developed to predict the deformation of loaded timber members. Hunt [8] demonstrated the pseudo-creep presence in condition of moisture changes, finding a compliance level below which any change of moisture content, whether sorption or desorption, causes an increase in creep. Mohager and Toratti [9] analyse long term bending creep in cyclic relative humidity stablishing the difference from a constant conditions consideration. Huang [10] concludes a simplified model under cyclic moisture changes, establishing three effects. A first mechano-sorptive effect with the load in the main component, a second amplification or reduction effect caused by the moisture content variation, which can be neutralized after a humidity cycle, and the third effect, corresponding to moisture changes-dependent visco-elactic induced by the amplified load effect.

More approaches for the simulation of the complex multy-physical behaviour have been developed, using for the mathematical treatment of the various factors the framework of the finite element method. Dubois et al. [11] proposed a generalized Kelvin-Voigt model with a shrinkage-swelling element depending on the mechanical and moisture content, concluding an incremental formulation of behaviour established in a finite element formulation. Huč and Svensson [12] developed a coupled two-dimensional modelling of viscoelastic creep where required viscoelastic material parameters are determined by calibration procedure, transferring the proposal implemented in a finite element software to a three wood species under constant tensile loading.

The mechanical and physics properties modifications due to environmental conditions constitutes a second line of investigation. The relation between moisture content and various strength properties is suggested by Wilson [13] in a pioneering analysis and Gerhards [14] An interesting review of the different factors affecting strain and stress in wood during temperature ad moisture content, and the difficult to obtain a model that satisfactorily fits the experimental results is elaborated by Sandland [15]. The relation between naturally varying climate and strength at different equilibrium moisture contents and temperature are also treated by Ranta-Maunus [16]. Internal stresses caused by multiple humidity cycles were estimated by Svensson and Toratti [17] from deformation measurements in members subjected to tensile and compressive loads. Their conclusions are interesting, establishing that if the mechano-sorptive behaviour and the moisture gradients in wood can be accurately described, it is possible to predict the stress distribution in a timber cross-section by knowing the climate history. Moisture induced-stresses due to constrained swelling or shrinkage strains in timber exposed members are transferred in some cases to unique climates, singular areas or specific wood [18]. Numerical FEM implementations from this models have been proposed continuously with certain singularities, such as the successive studies of Eriksson [19], Fortino et al. [20], Huč et al. [21].

Some works have been developed in relation to TTC systems with different objectives, trying to limit the various factors that intervene in the long-term behaviour, most have focused on the study of the behaviour of the connection, based on simple models and characterization test in relation to the shear capacity of the joint [22,23]. The number of studies developed in relation to the analysis of long-span elements in a long-time period is more reduced, and the latest studies focus specially on the cases of TCC (timber-concrete composite) systems [24–27]. even some recommendations and normative proposals have been promoted in relation to the analysis of the long-term behaviour of these TCC systems [28]. However, the development in timber-timber systems has not been parallel and there is less attention to the analysis of its long-term behaviour. Special mention requires the study developed by Riccadonna et al. [29] over 5 m. span floors (T section) in a 1.5 years period, where the γ-method for composite sections is applied. Numerical study from a previous experimental campaign over a 420 days period is developed by Nie et al. [30], working from constitutive models corresponding to the material implemented on general analytical bases of Eurocode 5 (EN 1995–1–1:2004) [31].

There is no agreement on how to implement this uniqueness of timber mechanical behaviour in a design process under standards considerations. From the consideration that long-term behaviour of structural wooden elements maintains a close relationship with these environmental conditions and load duration. This is stated in the different regulations, that consider the effect of these conditions on the behaviour estimation, both at ultimate and serviceability state. To avoid the material failure (tertiary stage of creep), associated to this condition where rate increases exponentially with stress, standards provide different factors to reduce the timber strength under a stress limit, considering load duration and/or environmental service situation.

Eurocode 5 [31] fix two factors to take into account these conditions. First of all, the k_{mod} factor, that modify the strength of wooden members, with a reduction in relation to the increase of the load duration (creep); the strength decrease in relation with the MC increase, and the strength decrease in member exposed to severe environment (mechano-sorption). The second factor is k_{def} that consider the same three phenomena: the deflection increase in relation with the load duration (creep); the deflection increase in member with high initial MC, and the deflection increase for members exposed to severe environment (mechano-sorption). The load influence is determinate trough a load-duration classes and the environmental conditions and MC content are considered in terms of service class, that take into account the temperature and relative humidity of the surrounding air.

AS 1720.1–2010 Timber Structures [32] considers a design capacity incorporating a k_{mod} factor as a product of another k_i factors that take into account the load duration(k_1), moisture content at time of loading and throughout its life (k_4), and temperature (k_6). For members in bending the calculated short-term deformation shall be multiplied by a modification creep factor, depending on initial moisture content and load-duration.

NDS National Design Specifications for Wood Construction [33] considers a load duration factor (C_D), in combination with a wet service factor (C_M) and a temperature factor (C_t), incorporating a time effect factor (λ) that depends on load combination. The deflection calculations under long-term loading incorporates a time-dependent creep factor (K_{cr}) depending on wood classes and dry or wet conditions.

All these premises show the interest to establish constitutive models to predict the behaviour of timber bending structural members. Complexity of the models differs and is connected to the number of material parameters needed in the particular formulation, demanding test campaigns to fit the adequate values of these parameter. It is usual for models of different complexity to be mathematically formulated and treated by numerical methodology or implemented in a finite element software. These models move away from the simplicity that a design and analysis process advises, and therefore they have not been incorporated as code provisions. In this sense, the treatment proposed by the most common standards is extremely simple and unrealistic, especially in situations of changing cyclical environmental conditions, as corresponds to the seasonality of unprotected structural members.

From a test campaign developed over three years (1200 days) under uncontrolled environmental conditions, a simple analytical model to predict creep and long-term deformation in timber bending members is proposed. The parameters of load-time, relative humidity and temperature incorporated in the form of moisture content, and the response against the cyclic process are incorporated in this model. Taking the bending test as a characterization basis, which determines the structural properties of the element instead of the properties of the materials, the model starts from a previous stiffness value, corresponding to the instantaneous deflection under permanent uniform load.

2. Test campaign

2.1. Test specimens

The test campaign is developed over Timber-Timber Composite beams of 8880 mm length in a π-Section with different conditions. The beams are composed of two inferior glulam webs made of Picea Abies with a strength class GL28 h [34] and a cross section of 160x210 mm., and an upper CLT flange CLT90S L3S [35] composed of three sheets of 30 mm Picea Abies C24 [36] with a cross section of 1200x90 mm (Fig. 2). The connection between the webs and the flange was made with 410x80x4 mm perforated plates in S235 hot-dip galvanized steel [37], glued to the wooden elements with a bi-component polyurethane adhesive. The circular drilled holes in the plates had a diameter of 10 mm and were spaced at 5 mm (Fig. 3). The arrangement of the plates is indicated in Fig. 4. The webs had a channel of 35x85 mm in its lower part in which an unbonded Dywidag-type threaded bar with a nominal diameter of 26,5 mm grade Y1050H [38] is arranged.

This configuration arises from a large previous experimental campaign. The characterization tests carried out on the materials and especially on the joint, together with previous numerical models on different configurations, allowed to establish an effective section for the case of long-span elements. The intended span was 9 m. and the slenderness conditioned to a ratio of L/30. This configuration allows a greater sensitivity of the element in serviceability conditions [39].

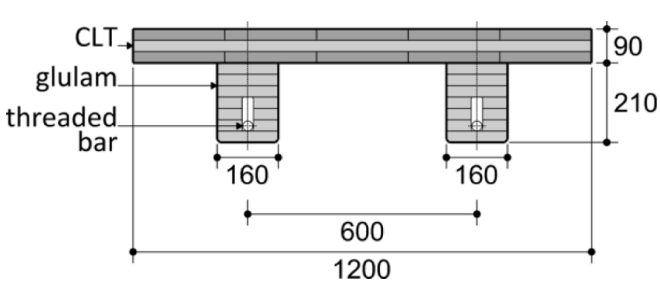

Fig. 2. Samples cross section.

The basic configuration allows the provision of a device capable of generating a self-tensioning that causes a positive effect on the piece in terms of behaviour. The test is transferred to two different configurations, since the presence of the self-stressing system causes a different stress distribution. A more detailed description of the device is made in the next section and its placement is shown in Fig. 8.

2.2. Test setup and results

A uniform load configuration is adopted instead of the usual four-point loading model used in short-term analysis. A more realistic simulation of the usual service conditions of the structural elements is intended, avoiding the shearing forces present in the four-point model. In this way, the effect of shear creep is minimized, which may not be negligible in the case of slender elements.

The self-weight of the beams was evaluated in 0.97 kN/m. The imposed load was applied by 44 boxes filled with water, with a 0.65 kN individual weight (Fig. 5) This configuration represents a uniform total load of 3.22 kN/m and an equivalent load of 3.5 kN/m^2, including self-weight (1.5 kN/m^2 from permanent load and 2.0 kN/m^2 from imposed load).

Midspan deflections measurements were carried out using a three linear variable differential transformer (LVDT) transducers via a multichannel. Measurements were daily at the beginning, increasing the time progressively until a monthly term.

Two different samples were tested from the basis configuration shown in Fig. 2, adopting a simply supported beam model with a span of 8.80 m. The first sample, free-beam, corresponds to a piece in which no tensioning control mechanism is provided. In the second one, tendon-beam, a tightening nut is place on tendon at each beam end, without applying any extra force, creating an interaction with the timber section. An instantaneous deflection of $w_{test,0}$ 26.15 mm (6.06 mm and 20.09 mm for self-weight and imposed load, respectively) was determined in the case of free-beam, and a value of $w_{test,0}$ 22.08 mm (6.06 mm and 16.02 mm) in the case of the sample with tensor-bar restriction.

The test campaign includes the evaluation of the behaviour of this samples with the described conditions under variable environmental conditions, equivalent to those defined as Service Class 2 in Eurocode 5 [31], that is, not directly exposed to moisture but to higher levels of humidity. The test was developed in Lugo, northern Spain, with an Atlantic continental climate conditions. The test protocol includes the measurement of the environmental conditions (relative humidity and temperature), the humidity of the beam components and the deformation at different moments of the process that lasted for 1200 days (Fig. 6). The environmental conditions were recorded by a thermo-hygrometer model LASCAR EL-USB-2 that collects data at half-hourly intervals. The temperature reached a minimum value of $T_{min} = 2.6\ ^\circ C$ and a maximum value of $T_{max} = 22.5\ ^\circ C$, with an average value of $T_{av} = 11.95\ ^\circ C$. The relative humidity varies from a minimum value of $RH_{min} = 57.0\ \%$ to a maximum value of $RH_{max} = 95.5\ \%$, with an average value of $RH_{av} = 78.12\ \%$. The moisture content of the wood member (web and flange) was measured at the same stages at which the control of beam deflection was carried out. A moisture meter model GANN Hydromette RTU 600 was used, obtaining for the case of the web a minimum value of $MC_{GLh,min} = 13.2\ \%$ and a maximum value of $MC_{GLh,max} = 19.7\ \%$, with an average value of $MC_{GLh,av} = 16.52\ \%$. The flange measurements determined a minimum value of $MC_{CLT,min} = 13.9\ \%$, a maximum value of $MC_{CLT,max} = 20.1\ \%$ and an average value of $MC_{CLT,av} = 16.22\ \%$. An initial value of $MC = 16.0\ \%$ was measured at the beginning of the test in both material, since the beams had previously been stored in a controlled environment.

Fig. 7 shows the midspan deflection measured in both samples, reflecting the cyclical behaviour due to the seasonal variation of the environmental conditions. These measurements show a 15.56 %

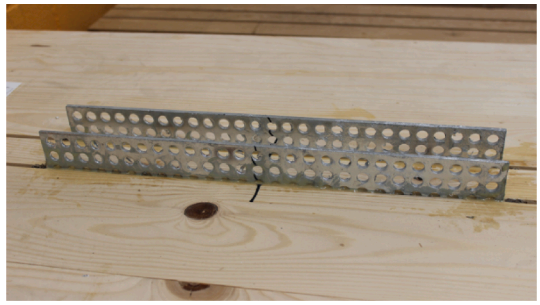

Fig. 3. Detail of the perforated plate connector.

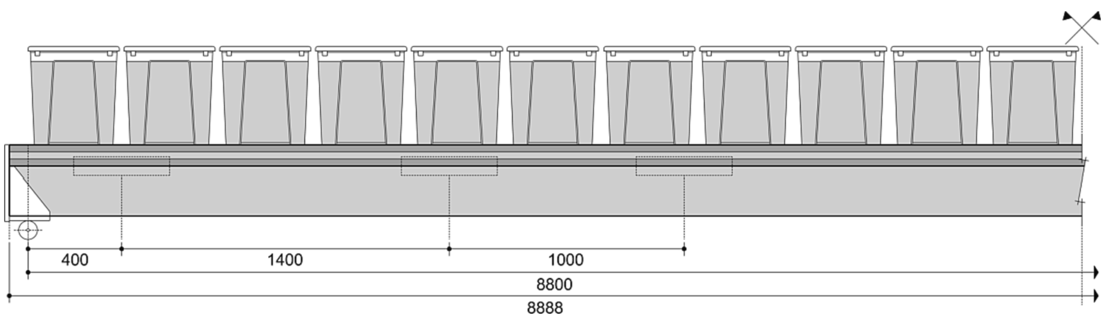

Fig. 4. Samples configuration.

Fig. 5. Imposed load and test configuration.

reduction in the value of the instantaneous deflection (t = 0 days) in the case of the tendon-beam compared to free-beam. A second comparison is made after a month of exposure, considering an adequate time for the acclimatization of the samples. In this case (t = 30 days) the deflection of the tendon-beam was $w_{test,30}$ 20.07 mm. and $w_{test,30}$ 26.56 mm. in the case of the free-beam, representing a difference of 24.43 %. The positive effect of the restriction generated by the tendon is maintained at all times and in all environmental conditions, showing the cyclical conditions derived from seasonality. At total time (1200 days) the final deflection of the tendon-beam was $w_{test,f}$ 21.20 mm, while in the case of the free-beam a final value of $w_{test,f}$ 30.36 mm. was measured, representing a reduction of 30.17 %.

Evaluating the final deflection after 1200 days, it is possible to see how, in the case of the tendon-beam, the measured value practically corresponds with the instantaneous deflection (t = 0 days), $w_{test,0}$ 21.20 mm and $w_{test,f}$ 22.08 mm respectively. However, in the case of the free-beam there is an increase in the value of the final deflection compared to the instantaneous deflection, $w_{test,f}$ 30.36 mm. and $w_{test,0}$ 26.15 mm. respectively.

From this starting point, and in order to calibrate the factors that could intervene in the analytical proposal, a second test campaign was developed. After unloading, the samples used in the first test campaign

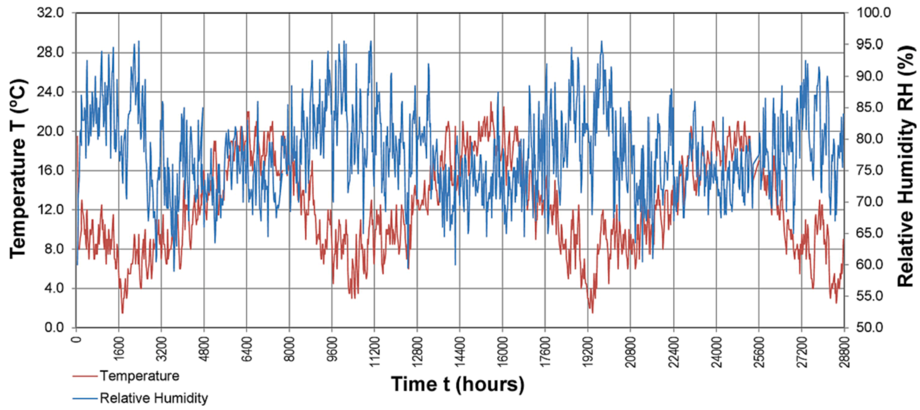

Fig. 6. Environmental values (reflecting daily measurement). First Test Campaign.

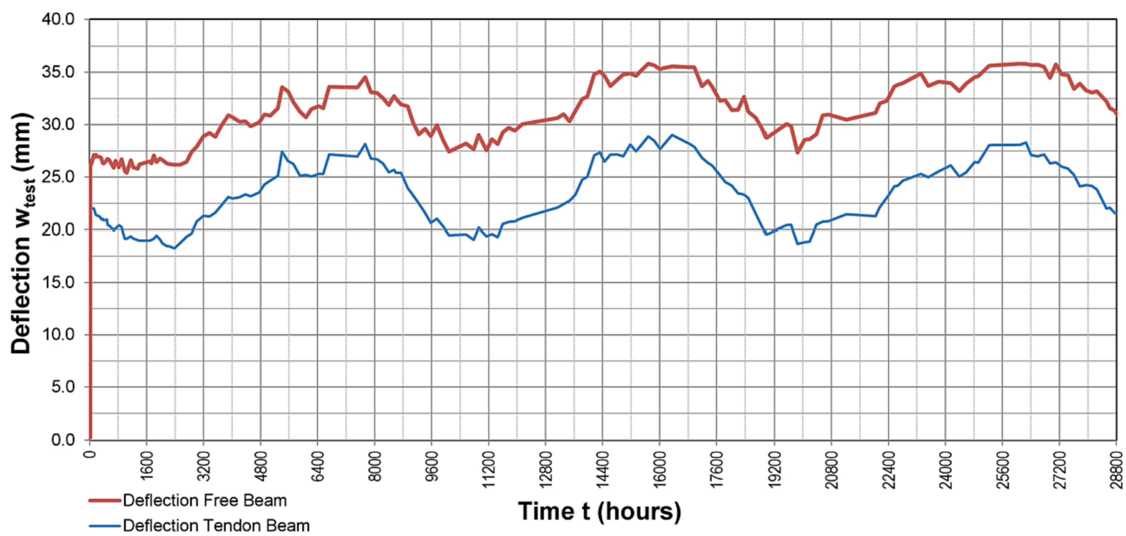

Fig. 7. Midspan deflection measurements.

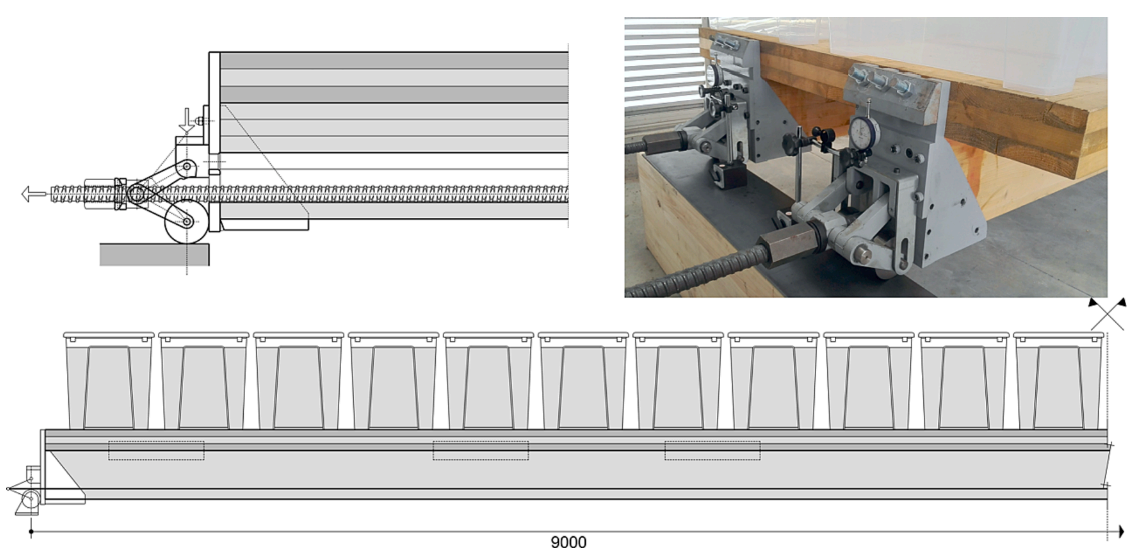

Fig. 8. Sample Configuration Second Test Campaign.

and an acclimatization period of 45 days where these pieces remained supported along their entire length. The focus of this campaign is to evaluate the long-term behaviour of the same pieces using a self-tensioning device, developed and patented by the authors. The self-tensioning device connected to the threaded bar transform the vertical displacement caused by gravitational effects into lengthening of the tendon (Fig. 8).

A complete analysis of this system, its advantages and short-term behaviour have been previously carried out by this research team [40,41], showing excellent behaviour in long-span configurations, with extremely slender sections that show high stiffness. The campaign was developed under the same variable environmental conditions, for a period of 630 days (15120 h). The control over these environmental conditions determined a temperature variation with oscillations between a minimum value of T_{min} = 2.5 °C and a maximum value of T_{max} = 24 °C, with an average value of T_{av} = 8.4 °C. The relative humidity reflected values from a minimum of RH_{min} = 53.5 % and a maximum value of RH_{max} = 103.0 % (supersaturated situation, singular and limited duration condition), with an average value of RH_{av} = 85.9 %. The MC content fluctuated between 13.1 % and 19.2 %, with and average value of 16.7 %, starting from an initial value of MC = 13.1 % (Fig. 9).

In this case, the arrangement of the self-tensioning device determines that the span between supports increase to 9.00 m., due to the geometry of the device. Two different devices were used, one in each sample. In the first one, sample TTC-1, the free friction between parts of the rotation device is allowed. In the second one, TTC-2, Teflon sheets were placed between these parts, reducing friction between them, thus achieving greater effectiveness in the device.

To translate the vertical action into horizontal action on the tendon the device descends and, therefore, the beam also descends. Thus, in order to determine the beam deflection, it is necessary to measure the movement in the middle of the span, and subtract the device settlement that occurs at the ends of the piece. In the case of simple TTC-1, the self-weight generates a deflection of $w_{test,sw,0}$ 5.05 mm., and an imposed load deflection of $w_{test,l,0}$ 17.49 mm., in both cases deducting the correspond settlement, with a total value of $w_{test,0}$ 22.54 mm. In the other case, TTC-2, the self-weight deflection was $w_{test,sw,0}$ 4.75 mm. and the imposed load deflection was $w_{test,l,0}$ 16.48 mm., with a total value of $w_{test,0}$ 21.23 mm., deducing the device settlement. Greater efficiency is appreciated in the device provide in simple TTC-2, where the Teflon washer reduce friction, despite the fact that is supposes a greater settlement (4.19 mm. in TTC-2 and 0.60 mm. in TTC-1 for imposed load situation).

Fig. 10 show the midpspan deflection of both samples, appreciating the cyclical behaviour related to environmental variations, similar to what was observed in the previous campaign.

3. Analytical model

Many creep coefficients according to rheological model have been developed, basically for constant environmental conditions, trying to integrate in a simple way the components of visco-elastic and mechano-sorptive creep and eventually, the pseudo-creep component. Schaenzlin [42] establishes a comparison between the models proposed by Toratti [43], Hanhijärvi [44], Märtensson [45] and Becker [46], determining different chained factors that try to integrate load components, changes of the moisture content or drying and annual cycling of the moisture content. The new analytical model of creep that is proposed collects all of these previous experiences, establishing a general methodology that attends to the prediction of the behaviour at each instant of time.

Taking as starting point the environmental conditions in which the loading process begins and the instantaneous deflection that occurs, three different conditions are considered in this analytical model. Time-dependent creep (visco-elastic) is considered through the factors of time and load classification. Mechano-sorptive creep as a result of varying environmental conditions participates in analysis prior consideration of timber equilibrium moisture content, considering the volumetric shrinkage as a singular wood property. Pseudo-creep, derived from the cyclical conditions, is considered through a factor that takes into account the damping derived from the repetition of environmental conditions over time. Each of the components is analysed independently, taking into account the different factors that affect it, thus resulting in a general model that can be adapted to the particular conditions of any case.

From these bases, a simple predictive model is proposed, determining the deflection in any time, takin into account the environmental conditions, both at the specific moment and the evolution in all the time that has elapsed since the beginning of the loading process.

$$w_f = w_i + w_t + w_{EMC} \cdot K_p \tag{1}$$

W_f represent the total deflection at age t (hours).

W_i represent the instantaneous deflection due to self-weight ($W_{i,sw}$) and the permanent load ($W_{i,pl}$).

W_t represent the creep time-dependent at age t (hours).

W_{EMC} represent the mechano-sorptive creep component.

K_p represent the pseudo-creep factor.

3.1. Load-duration

Time-dependent creep is considered in relation to the parameters of time (t) elapsed since the start of the test, computed in hours and considering a factor (K_L) that take into account the type of load. This factor can be considered equivalent to the strength modification factor for service classes and load-duration classes considered in some

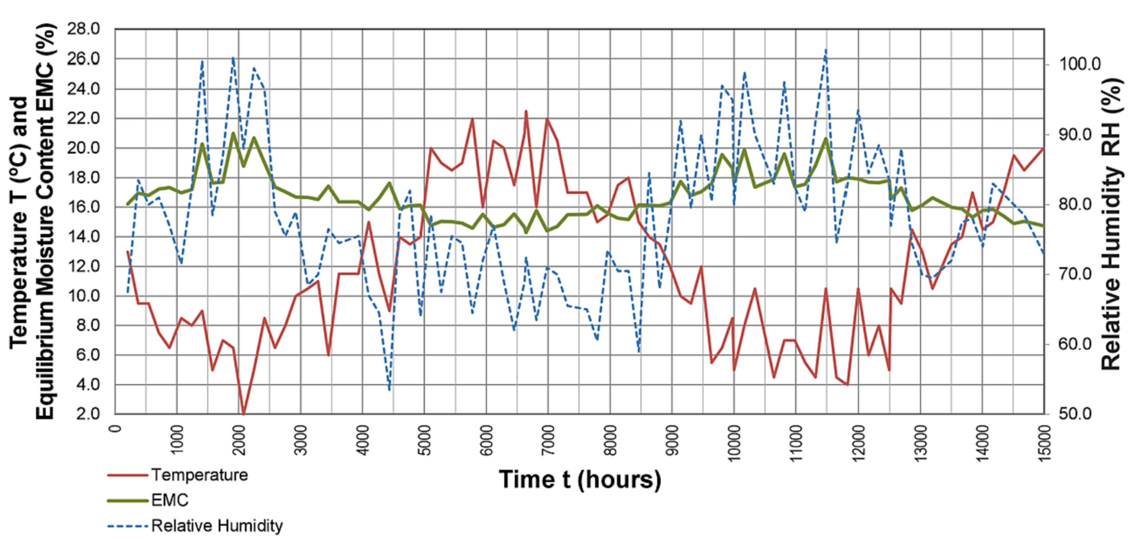

Fig. 9. Environmental values (reflecting weekly measurement). Second Test Campaign.

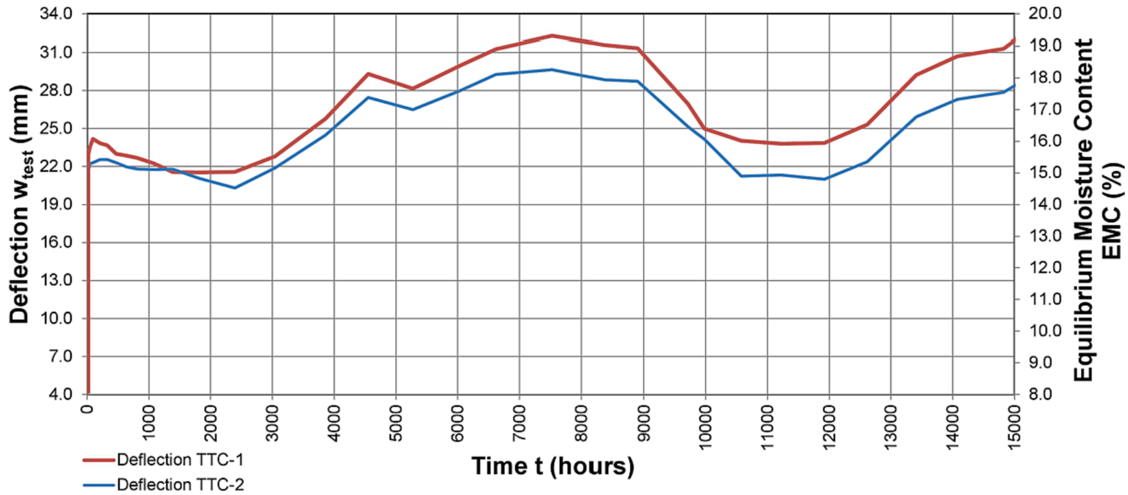

Fig. 10. Midspan deflection for pieces with self-tensioning system.

standards (for example the K_{mod} factor given in Eurocode 5). The value of this factor depending on the type of load is taken in equivalence to the mentioned K_{mod}, corresponding in this case for the situation of permanent imposed load a value of $K_L = 0{,}60$.

A simple expression is considered to establish a pure creep-time coefficient (ϕ_t) that considers the age and time load-duration.

$$\phi_t = \frac{t^{0,7}}{508,75 + t^{0,7}} \tag{2}$$

Starting from this coefficient it is possible to estimate de creep deflection due to time consideration at a given instant, applying the next expression that consider a non-linear amplification of the instantaneous deflection (Fig. 11).

$$w_t = \phi_t \cdot (w_{i,sw} + w_{i,pl}) \cdot K_L \tag{3}$$

3.2. Moisture Content. Relative humidity and temperature

Simpson [47] provides the following equation to evaluate equilibrium moisture content of wood (EMC) from relative humidity (RH) and temperature (T) of the air surrounding it, taking as a starting point a group of coefficients of an adsorption model previously developed by Hailwood and Horrobin [48]. This proposal, subsequently developed by the U.S. Forest Service, contents some approximations for EMĆs wood exposed to outdoor atmosphere in different cities and countries, such Bilbao in Spain, a climate environment similar to this case.

$$EMC = \frac{1800}{W} \cdot \left(\frac{K \cdot RH}{1 - K \cdot RH} + \frac{K_1 \cdot K \cdot RH + 2 \cdot K_1 \cdot K_2 \cdot K^2 \cdot RH^2}{1 + K_1 \cdot K \cdot RH + K_1 \cdot K_2 \cdot K^2 \cdot RH^2} \right) \tag{4}$$

$$W = 349 + 1.29 \cdot T + 0.0135 \cdot T^2 \tag{5}$$

$$K = -0.805 + 0.000736 \cdot T - 0.00000273 \cdot T^2 \tag{6}$$

$$K_1 = 6.27 - 0.00938 \cdot T - 0.000303 \cdot T^2 \tag{7}$$

$$K_2 = 1.91 + 0.0407 \cdot T - 0,000293 \cdot T^2 \tag{8}$$

EMC estimated equilibrium moisture content.
RH relative humidity (%).
T temperature (°C).

This proposal has been used for practical applications, but presents some limitations. Wood exhibits hysteresis, so in particular cases the values obtain from this expression may be adjusted to take account factor such as the effective diffusion process. As the proposal itself expresses, the EMC will be slightly higher if this equilibrium is reached by losing moisture than it would be if it reaches equilibrium by gaining

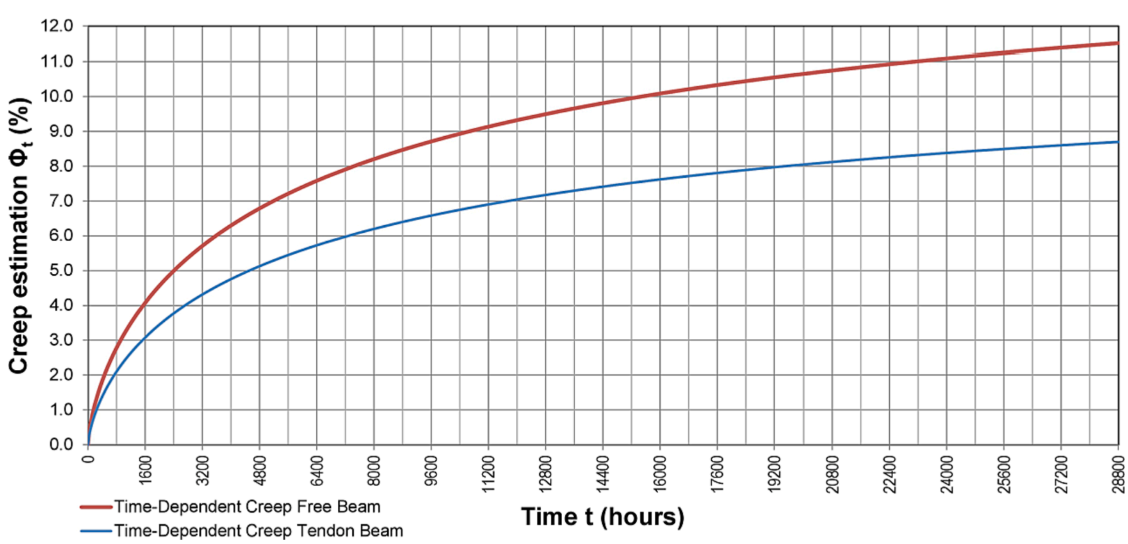

Fig. 11. Time creep deflection.

moisture. Applying this expression to our case shows how the EMC values obtained for extreme relative humidity values, especially in combination with extreme temperature values, are far from values obtained by direct measurement in pieces (Figs. 12, 13). The expression determines very close values in cases in which the relative humidity ranges from 65 to 80 % and temperature from 12 to 20 °C.

Therefore, a correction of the value obtained is proposed that takes into account the cases in which the humidity and/or temperature deviate from the predetermined limits. A first factor (F_{HR}) takes as reference the limit relative humidity (RH) of 80 % and a second factor (F_T) considers a new reference in relations to the limit temperature (T) of 12 °C. In this way, an EMC_{REF} value adjusted to the particular conditions of the place is obtained.

$$RH \leqslant 80\% \rightarrow F_{HR} = \left(\exp^{\left(\frac{80-HR}{100}\right)}\right)^2 \tag{9}$$

$$RH > 80\% \rightarrow F_{HR} = \exp^{\left(\frac{80-HR}{100}\right)^2} \tag{10}$$

$$T \leqslant 12^{\circ}C \rightarrow \exp^{\left(\frac{12-T}{100}\right)} \tag{11}$$

$$T > 12^{\circ}C \rightarrow \left(\exp^{\left(\frac{12-T}{100}\right)}\right)^2 \tag{12}$$

$$EMC_{REF} = \left[\frac{1800}{W} \cdot \left(\frac{K \cdot RH}{1 - K \cdot RH} + \frac{K_1 \cdot K \cdot RH + 2 \cdot K_1 \cdot K_2 \cdot K^2 \cdot RH^2}{1 + K_1 \cdot K \cdot RH + K_1 \cdot K_2 \cdot K^2 \cdot RH^2}\right)\right] \cdot F_{HR} \cdot F_T \tag{13}$$

The creep value due to environmental conditions (w_{EMC}) is determine by the next expression, where v_S represent wood volumetric shrinkage, considered in this case with a value of 12 %.

$$w_{EMC} = -4050 \cdot V_s \cdot (EMC_{REF} - 14) \cdot \exp^{\left(\frac{10^{-1} \cdot V_S}{10 - V_S}\right)} \tag{14}$$

In this expression the value of 14 % represent a reference EMC, while the value of the volumetric shrinkage can be obtained in an easy way from bibliography [49] or through characterization test [50,51].

From this consideration, the estimation of the creep component determinate by environmental values reflects the intimate relationship between these conditions, expressed through the determined EMC. The asymmetry of the graphs (Fig. 14) that reflect both values over time show how the decrease in the EMC value implies a proportional increase in the creep value. So it is assumed the well-known effect that sorption of timber induces a reduction in downward deflection, whereas the desorption causes an increase in deflection.

3.3. Cyclic environment variation

The long-term behaviour under constant load does not show a linear distribution, but this non-linearity becomes more noticeable when the analysis includes cyclically changing environmental conditions. In the first moments or cycles, the effect of the variation of the environmental conditions is notable, while the effect is dampened over time with the successive cycles [10]. Practically, all existing models have been validated within as reference a short range of time, corresponding with test time. Both models, those that consider the normal creep and the mechano-sorptive creep modelled as a series of simple rheological models, as the others where the simple rheological models are linked in parallel, present certain inadequacies when the prediction is transferred to long-term consideration. Schänzlin [42] shows the differences between various models when the proposals are applied to a time range of 10,000 h. Fragiacomo [52] insists on the need to recalibrate the models elaborated from experimental tests performed over a limited amount of time. This condition is also transferred to the case of the most recent works in relation to the long-term behaviour of timber-timber composite T sections [29], concluding that both, mechano-sorptive strain and the free shrinkage strain due to moisture content variations, are determining factors not yet correctly understanding.

In this model the environmental variations subject to cyclical conditions due to seasonality are considered through K_P factor from three factors that take into account relative humidity (K_H), temperature (K_T) and time (K_t).

$$K_P = K_H \cdot K_T \cdot K_t \tag{15}$$

The first two factors (K_H and K_T) are set in relation to the previous determination of the average values of relative humidity and temperature resulting from the test measurements. The climatic conditions repeated over time in each place allow this average value to be established in a simple way, but based on the measurements made over the 1.200 days that the test has lasted it is possible to establish an average relative humidity of $\Delta HR = 78.12$ % and an average temperature of $\Delta T = 11.95$ °C.

$$RH \geqslant DRH \qquad K_H = 2.0 \tag{16}$$

$$RH < DRH \qquad K_H = 1.0 \tag{17}$$

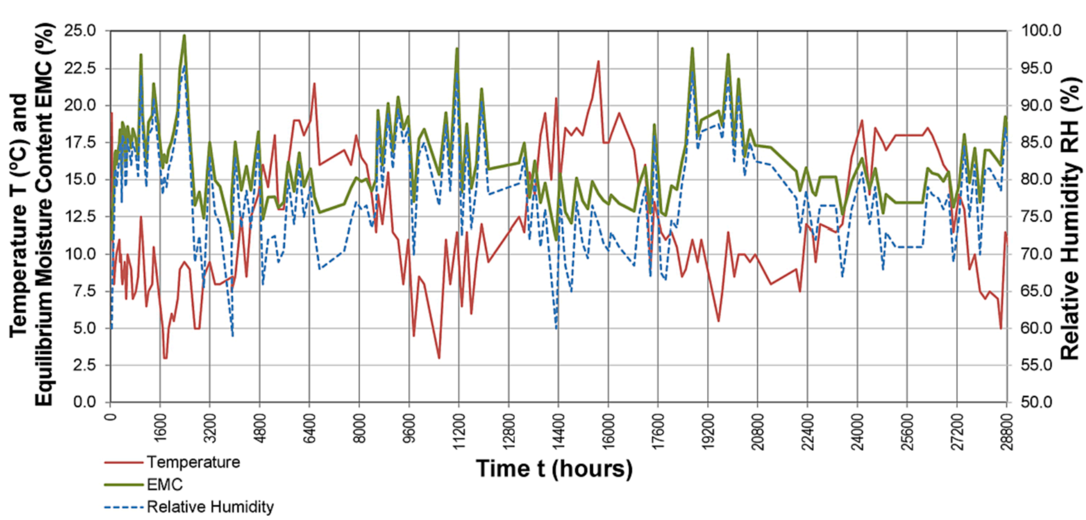

Fig. 12. Environmental values in relation to estimate EMC.

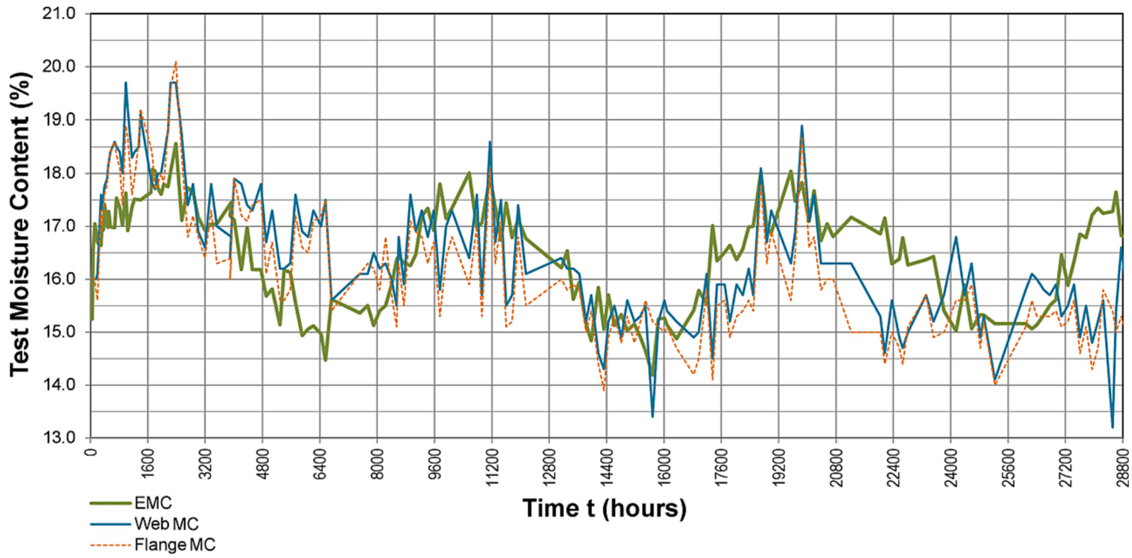

Fig. 13. Moisture content in relation to estimate EMC.

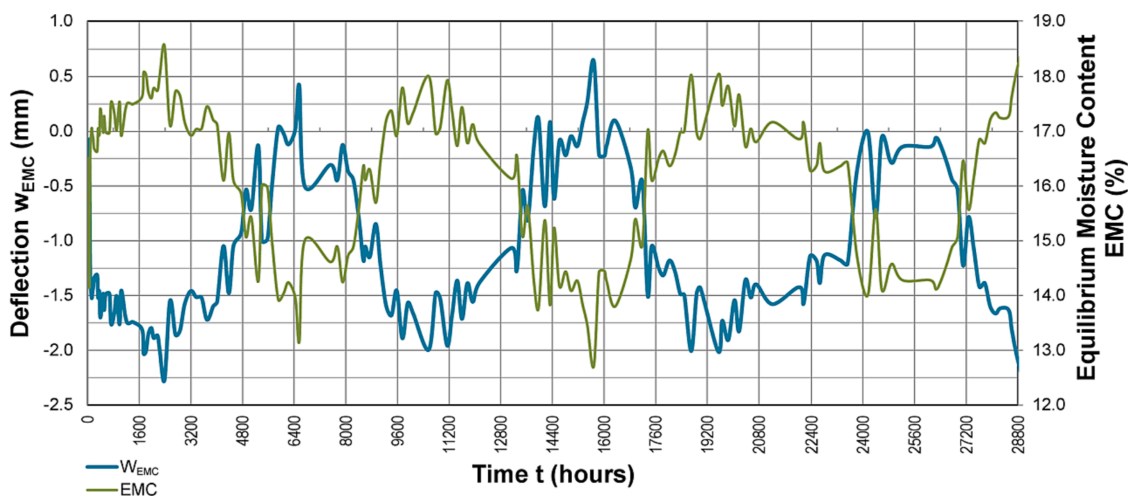

Fig. 14. EMC and estimated W_{EMC}.

$$T \geqslant 12^{\circ}C \qquad K_T = 1.0 \tag{18}$$

$$T < 12^{\circ}C \qquad K_T = 1.5 \tag{19}$$

The damping effect determined by cyclic conditions is considered by a third factor (K_t) resulting from a behaviour that can be evaluated from the following expression, which leads to a damped sine wave

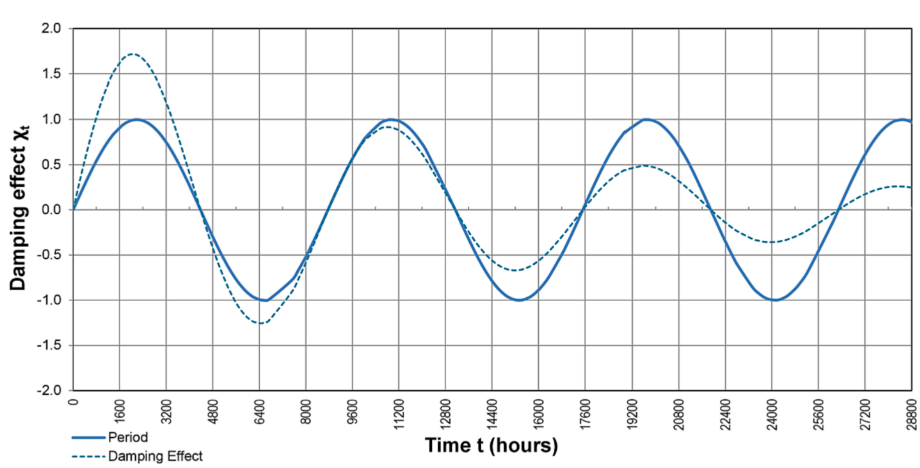

Fig. 15. Damping time-cycle effect (χ_t).

representation. Starting from a comparative value of t = 8760 h (1 year-seasonality) the mathematical expression results:

$$\chi_t = -2\cdot\left(\cos\frac{2\pi}{17520}\cdot t\right)\cdot\left(e^{\frac{-2\pi}{87600}\cdot t}\right) \tag{20}$$

Where, the period is represented by the first parenthesis and the damping effect corresponds with the second parenthesis (Figs. 15, 16).

From this point the K_t factor can be determine for any time, after a first cycle of 1 year or 8760 h, expressed by:

$$t < 8760\ h \rightarrow K_t = 1.0 \tag{21}$$

$$t \geqslant 8760\ h \rightarrow K_t \max\left|\begin{array}{c}1.0+\chi_t\\ 1.0\end{array}\right. \tag{22}$$

4. Analytical model applications

The simplicity of the analytical model allows an easy handmade calculation or a practical implementation in a spreadsheet, allowing a comparison of the results obtained in the tests and the predictive capacity of the model (Fig. 17).

The maximum difference between test results and prediction in the case of free-beam correspond with a value of + 4,83 mm. at 173 h, where the efficiency of the model is reduced based on the minimum acclimatization of the wood to the environmental conditions. Another abnormal value is detected at age of 13,470 h, where the relative humidity and temperature show much lower values than in the preceding and subsequent days. Beyond these singular values, the model allows to correct these extreme conditions, showing a trend adjusted to the test results, with an estimated final deflection of w_f 31.35 mm. ($w_{test,f}$ 30.36 mm.), representing a difference of − 0.99 mm. after the 1200 days' campaign. In the case of the tendon-beam the initial difference is reduced after the first cycle, determining a final estimated deflection w_f 22.05 mm. ($w_{test,f}$ 22.08 mm.) with a difference of − 0,03 mm. at 8760 h' age.

The analytical model reproduces the trend, with a maximum difference under desorption condition, when EMC value is decreasing. The model considers a homogenous behaviour, with no difference mechano-sorption in tension and compression. Morlier [53] attends to this non-symmetrical behaviour in tension and compression, although the final magnitude appears to be similar. Ozyhar et al. [54] and Hassani et al. [55] studied this process, and a complete analysis was developed by Florisson [56]. Under this consideration the model is able to recover the precision after each cycle, and the corresponding stage of adsorption allows to return to the accuracy.

In order to calibrate the analytical model, the proposal has been applied to the singular configuration adopted in the second test campaign, where the self-tensioning device was applied at both ends. In this campaign the deflection data were recorded at intervals of 1 day, during the first week, 1 week during the first three months and only one record per month in the rest of the time. Therefore, a certain lack of homogeneity is expected, as the graphs show in Figs. 18 and 19. The first one correspond with the measured environmental values during the campaign, in relation to the EMC value estimated by applying the expression (4).

The proposed predictive model shows this same lack of homogeneity, but it is able to correct this condition in each cycle (seasonal environmental conditions), accurately reproducing the results obtained in the test campaign. The mathematical model determines a final deflection, after 15,120 h, of w_f 31.99 mm. in the case of sample TTC-1, and w_f 30.11 mm. in the case of TTC-2, representing a difference of + 0.35 mm. (-1.1 %) and –1.40 mm. (-4.6 %), respectively (Fig. 19).

Another comparative analysis was carried out, applying the analytical model to an experimental campaign develop by Riola [57]. This test campaign was developed with different beam configurations, including a long-term analysis over glulam beams with a duration of 1 year (8760 h). Three fundamental differences occur in relation to the reference test campaign developed by our team. The first refers to the specimen configuration, both due to the timber section (200x75 mm) and the slenderness, since the test span in this case was 4.0 m., resulting a relative slenderness of L/53.33, compared to the value of L/30 in the reference test. The second refers to the loading conditions, since in the reference test a uniformly distributed load was adopted, while in this campaign the usual four-point loading model was selected. The third difference refers to the environmental conditions, since this campaign was developed in an interior controlled environment, with an average temperature of 24.1 °C, without notable variations over time, and an average relative humidity of 36.75 %, with certain variations, visible in the Fig. 20. Therefore, corresponding to a Service Class 1 (EC-5), as the campaign description assumes. The MC content was found to fluctuate between 9 % and 11 %, so a value of 10 (10 %) is applied in expression (14), instead the value of 14 consider in reference campaign. In this case, the model adopts a value of K_L = 0,70, corresponding for the situation of long-term (1 year) imposed load and equivalent to a K_{mod} value considered in EC-5. The value of the total load imposed was 2.83 kN and the beam self-weight was estimated in an equivalent 0,063 kN/m. The instantaneous deflection corresponds with $w_{test,0}$ 42.01 mm. (specimen Glulam K04) and $w_{test,0}$ 39.32 (Glulam *K*10) and the final deflections were $w_{test,f}$ 59.13 mm. and $w_{test,f}$ 57.68 mm., respectively.

Fig. 21 shows the results of the campaign in relation to the results obtained by applying the analytical proposal. The predictive model determines a final deflection of w_f 60.56 mm. for specimen Glulam K04

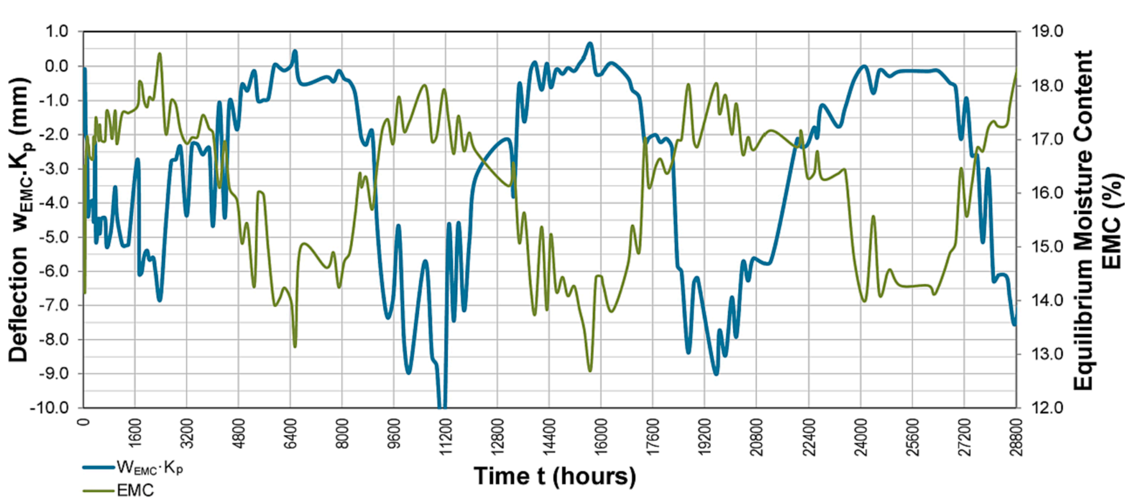

Fig. 16. Relation between EMC and mechano-pseudo-sorptive creep.

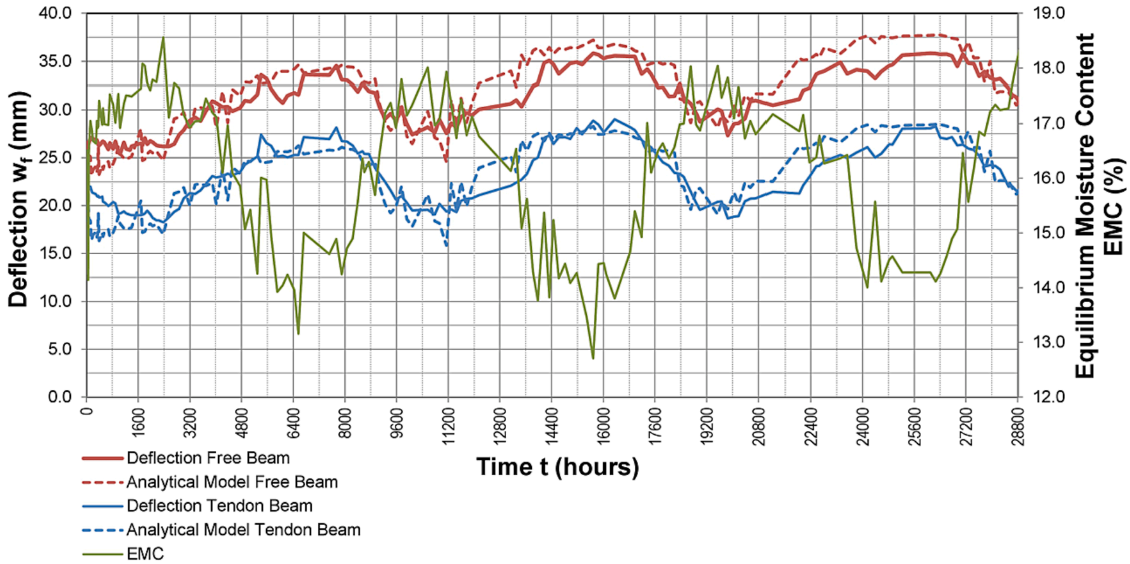

Fig. 17. Comparison test results and model predictions (EMC history graphic overlay).

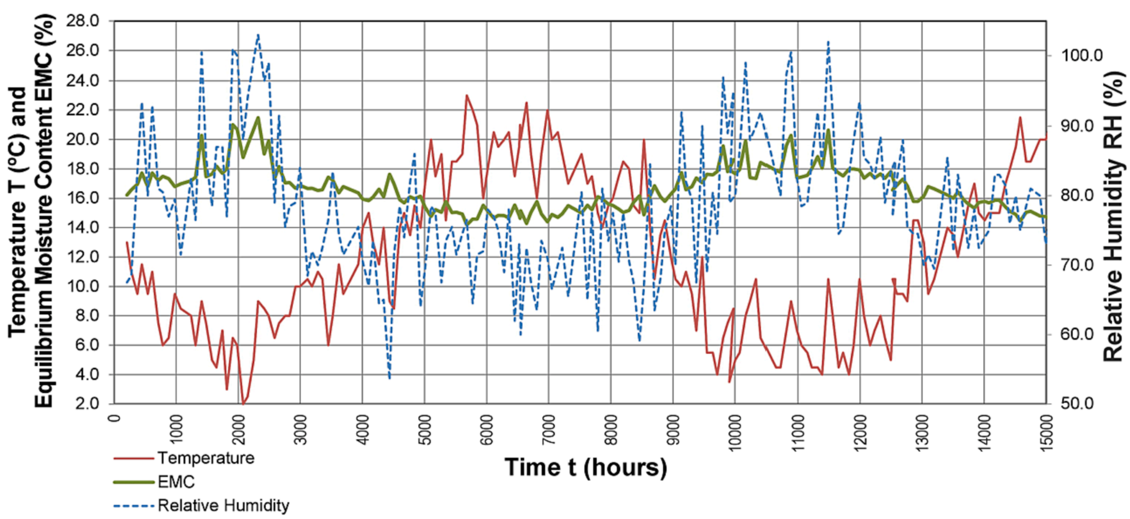

Fig. 18. Environmental values in relation to estimate EMC.

and w_f 56.87 mm. for specimen Glulam *K*10, representing a difference that can be evaluated in a + 2.42 % and − 1.40 % respectively.

Based on the principles contemplated in the analytical proposal, a prediction of the long-term behaviour of the samples used in the reference test has been made. Taking into account the seasonality of the environmental conditions, and adopting temporary cycles of 3 years the repetition of the environmental values obtain in test campaign has been assumed. Therefore, the data corresponding to the final 36 months of the test campaign have been selected, repeating these values cyclically over a period of 600 months (Fig. 22).

The damping effect that results from the cyclical repetition that is incorporated into the analytical proposal determines incidence stages that can be established in 5 and 15 years (43200 h and 129,600 h). Considering the free-beam model with an instant deflection (t = 0) of $w_{test,0}$ 26.15 mm., the analytical model allows establishing an estimate deflection at 3 years (t = 25920 h) of $w_{f,3}$ 37.70 mm, at 5 years (t = 43200 h) of $w_{f,5}$ 38.98 mm, at 15 years (t = 129600) of $w_{f,15}$ 40.33 mm. and at 50 years (t = 432000 h) of $w_{f,50}$ 41.92 mm. These estimated values correspond to successive increments from the initial instantaneous deflection of 44.17 % (3 years), 49.06 % (5 years), 54.22 % (15 years) and 60.30 % (50 years). The relative increases in each stage are 44.17 % (from t = 0 to t = 25920 h), 3.40 % (from t = 25920 to t = 43200 h), 3.46 % (from t = 43200 to t = 129600 h) and 3.94 % (from t = 129600 to t = 432000 h). The application of the analytical model to the tendon-beam sample offers similar results, since the starting bases and the concurrent factors are the same.

5. Conclusions

A new analytical model for the estimation of the long-term behaviour of timber beams (floors) is proposed, which takes into account the loading history and the environmental conditions of service.

The stiffness properties of the section are considered from the initial value of the instantaneous deflection caused by the load, and the alteration of the wood properties due to the variation of the environmental conditions are considered from the volumetric shrinkage, associated with the type of wood.

An equilibrium moisture content (EMC) is considered from the values of relative humidity and ambient temperature, values that in the case of outdoor spaces respond to consecutive cycles determined by the annual seasons, so they can be easily known. Correction factors are introduced that take into account the expected average values for

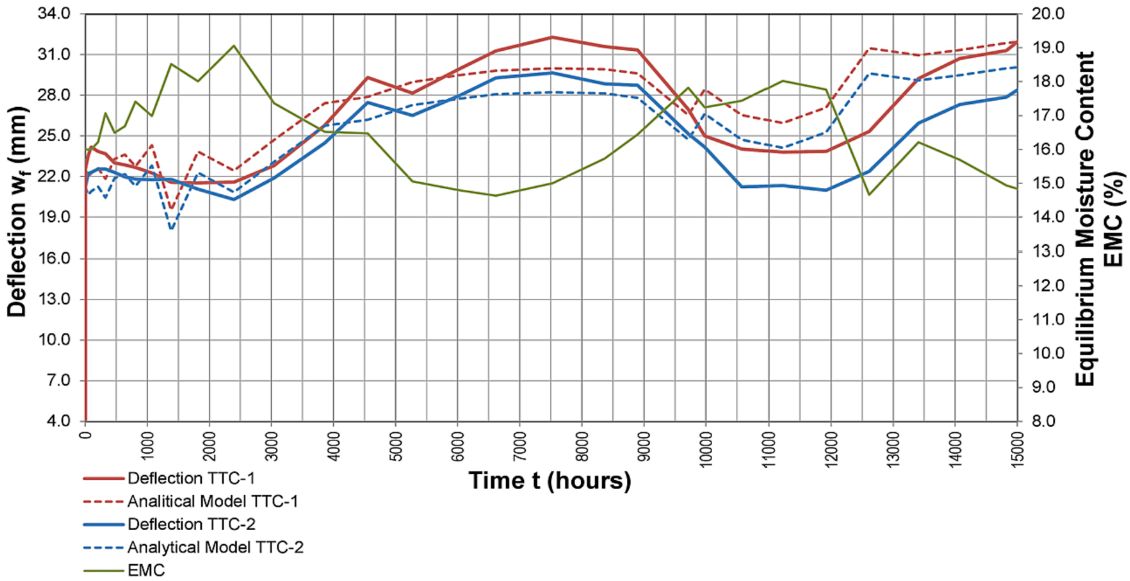

Fig. 19. Comparison test results and model predictions (EMC history graphic overlay).

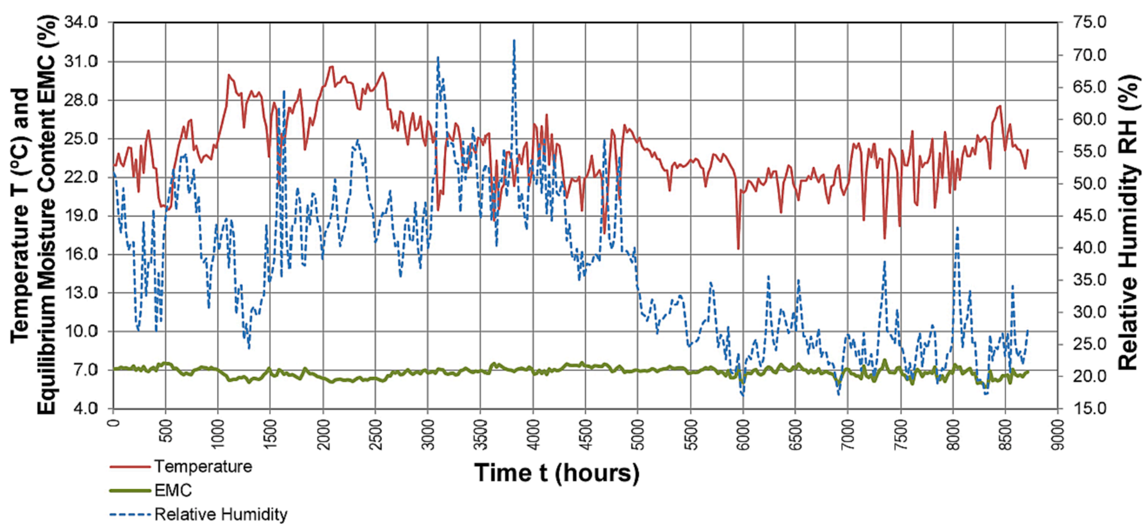

Fig. 20. Environmental values in relation to estimate EMC. Riolás experimental campaign.

relative humidity and temperature, and the cyclic repetition of conditions over time is considered through a damping factor.

The predictive model has been applied to three different cases, taking as reference the result of experimental campaigns. Different timber sections have been considered, from the reference T sections with slenderness of L/30 to simple rectangular sections with a slenderness of L/53.33. Different environmental conditions have been considered, from outdoor environments to controlled environments in climatic chambers, which determines a very different wood behaviour in terms of variations of the properties that dominate its bending stiffness. Different load configurations have been contemplated, from the most realistic situation of uniformly distributed load, to the conventional four-point test situation. These load considerations also differ in analysis time, from a minimum value of 1 year to a maximum of 3 years, which in case of outdoor environment means the presence of 3 seasonal cycles. The model also contemplates three different conditions of distribution of the compression and tension areas in bending, from the usual situation that determines the free-beam, to the extreme condition that generates the presence of a self-tensioning device, including the restricted deflection model (tendon-beam). In all these cases, the analytical proposal shows extreme precision, in direct relation to the extension of the data on environmental conditions. The difficulty of establishing a precise deflection value at each time instant is directly related to the difficulty of determining the mechanical and physical properties at that instant, which requires knowing the history of environmental conditions and transferring them according to the absorption or desorption capacity of the material. The analytical model allows a self-correction of the creep deflection due to this randomness, considering the periodicity of the exposure conditions to which the structural elements are subjected in a long-term service condition.

The minimal differences in the deflection values shown by the analytical model in all cases, especially if we consider these values in ages corresponding to complete cycles, allows to determine the predictive nature of the proposed model. The mathematical simplicity makes it a very useful tool in estimation of the long-term behaviour of timber structural elements subjected to bending conditions.

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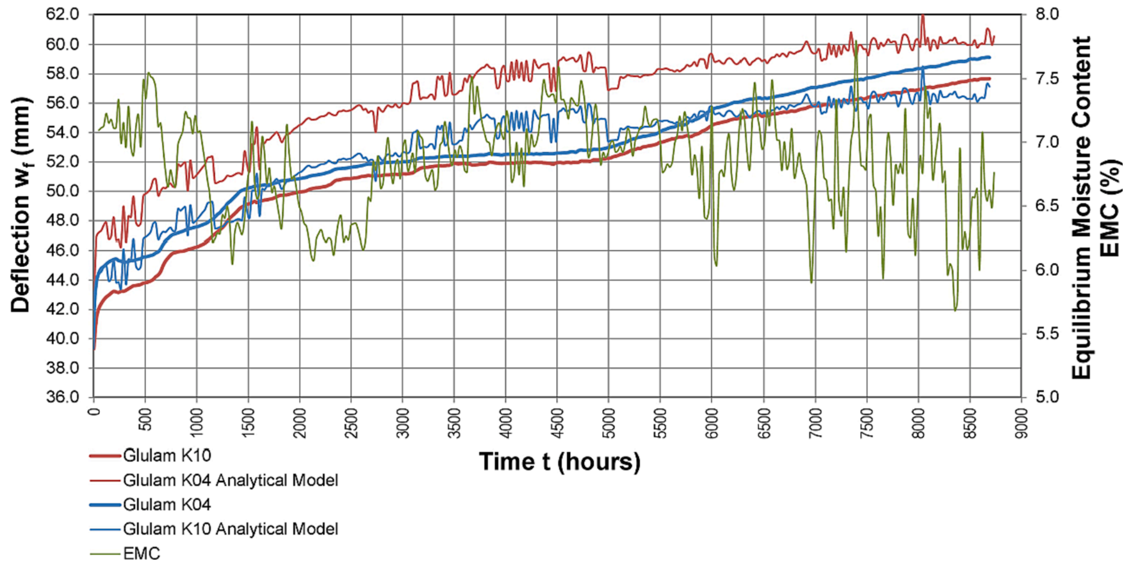

Fig. 21. Comparison test results model predictions. Riolás experimental campaign.

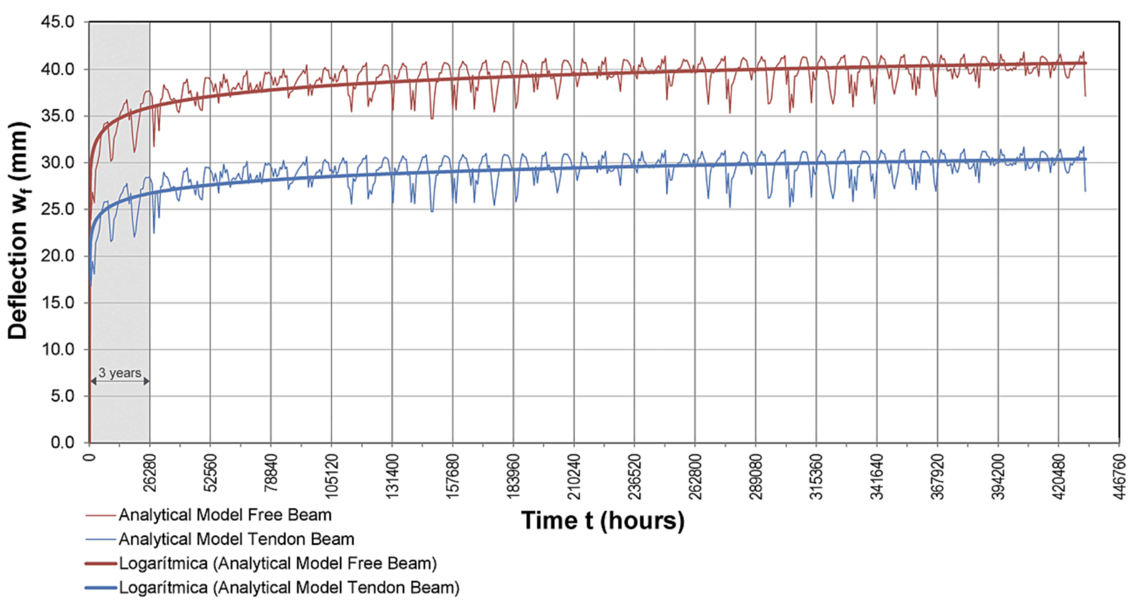

Fig. 22. Estimated deflection in a 50 years' period. First Test Campaign samples.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] Mindess, S. Environmental deterioration of timber. Transactions on State-of-the-Art in Science and Engineering. Vol. 28. Wit Press, 2007. doi:10.2495/978-1-84564-032-3/09.

[2] Honfi, D., Hochreiner, G., Ilharco, T. Serviceability limit states in structural timber design. In Basis of Design Principles for Timber Structures. A state-of-the-art report by COST Action FP1402/WG 1.2018 (European Cooperation in Science&Technology from Research to Standards). Aachen 2018.

[3] Findley, W., Lai, J., Onaran, K., Creep and relaxation of nonlinear viscoelastic materials, North-Holland Series in Applied Mathematics and Mechanics, 18, North-Holland Publishing Company, 1976.

[4] D.G. Hunt, A unified approach to creep of wood, Proc. R. Soc. Lond. Acad. 455 (1999) 4077–4095, https://doi.org/10.1098/rspa.1999.0491.

[5] S.K. Holzer, J.R. Loferski, D.A. Dillard, A review of creep in wood: Concepts relevant to develop long-term behaviour predictions for wood structures, Wood Fiber Sci. 21 (4) (1989) 376–392.

[6] D. Tong, A. Brown, D. Corr, G. Cusatis, Wood creep data collections and unbiased parameter identification of compliance functions, Holzforschung Wood Research and Technology 74 (11) (2020) 1011–1020, https://doi.org/10.1515/hf-2019-0268.

[7] L.D. Armstrong, R.S.T. Kingston, Effect of moisture changes on creep in wood, Nature 185 (1960) 862–863, https://doi.org/10.1038/185862c0.

[8] D.G. Hunt, Creep trajectories for beech during moisture changes under load, J. Mater. Sci. 19 (1984) 1459–1467, https://doi.org/10.1007/BF00563040.
[9] S. Mohager, Toratti T, Long Term bending creep of wood in cyclic relative humidity, Wood Science Technology 27 (1992) 49–59, https://doi.org/10.1007/BF00203409.
[10] J. Huang, Creep behaviour of wood under cyclic moisture changes: interaction between load effect and moisture effect, Journal of Wood Science 62 (2016) 392–399, https://doi.org/10.1007/s10086-016-1565-4.
[11] F. Dubois, H. Randriambololona, C. Petit, Creep in wood under variable climate conditions: Numerical modelling and experimental validation, Mechanics of Time-Dependent Materials 9 (2015) 173–202, https://doi.org/10.1007/s11043-005-1083-z.
[12] S. Huč, S. Svensson, Coupled two-dimensional modelling of viscoelastic creep of wood, Wood Science Technology 52 (2018) 29–43, https://doi.org/10.1007/s00226-017-0944-3.
[13] T. Wilson, Strength-moisture relations for Wood, Technical Bulletin Unites States Department of Agriculture 282 (1932).
[14] C. Gerhards, Effect of moisture content and temperature on the mechanical properties of wood: an analysis of immediate effects, Wood and Fiber 14 (1) (1982) 4–36.
[15] K.M. Sandland, Stress and strain in drying Wood- a literature survey, Norks Treteknisk Institut, Norwegian Institute of Wood Technology, 1997. Report 34.
[16] A. Ranta-Maunus, Effect of Climate and Climate Variations on Strength, Timber Engineering, John Wiley&Sons Incorporated, 2003.
[17] S. Svensson, T. Toratti, Mechanical response of wood perpendicular to grain when subjected to changes of humidity, Wood Sci. Technol. 36 (2002) 145–156, https://doi.org/10.1007/s00226-001-0130-4.
[18] M. Fragiacomo, S. Fortino, D. Tononi, I. Usardi, T. Toratti, Moisture-induced stresses perpendicular to grain in cross-sections of timber members exposed to different climates, Eng. Struct. 33 (11) (2011) 3071–3078, https://doi.org/10.1016/j.engstruct.2011.06.018.
[19] J. Eriksson, S. Omarsson, H. Petersson, Finite-element analysis of coupled nonlinear heat and moisture transfer in wood, Numerical Heat Transfer, Part A: Applications, An International Journal of Computation and Methodology 50, Issue 9 (2006), https://doi.org/10.1080/10407780600669282.
[20] S. Fortino, Mirianon, F.m Toratti, T., A 3D moisture-stress FEM analysis for time dependent problems in timber structures, Mechanics of Time-Dependent Materials 13 (4) 33 (2009) 333–356, https://doi.org/10.1007/s11043-009-9103-z.
[21] S. Huč, S. Svensson, T. Hozjan, Numerical analysis of moisture-induced strains and stresses in glued-laminated timber, Holzforschung, Wood Research and Technology 74 (5) (2020) 445–457, https://doi.org/10.1515/hf-2019-0025.
[22] N. Jacquier, U. Girhammar, Tests on glulam-CLT shear connections with double-sided punched metal plate fasteners and inclined screws, Constr. Build. Mater. 72 (2014) 444–457, https://doi.org/10.1016/j.conbuildmat.2014.08.095.
[23] J.W.G. Van De Kuilen, Duration of load effects in timber joints, Building and Construction (1999). Delft university of technology (TU Delft.
[24] J. Schänzlin, M. Fragiacomom, Analytical derivation of the effective creep coefficients for timber-concrete composite structures, Eng. Struct. 172 (2018) 432–439, https://doi.org/10.1016/j.engstruct.2018.05.056.
[25] D. Yeoh, Behaviour and design of timber-concrete composite floor system, University of Canterbury, Department of Civil and Natural Resources, 2010.
[26] Fragiacomo, M., Ceccotti, A., Long-term behavior of timber-concrete composite beams. I: Finite element modeling and validation, Journal of Structural Engineering, 132, 2006, 13-22. https://doi.org/ 10.1061/(ASCE)0733-9445(2006)132:1(13).
[27] Hailu, M., Shresta, R., Crews, K., Long-Term Deflection of Timber-Concrete Composite Beams in Cyclic Humidity Conditions in Bending, International Conference on Composite Construction in Steel and Concrete, 2013. http://doi.org/ 10.1061/9780784479735.012.
[28] Dias, A., Schänzlin, Dietsch, P., Design of Timber-Concrete Composite Structures, COST Action FP1402/WG 4(European Cooperation in Science&Technology from Research to Standards). Aachen 2018.
[29] D. Riccadonna, K. Walsh, G. Schiro, M. Piazza, I. Giongo, Testing of long-term behaviour of pre-stressed timber-to-timber composite (TTC) floors, Constr. Build. Mater. 236 (2019), 117596, https://doi.org/10.1016/j.conbuildmat.2019.117596.
[30] Y. Nie, H.R. Valipur, Experimental and numerical study of long-term behaviour of timber-timber composite (TTC) connections, Constr. Build. Mater. 304 (2021), 124672, https://doi.org/10.1016/j.conbuildmat.2021.124672.
[31] EN 1995-1-1:2004. Eurocode 5: Design of timber structures. Part 1-1: General-Common rules and rules for building, European Committee for Standardization (CEN), Brussels, Belgium, 2004.
[32] AS 1720.1-2010 Timber Structures. Part 1: Design Method. Australian Standards, Committee TM-001, Timber Structures and Framing, Sydney, Australia, 2010.
[33] NDS National Design Specification for Wood Construction, American Wood Council, Leesburg, US, 2018 Edition.
[34] EN 14080, Timber Structures. Glued laminated Timber and Glued Solid Timber, Requirements, European Committee for Standardization (CEN), Brussels, Belgium, 2013.
[35] ETA 14/0349 CLT-Cross Laminated Timber, European Technical Assesment, Brussels, Belgium, 2014.
[36] EN 338, Structural Timber. Strength Classes, European Committee for Standardization (CEN), Brussels, Belgium, 2009.
[37] EN 1993-1-1:2005. Eurocode 3: Design of Steel Structures, Part 1-1: General rules and rules for building, European Committee for Standardization (CEN), Brussels, Belgium, 2005.
[38] prEN 10138-4. Prestressing Steels. Part 4: Bars. European Committee for Standardization (CEN), Brussels, Belgium, 2000.
[39] J. Estévez-Cimadevila, D. Otero-Chans, E. Martín-Gutiérrez, F. Suárez-Riestra, Long-span wooden structural floors, Constr. Build. Mater. 102 (2016) 852–860, https://doi.org/10.1016/j.conbuildmat.2015.11.024.
[40] J. Estévez-Cimadevila, F. Suárez-Riestra, D. Otero-Chans, E. Martín-Gutiérrez, Experimental analysis of pretensioned CLT-Glulam T-Section beams, Advances in Materials Science and EngineeringArt. ID 1528792 (2018), https://doi.org/10.1155/2018/1528792.
[41] E. Martín-Gutiérrez, J. Estévez-Cimadevila, D. Otero-Chans, F. Suárez-Riestra, Self-tensioning long-span T-shaped spruce and oak web floors with a CLT upper flange, An experimental approach, Engineering Structures 168 (2018) 300–307, https://doi.org/10.1016/j.engstruct.2018.04.086.
[42] J. Schänzlin, Modeling the long term behaviour of structural timber form typical serviceclass-II-conditions in South-West Germany. IKEAHV, Nr 2010–2, Universtät Stuttgart, 2010.
[43] T. Toratti, Creep of timber beams in a variable environment, Helsinki University of Technology, Espoo, 1992. PhD Thesis.
[44] A. Hanhijärvi, Modelling of creep deformation mechanism in wood, Technical Research Centre of Finland, VTT Publications, Espoo, FI, 231, 1995..
[45] A. Märtensson, Mechanical behaviour of wood exposed to humidity variations, Lund University Publications, 1992. PhD Thesis.
[46] Becker, P., Modellierung des zeit- und feuchteabhängigen Materialverhaltens zur Untersuchung des Langzeitverhaltens von Druckstˈaben aus Holz, Bauhaus-Universität, Weimar, 2002 PhD Thesis.
[47] W.T. Simpson, Predicting equilibrium moisture content of wood by mathematical models, Wood and Fiber 5 (1) (1973) 41–49.
[48] A.J. Hailwood, S. Horrobin, Absorption of water by polymers: analysis in terms of a simple model, Transactions of Faraday Society 42B (84–92) (1946) 94–102.
[49] Glass, S., Zelinka,S., Moisture relations and physical properties of wood, in Wood Handbook. Wood as an engineering material, US Department of Agriculture Forest Service, General Technical Report FPL-GTR-190, 2010.
[50] ISO 13061-14:2016. Physical and mechanical properties of wood — Test methods for small clear wood specimens — Part 14: Determination of volumetric shrinkage. International Standardization Organization.
[51] UNE 56533:1977. Physical-mechanical characteristics of wood. Determination of lineal and volumetric contraction.
[52] M. Fragiacomo, J. Schänzlin, Can moisture be considered as an action for the design of timber and composite structures, Cost-e55 Meeting Modelling of the Performance of Timber Structures, COST-European Science Foundation, Zagreb, 2008.
[53] Morlier, P., Creep in timber structures, Rilem Report 8, Rilem Technical Committee, 1994, CRC Press. https://doi.org/10.1201/9781482294750.
[54] T. Ozyhar, S. Hering, P. Niemz, Viscoelastic characterization of wood: Time dependence of the orthotropic compliance in tension and compression, J. Rheol. 57 (2013) 699–717, https://doi.org/10.1122/1.4790170.
[55] M.M. Hassani, F.K. Wittel, S. Hering, H.J. Herrmann, Rheological model for wood, Comput. Methods Appl. Mech. Eng. 283 (2015) 1032–1060, https://doi.org/10.1016/j.cma.2014.10.031.
[56] S. Florisson, Moisture-Induced stress and distortion of Wood. A numerical and experimental study of woods drying and long-term behaviour, Linnaeus University Press, 2021. PhD Thesis.
[57] F. Riola, Timber-steel hybrid beams for multi-storey buildings, Technische Universität Wien (2016). PhD Thesis.