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The Time-Dependent Behavior of Glulam Beams from European Hornbeam

Jelena Lovrić Vranković [1,*], Ivica Boko [1], Ivana Uzelac Glavinić [1], Neno Torić [1] and Mario Abramović [2]

[1] Faculty of Civil Engineering, Architecture and Geodesy, 21000 Split, Croatia; ivica.boko@gradst.hr (I.B.); ivana.uzelac@gradst.hr (I.U.G.); neno.toric@gradst.hr (N.T.)
[2] Drvene Konstrukcije d.o.o, 33522 Voćin, Croatia; mario@drvene-konstrukcije.hr
* Correspondence: jelena.lovric@gradst.hr; Tel.: +385-21303345

Abstract: This paper presents the results of an experimental investigation of glued laminated timber (glulam) beams made from European hornbeam (*Carpinus betulus* L.) under constant loading for three months. Glulam beams were experimentally tested as a part of the last phase of the research project conducted by Drvene konstrukcije Ltd. and the Faculty of Civil Engineering, Architecture and Geodesy, Split. Beams were loaded in four-point bending tests with the applied load levels of 20% and 30% of the maximum force obtained from previously performed short-term tests. The experiments were carried out under minor environmental changes at the specialized laboratory unit at the Faculty of Civil Engineering, Architecture, and Geodesy, Split. The objective of this study is to present the research results of bending creep tests for hardwood species not included in the European Assessment Document. The experimentally obtained deflection-time curves were fitted with the power law equation used for the prediction of creep behavior. The results indicate that the power law fits well with experimental data. A comparison with requirements from Eurocode 5 is given.

Keywords: creep; European hornbeam; glulam; power law; curve fitting

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1. Introduction

Nowadays, engineered wood products (EWP) have gained popularity due to their environmental and mechanical characteristics. However, the exposure of the EWPs to constant load induces a creep strain, sometimes followed by a structural failure. Therefore, the serviceability limit state is often a decisive criterion for structural design. Timber is a time-dependent and viscoelastic material that exhibits elastic behavior under lower stress levels [1]. The time-dependent behavior is investigated by means of creep as a slow continuous strain under constant stress. Creep behavior of generally used building materials can be described in three stages, with the initial deflection depending on the magnitude of loading. The initial deflection is usually considered instantaneous, combining elastic and delayed elastic deformation. The curve shown in Figure 1 represents creep strain in the time domain. The first stage includes a continuous strain increase at a slowing rate (primary creep); the second assumes a linear creep curve at an almost constant rate which at low temperatures and low load levels may stabilize; and the third stage, which is far less investigated, includes increasing rate and fracture.

Since timber is a natural and anisotropic material, general conclusions connected with creep behavior are difficult to summarize. Many parameters influence creep behavior changing the slope of the deflection curve, including moisture content (MC), temperature, relative humidity, load type, size of the beam, knots, and grain deviation. The influence of these parameters can be determined experimentally. Numerous studies [2–10] concluded that the variation of relative humidity affects the MC of timber and increases creep, known as a mechano-sorptive creep, in comparison to conditions of constant relative humidity. For a given ambient temperature and relative humidity, wood adjusts a MC in equilibrium with the environment. Higher MC increases creep while the lower MC level may be neglected in calculating wood creep for constant temperature and relative humidity [11]. However, experimental investigations have shown that large-scale wood members used for indoor purposes exhibit minimal moisture fluctuations, which implies a minor mechano-sorptive creep effect [12]. Variable temperatures result in a complex creep behavior followed by decreasing elastic modulus, with constant temperatures below 50 °C having a negligible influence on creep [13,14]. During bending creep tests, it was shown that in the temperature interval from 20 °C to 50 °C, the creep rate slightly increased. However, the creep rate increases more pronouncedly above 50 °C [15]. Furthermore, a different creep rate level was obtained for different stress actions (tension, compression, bending) [16–18] and for loading parallel or perpendicular to the grain [19]. Experimental investigations have shown almost equivalent creep performance of solid timber and timber products under different environmental conditions [20]. The higher creep parameters are obtained for softwood in comparison with hardwood, but further investigations are necessary for deriving solid scientific conclusions [11].

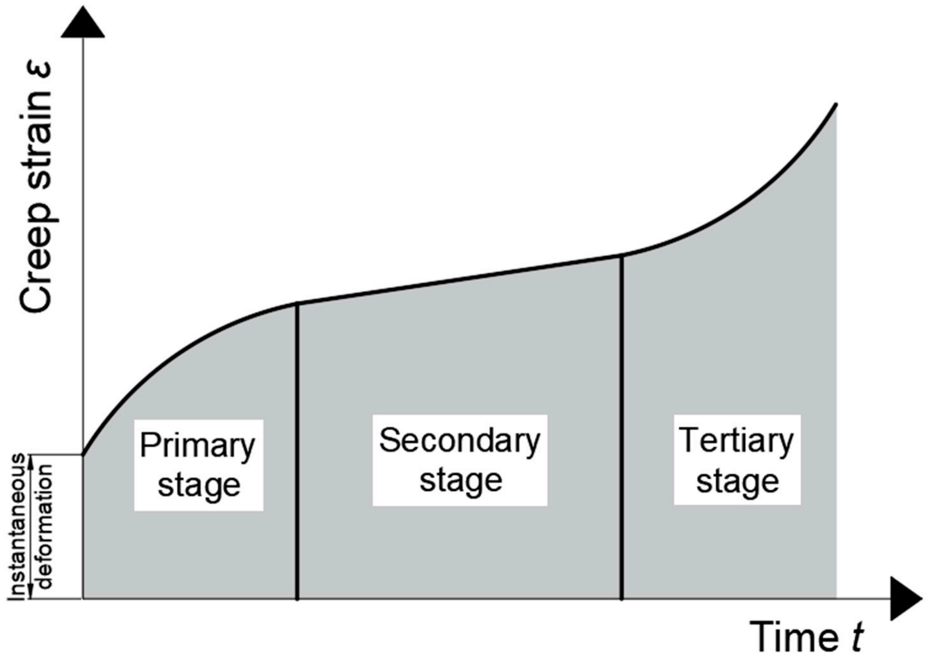

Figure 1. Creep stages.

According to European standards, during the building lifespan, structural elements are expected to fulfill requirements for serviceability and ultimate limit state. A bending moment may occur if a structural element is exposed to an external load applied perpendicular to a longitudinal axis of the element. The most common structural member subjected to bending is a beam. Long-term loading causes beam sagging to some extent over time; that is, the deflection increases over time in comparison to the initially measured deflection. The creep behavior of beams as an important consideration in the design of timber structures must be included in the limit state calculation since static testing is often not sufficient for describing the behavior of structural elements. In order to reduce the design value of a strength property X_d and to avoid the tertiary creep stage, Eurocode 5 [21] defines a modification factor k_{mod} which considers the effect of the load duration and the moisture content as:

$$X_d = k_{mod} \frac{X_k}{\gamma_M} \quad (1)$$

where X_k presents the characteristic value of a strength property and γ_M is the partial factor for a material property. According to this standard, the serviceability limit state includes the calculation of the instantaneous deformation u_{inst} and the final deformation u_{fin} under permanent action by using the following equation:

$$u_{fin} = u_{inst}\left(1 + k_{def}\right) \quad (2)$$

where k_{def} is the factor for the evaluation of creep deformation considering the relevant service class. It defines a relation between the initial deformation and the final deformation under permanent loading. Expected values of k_{def} are between 0.6 and 2.0 for solid and glued laminated timber, which implies creep deformation as twice the instantaneous deformation for service class 3. The instantaneous deformation should be calculated for the characteristic combination of action, using average values of the relevant modulus of elasticity. European codes define the criteria for the design of glued laminated timber made of softwood and poplar. EOTA (European Organisation for Technical Assessment) implemented EAD (European Assessment Document) in 2021, focusing on glued laminated timber made from specific hardwood species [22]. Due to climatic changes and afforestation policy, hardwood species are increasing their share in European forests. Also, hardwood species show enhanced mechanical properties compared to softwood but due to diversities between hardwood species, a complex manufacturing technology is required. According to that, extensive studies have been performed during the last decade in order to improve the insufficiently used potential of hardwood and to create a standardized European framework for glulam made from hardwood.

Numerous investigations were performed during the past century dealing with determining the creep response of timber under constant load and under changing and constant temperature and humidity. Due to a complex structure and various parameters influencing timber behavior that can be determined only experimentally, there is no standardized method for describing the creep behavior of timber. It has been experimentally confirmed that wood shows non-linear behavior across the entire stress range, but within specific stress boundaries and under constant MC and surrounding conditions, it is assumed as a linear viscoelastic material [3,4,23–26]. According to that, Boltzmann's superposition principle can be applied under low stresses [27]. Constant loadings with values lower than 45 to 60% of the maximum short-time load do not cause failure in the beams during this time [28]. A study [23] has indicated that the deformation-stress relationship of maple exposed to creep in tension parallel to the grain is dominantly linearly elastic under conditions of sufficiently low stress, moisture content, and temperature.

Currently, the authors are unaware of any existing studies on the creep behavior of glulam beams made from European hornbeam. Experimental investigations are needed in order to form a relationship between creep, deflection, time, and load level. In the framework of the research project conducted by Drvene konstrukcije Ltd. and the Faculty of Civil Engineering, Architecture, and Geodesy, Split, short-term bending tests were carried out to calculate the modulus of elasticity and ultimate strength of glulam made from European hornbeam. Since the static testing of materials is often not sufficient for the determination of their behavior in structural design, creep tests were also performed in order to determine the creep model. This study presents the bending creep behavior of glulam made from European hornbeam at different levels of the maximum short-term load during the period of three months. The relationship between creep deflection, time, and load level has been shown. The information was not available in the literature for glulam made from hornbeam except for the study of Moosavi [29]. The effect of altitude on creep parameters was examined during three-point bending tests of small specimens from hornbeam at 20% of the maximum bending load for 14 h.

2. Analytical Approach for Creep

Several mathematical models have been developed in order to estimate the creep response of linear and non-linear materials at constant and varying temperatures and humidity. Studies performed so far described creep behavior through different aspects, including deflection, compliance as the inverse of stiffness, relative deflection, and relative strain. A few empirical models were presented by Holzer et al. [12] for developing long-term behavior of timber under constant environment using the following expressions for creep compliance $J(t)$:

$$J(t) = J_0 + A_1 \log(t+1) \tag{3}$$

$$J(t) = J_0 + A_1 \log(t+1) + A_2 \log^2(t+1) \tag{4}$$

$$J(t) = J_0 + mt^n \tag{5}$$

where A_1, A_2, m and n are material properties, $J_0 = \frac{1}{E_0}$ corresponds to instantaneous compliance for $\sigma = 1$, E_0 is the elastic modulus. Although the appropriate equation depends on the required accuracy, the length of modeling time, and the researcher's choice, the last equation presents the power law form, which appears to be the most suitable equation with predictive capabilities for describing creep behavior. Refs. [11,18,28,30] found the power law the most appropriate equation for modeling the long-term behavior of Douglas-fir, spruce, and beech in bending under a constant environment. When validating a creep model, bending test results are preferable in comparison to tension and compression because of larger deformations which are easier to measure and simpler load method [12].

In the study [28], a power law equation is given in the aspect of deformation in time, and the creep behavior up to the point of inflection is described by an empirical expression:

$$\varepsilon(t) = \varepsilon_0 + at^m \tag{6}$$

where $\varepsilon(t)$ is the total strain at time t, ε_0 is the initial strain dependent on stress level at $t = 0$, a and m are constants obtained by experimental testing. Parameter m is independent of stress level, while ε_0 and a are dependent. It has also been applied to describe creep under compression and tension transverse to the grain.

3. Materials and Experimental Program

The hardwood species *Carpinus betulus* L. (European hornbeam) was used for the production of three sets, including 12 glulam beams, at the production facility held by the company Drvene konstrukcije Ltd. European hornbeam, a diffuse-porous hardwood accounting for nearly 8.5% of the overall wood reserve in Croatia, is supplied from a forest area in Virovitica—Podravina county. Lamellas were exposed to three diverse surface methods, planing, sanding with grit 60, and sanding with grit 80. Lamellas adhered with Prefere 4535 as a melamine-urea adhesive and Prefere 5035 as a hardener in relation to 100:25. Finally, 12 glulam beams were planned on each side with required dimensions of 60 mm × 80 mm × 1700 mm with no finger joints.

3.1. Short-Term Bending Tests

During the early phase of the previously mentioned research project [31–34], short-term bending tests were performed on 18 glulam beams made from European hornbeam according to EN 408 [35] at the specialized laboratory unit at the Faculty of Civil Engineering, Architecture and Geodesy, University of Split. Lamellas were treated with three different surface methods (planing—P, sanding with grit 60—S60, and sanding with grit 80—S80). The determined strength and stiffness were analyzed using ANOVA (analysis of variance) to assess the impact of various surface treatments on lamellas at a 95% confidence level [31]. The results revealed that there was no statistically significant impact of diverse surface treatments on the bending strength and the modulus of elasticity of glulam beams manufactured from European hornbeam. Also, the load-deflection graph from the bending tests confirmed comparable flexural behavior for diverse surface treatments. The average value of the maximum load F_{max} was 28.84 kN for planing, 31.99 kN for sanding with grit 60, and 31.09 kN for sanding with grit 80, respectively.

3.2. Creep Performance of Glulam Beams

Within the framework of the above-mentioned research project, the creep response of 12 glulam beams made from *Carpinus betulus* L. (European hornbeam) was investigated for three months under constant loading. Lamellas used for the production of glulam were processed at the production facility held by the company Drvene konstrukcije Ltd. with three diverse surface preparations of the lamellas. Preceding the gluing process, the moisture content of each lamella was determined using a moisture measuring device (Gann Hydromette HT 65). The recorded moisture content for each lamella ranged between 8% and 13%, with the greatest variability in moisture not exceeding 2% in each beam. Prefere 4535 as a melamin urea adhesive and hardener Prefere 5035 was used for gluing lamellas with a few modifications of the existing technology previously used for softwood. When applying adhesive to lamellas, the open assembly time persisted for up to 5 min, whereas the closed assembly time ranged from 5 to 15 min. Finally, glulam beams were produced with a cross-section of 60 mm × 80 mm and a length of 1700 mm without finger joints.

All specimens were kept in identical room conditions before performing tests. The tests were initiated in December 2022 and ended in June 2023 at the specialized laboratory unit of the Faculty of Civil Engineering, Architecture, and Geodesy, Split. Moisture content and density were determined before testing. Glulams were positioned symmetrically between supports made from stainless steel and loaded at two points with a constant load, as it is shown in Figure 2. For each surface treatment, two beams were loaded with 20% of a maximum short-term load F_{max} and the remaining two beams were loaded with 30% of F_{max}. Eight beams were loaded continuously with concrete blocks (Figure 3a), while four beams were loaded with sand (Figure 3b), both in two points. The mean density for European hornbeam was 780 kg/m^3.

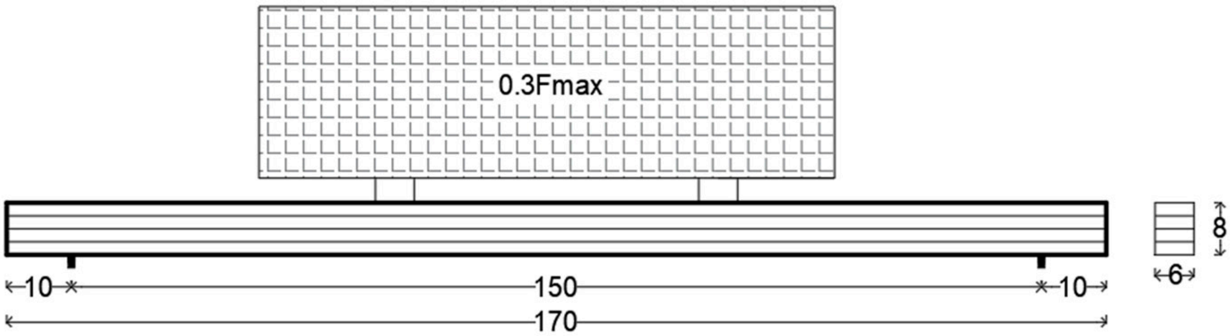

Figure 2. Flexural creep test arrangement for constant loading $0.3F_{max}$ with dimensions in *cm*.

(**a**) (**b**)

Figure 3. Glulam beams loaded with (**a**) concrete blocks; (**b**) sand.

The instantaneous elastic vertical deflection was determined manually after loading at the midspan with the Mituyoto dial indicator, capable of registering 0.01 mm. Also, deflections were recorded each hour during the first day of applying load, and then at daily intervals for three months. Creep was calculated as the difference between measured deflection and instantaneous elastic deflection. At the same time, the temperature and relative humidity (RH) were recorded continuously by a handheld sensor. Furthermore, the MC of each tested glulam beam was measured daily.

4. Results and Discussion

The creep arrangement was conducted in order to determine the time-dependent behavior of glulam beams made from European hornbeam in laboratory conditions with small changes in temperature and relative humidity. Previously, maximum load was obtained from static bending tests performed on glulam beams made from European hornbeam. The creep response of six glulam specimens was investigated under a constant load of $0.3F_{max}$, while the other six specimens were investigated under a constant load of $0.2F_{max}$. Since short-term tests have shown that surface treatment of lamellas does not affect the bending strength and stiffness, the average maximum load of 30.64 kN was calculated for all glulam beams independent of different surface treatments with the average global modulus of elasticity of 17,678 MPa.

The first group of specimens, including glulam of European hornbeam processed with sanding with grit 80, was tested between December 2022 and March 2023, while the second group, including glulam processed with planing and planing and sanding with grit 60, was tested between March 2023 and June 2023. Minor changes in temperature and RH are recorded, as shown in Figure 4. According to Eurocode 5, these conditions correspond to service class 1, which includes a temperature of 20° and a relative humidity exceeding 65% for a few weeks per year. The measured moisture content of each glulam beam changed with daily and seasonal changes in humidity, and it was recorded between 8 ± 2%. Due to some small moisture changes recorded during the test, the results are assumed to be representative of European hornbeam within the ambient relative humidity and temperature range.

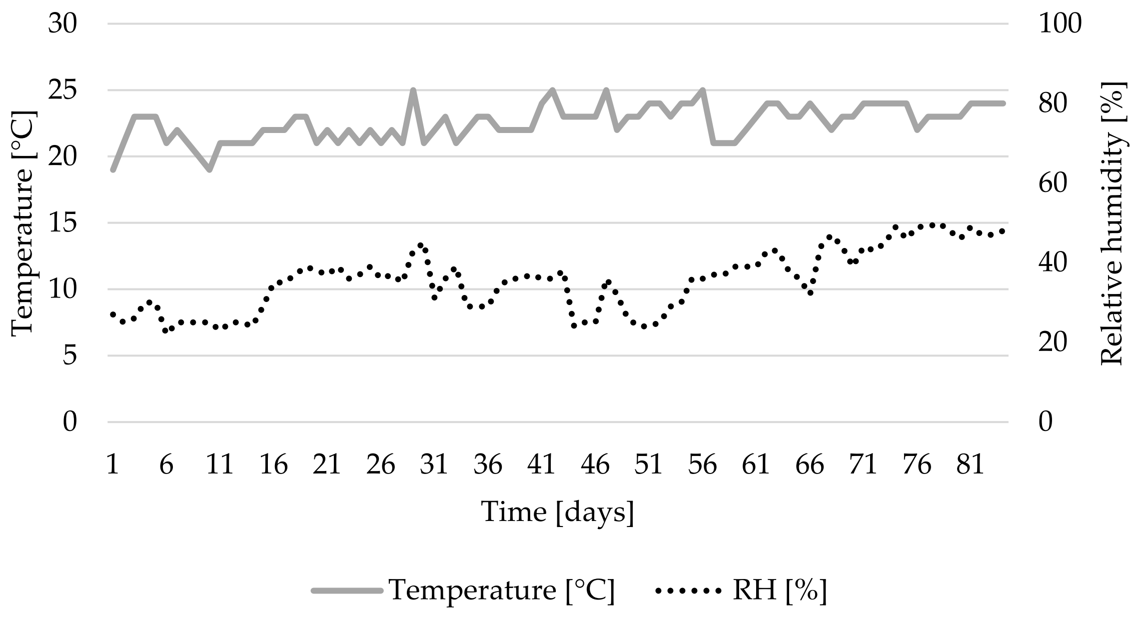

Figure 4. Changes in temperature and relative humidity during test time for the second group of specimens.

Deflections were recorded daily for each specimen, and the final deflection after three months was compared with the initial deflection. None of the tested beams exhibited a tertiary creep stage during the three months of performing the experiment due to a lower level of the maximum short-term load. The influence of load level on the mid-span deflection was investigated. The large initial rate of creep deflection can be observed, representing the primary creep stage. Afterward, the decreasing rate with small up-and-down changes in creep deflection was recorded, indicating the secondary creep stage and assuming a linear creep curve at an almost constant rate for an extended test period. The instantaneous mid-span deflection of specimens increased with increasing load levels from $0.2F_{max}$ to $0.3F_{max}$. Also, a creep part of the deflection increased with the increasing load level for each surface treatment of lamellas. Thus, it can be concluded that the difference in the final deformation between the load levels of $0.2F_{max}$ and $0.3F_{max}$ was caused by both creep deformation and instantaneous deformation. During the observed period of three months, the initial deflection was increased by approximately 30% for glulam beams under the load level of $0.2F_{max}$. Also, the initial deflection increased by approximately 35% for glulam beams under the load level of $0.3F_{max}$ after three months, except for glulam beams sanded with grit size S80 for which the initial deflection increased by 40%. The results of short-term experimental tests have shown insignificant differences in the obtained results for global modulus of elasticity with standard deviations of 1343.6 for planing, 859.7 for sanding with grit 60, and 1769.3 for sanding with grit 80, respectively. Since the values of the mid-span deflections of glulam beams depend on a global MOE, there are differences in measured initial deflections as well as in the creep part of deflections. Further investigations into larger sample sizes are needed in order to define a more detailed conclusion.

Deflection-time plots were obtained, and smooth curves were drawn through a sufficient number of experimentally obtained points in order to accurately describe the creep properties of glulam made from European hornbeam, as it is shown in Figures 5 and 6 under constant loading of $0.2F_{max}$ and $0.3F_{max}$, respectively.

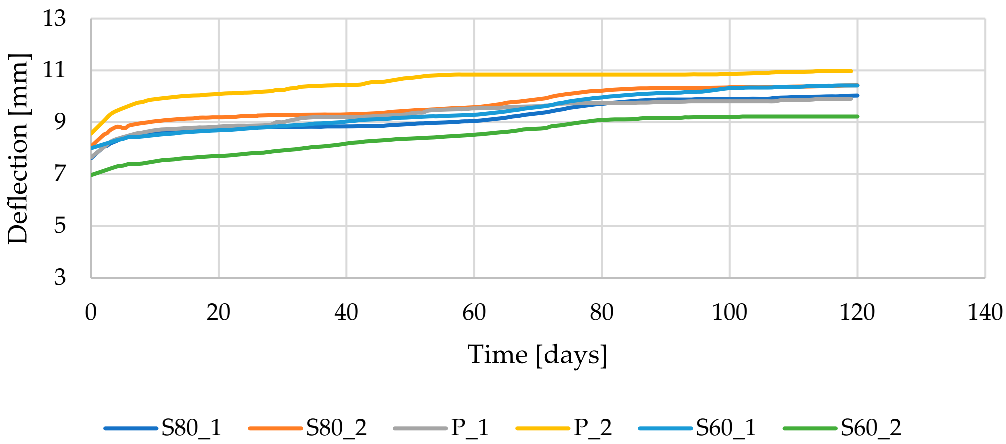

Figure 5. Experimental deflection-time graph for six glulam beams under constant loading of $0.2F_{max}$.

The power law was used for a description of the creep behavior before the point of inflection was reached. In comparison with other typical models, the power law is a simple exponential model with two parameters:

$$u(t) = u_0 + At^B, \tag{7}$$

where $u(t)$ is the total midspan deflection at time t, u_0 is the initial deflection dependent on stress level at $t = 0$, A and B are constants greater than 0, obtained by fitting experimental data. The experimentally obtained data were parameterized by fitting the power law using a non-linear least square method in Matlab Curve Fitter. The parameters A and B are determined and presented in Table 1. Due to higher values of the coefficient of determination R^2, close to 1, it can be concluded that the regression curve fits well with the experimental data and that the power law is suitable for describing the behavior of glulam from European hornbeam. As it is previously mentioned, the theory of linear viscoelasticity can be accepted for the lower load ratio, which is valid for this study. Generally, it can be noticed that the overall deformation curve exhibited a primary creep stage and part of the secondary stage.

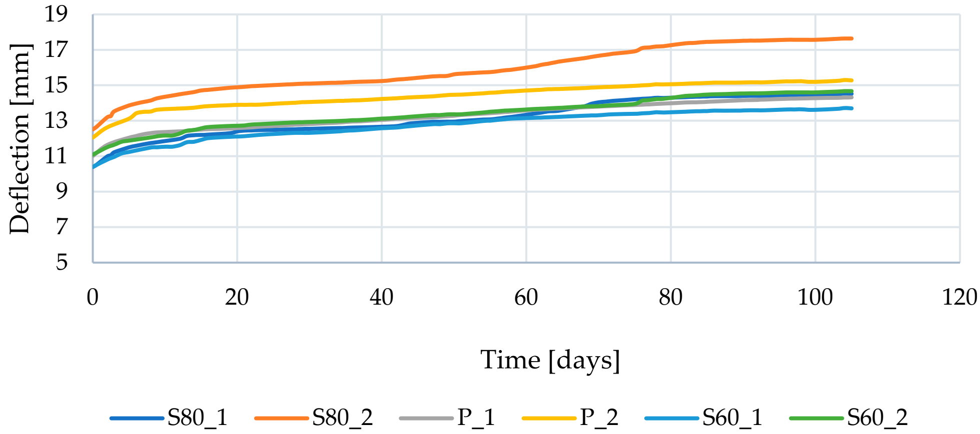

Figure 6. Experimental deflection-time graph for six glulam beams under constant loading of $0.3F_{max}$.

Table 1. Obtained parameters for the creep model.

Load Level	Surface Treatment	Parameter A	Parameter B	R^2
$0.2F_{max}$	S80	0.27	0.45	0.90
	P	0.35	0.31	0.96
	S60	0.20	0.61	0.98
$0.3F_{max}$	S80	0.40	0.52	0.96
	P	0.43	0.48	0.98
	S60	0.41	0.44	0.98

According to Eurocode 5, the expected value for the factor for the evaluation of creep deformation during building lifespan and under permanent loading is 0.6 for service class 1. In comparison, during this research, the increase of the initial deflection for three months was calculated with a value between 1.3 and 1.4 of initial deflection for glulam in bending and under constant loading of 20% and 30% of maximum loading from short-term tests, respectively. It is important to mention that the applied stress during the bending creep test was 25 Mpa and 37 Mpa for 20% and 30% of maximum loading from short-term tests, respectively.

5. Conclusions

Describing wood creep behavior is a complex procedure affected by its natural anisotropy, assumed orthotropy for engineering structures, and other various parameters like temperature, humidity, and loading type. Another difficulty is collecting data through a long-term period since tests lasting for a few months are short in comparison to 50 years of the expected building's lifespan. The authors are unaware of any study currently carried out on glulam beams made from European hornbeam. This study was carried out during the last phase of the aforementioned research project in order to understand the load duration characteristics of glulam made from European hornbeam harvested in Croatian forests and for which there is no technical assessment. Considering the outcomes of this study, the following conclusions can be established:

- The creep curves for three sets of glulam beams under each load level were similar. The negligible influence of surface treatment of lamellas on the flexural performance of glulam beams was confirmed when analyzing creep behavior. One exception for glulam beams sanded with grit size S80 under the load level of $0.3F_{max}$ was observed since the initial deflection increased by 40% after three months in comparison to 35%

for planing and sanding with grit size 60. Further investigations into larger sample sizes are needed in order to define a more detailed conclusion.

- The results have shown that the power law fits well with experimental data under observed two load levels of $0.2F_{max}$ and $0.3F_{max}$. The fitted curve was in an overall good agreement due to high values of R^2.
- Within a sustained load of $0.2F_{max}$ and $0.3F_{max}$ for three months, all glulam beams exhibited only a secondary creep stage. The creep increased with the higher level of load.
- Based on the obtained test results, the estimated value of bending deflection is higher than it is presented in Eurocode 5.
- The mechano-sorptive effect is negligibly small since the relative humidity and temperature in the Laboratory had small variations over time.

Further long-term experiments need to be conducted on a larger sample, including variability of timber-like grain deviation. Also, the effects of changes in temperature and relative humidity related to changes in moisture content of glulam made from European hornbeam have to be considered for application in engineering since they can cause an unknown amount of creep deflection. Other types of testing (compression, tension) have to be taken into account during the same season in order to study their effect on creep response. This study presents a contribution to the determination of creep characteristics of hardwood species by expanding the available database.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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