Original article

Danyang Tong, Susan Alexis Brown*, David Corr and Gianluca Cusatis

Wood creep data collection and unbiased parameter identification of compliance functions

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Abstract: Rising global emission have led to a renewed popularity of timber in building design, including timber-concrete tall buildings up to 18 stories. In spite of this surge in wood construction, there remains a gap in understanding of long-term structural behavior, particularly wood creep. Unlike concrete, code prescriptions for wood design are lacking in robust estimates for structural shortening. Models for wood creep have become increasingly necessary due to the potential for unforeseen shortening, especially with respect to differential shortening. These effects can have serious impacts as timber building heights continue to grow. This study lays the groundwork for wood compliance prediction models for use in timber design. A thorough review of wood creep studies was conducted and viable experimental results were compiled into a database. Studies were chosen based on correlation of experimental conditions with a realistic building environment. An unbiased parameter identification method, originally applied to concrete prediction models, was used to fit multiple compliance functions to each data curve. Based on individual curve fittings, statistical analysis was performed to determine the best fit function and average parameter values for the collective database. A power law trend in wood creep, with lognormal parameter distribution, was confirmed by the results.

Keywords: creep; database; long-term prediction; parameter identification; wood.

***Corresponding author: Susan Alexis Brown**, Northwestern University, 2145 Sheridan Rd A236, Evanston, IL, 60208, USA, E-mail: susanalexisbrown@u.northwestern.edu. https://orcid.org/0000-0002-7467-3991
Danyang Tong, David Corr and Gianluca Cusatis: Northwestern University, 2145 Sheridan Rd A236, Evanston, IL, 60208, USA, E-mail: d-corr@northwestern.edu (D. Corr), g-cusatis@northwEstern.edu (G. Cusatis), https://orcid.org/0000-0001-8429-228X (D. Tong) , https://orcid.org/0000-0001-7436-3910 (G. Cusatis)

1 Introduction

The long-term shortening of structures due to sustained loads is a critical design consideration for engineers. The total deformation exhibited throughout the building's lifespan can exceed twice that of the instantaneous deflection (Ross 2010). Many empirically-based models have been developed to predict this behavior for different structural materials. Two main material behaviors are linked to long-term shortening: Shrinkage, driven primarily by moisture movement within a material, and creep, the tendency of a solid to deform over time under the effect of constant stresses. In concrete the combined effects of shrinkage and creep are well studied and modeled. In 1978, Bažant started a concrete database for creep and shrinkage tests to use as verification of long-term models (Hubler et al. 2015). This database now consists of 1400 sets of creep curves, accumulated over decades of testing. It is the basis for the calibration of the four prediction models currently used in ACI code. These models consider factors such as concrete composition, curing environment, geometry, loading history, and stress conditions (ACI 2008). This allows for confident prediction of building behavior, from single-story homes to skyscrapers.

However, carbon emissions due to concrete have become concerning a as rising urban population demands increasing high density construction. Currently over 8% of global carbon emissions come from cement production (Lehne and Preston 2018). While there is work to reduce the global emissions associated with concrete construction, focus has also shifted to timber as a structural material. Historically constrained to six stories or less, modern innovation in timber engineering now allows for mass timber structures up to 18 stories, such as the current record holder Mjøstårnet, standing at 81 m in Brumunddal, Norway (Abrahamsen 2017). This has great potential to decrease the carbon impact of urban construction. However, at that height, creep and shrinkage become a much greater concern. As a biopolymer, wood has different impacting factors associated with time-based behavior and much higher variation of material parameters between similar specimens, compared with an engineered material such as concrete. Therefore a comprehensive understanding of wood behavior over the long-term is critical.

Wood shrinkage is well studied and can be modeled to a high level of accuracy. It is generally calculated to be linearly related to the change in moisture content (MC), approximated as 1% change in length for every 4% change in moisture content (Ross 2010). If more accurate values are needed there are references which provide specific relationships depending on species and orientation (Ross 2010). The engineer can determine, based on assumed factory MC and on-site equilibrium humidity, what the expected shrinkage will be. They may then design for this movement, for example to prevent differential shifting (between wood and other materials) or issues with mechanical, electrical, and plumbing design (McLain and Steimle 2017).

Unlike shrinkage, wood creep is significantly less understood, and its modelling and prediction are in no way standardized. Creep varies significantly due not only to environmental conditions, but also internal cell structure. Even within the same species, creep behavior may vary due to the age of the tree when it was cut and the MC history (Ross 2010). Some studies have attempted to isolate these issues to develop a prediction model for wood creep. For example, Holzer et al. (1989) presents a review of creep studies, discussing the effects of MC and orthotropy. However, the authors note that many studies have “conflicting experimental objectives” and are not suitable for long term predictions. Additionally, many studies use bending tests, which combines both tension and compression behavior, while others test only in tension or compression. Combining these tests into one database would assume that the tension and compression creep behavior of wood is necessarily similar, which may not be true (Hassani et al. 2015; Ozyhar et al. 2013). Additionally, aspects such as the orthotropic behavior are still unclear.

Another issue is the difficulty in gathering long-term data. While there are many tests spanning a few months, this is extremely short compared to the 50–100 years expected from most buildings. Indeed, the authors could only find a single study spanning more than 5 years (Gressel 1984). Recently, studies on long-term compression orthogonal to grain have been performed, with tests lasting 2.5 years, including an initial phase at constant environmental conditions (Massaro and Malo 2019a,b). Additional studies interpreted short- and long-term creep as two separate but related phenomena (Hunt 2004); other studies have attempted to use a time-temperature superposition method, derived from polymer theory, to compensate for this limitation (Hunt 1999). However, extrapolation to the scale of a structure is difficult when only considering two or three sets of data, as many individual studies produce.

Further consideration must also be given to the type of prediction model which should be utilized. The modeling of wood creep has historically taken the form of either empirical models or mechanical (or rheological) models (Bodig and Jayne 1982; Pentoney and Davidson 1962; Schniewind 1968). Of these, empirical models are parameter-based functions obtained by fitting a mathematical expression to experimental data. A common example is the power law, with three parameters. Conversely, a common mechanical model used in compliance may be expressed as a series of Kelvin chains. These include springs and dashpots in parallel to simulate the time-dependent behaviors. The model contains NK units, as necessary to mimic the creep phenomenon. Authors have used a varying number of Kelvin units to fit Kelvin chains to their experimental data. For example, Grossman and Kingston (1954) fitted test curves using three and four K units. Mukudai (1983) used three K units to fit 10 h bending tests. Gressel (1984) used one K element to fit 10 year experimental results. Mechanical models are rate-type models, which is preferred for computational implementation. However, for three or more units the model would have at least six non-unique parameters, and it may be difficult to determine trends in the results, e. g., a relationship between the parameter values and MC. Thus a prediction model would not be able to uniquely take in material values, such as elastic modulus and MC, and directly determine parameter values. This study therefore only considers empirical models to better discuss results within the context of the database.

Due to the aforementioned difficulties, there is no robust method for predicting creep behavior in structures. Current design guidelines provide only a 1.5 × or 2 × coefficient on the elastic bending deflection to account for long-term behavior, and lack any recommendations for columns (NDS 2017). Considering the current trend in tall timber, this could have important consequences. The difference of a few percent can have significant repercussions for a 50 m building, where it would have been easily handled for one of 10 m. One particular issue is differential vertical shortening. Mass timber design often includes a concrete core for lateral support; these cores are heavily reinforced for lateral stiffness, and carry little vertical load aside from self-weight. They thus exhibit minimal creep past initial construction. However, the timber columns in the self-same structure carry very high loads, and those high stresses can causes significant creep over the lifespan of the structure (Willebrands 2017). The difference in creep deformations between these two elements has the potential to create extreme cases of differential shortening that may not be fully known during design and construction. It is imperative that renewed attention be given towards how creep and other long-term behaviors will effect the shortening of mass timber buildings.

To address this problem, this paper proposes the formation of a wood creep database a la Bažant and Baweja for concrete (Bažant and Baweja 2000). It is the intent of the authors to standardize future work and allow for unbiased model prediction comparisons.

1.1 Wood creep

To develop a database and prediction model, it is first necessary to understand how various factors influence the long-term shortening of wood. First consider that wood is an anisotropic material, generally assumed orthotropic for engineering purposes. Indeed, wood is typically stiffer and stronger in the direction parallel to the grain, verses perpendicular to the grain, even in creep. In the majority of studies it is relevant to test parallel to the grain, though some such as Ranta-Maunus (1993) and more recently Massaro and Malo (2019a), also conducted tests perpendicular to the grain. In the present study it is assumed that the elastic properties are time-independent and the reported experimental values are given parallel to the grain.

Three types of creep are identified in wood. The first, occuring in service conditions and constant relative humidity, is most studied and of most interest. The second type of creep is associated with transient MC changes and is generally known as mechano-sorptive creep. The source of mechano-sorptive creep is not fully known, but its effects can be quite large. The third type consists of pseudo creep and recovery phenomenon. In this paper only the first type of creep is considered.

The evolution of creep deformations is divided into three stages. In the initial stage, or in primary creep, the strain rate is relatively high. As secondary creep begins, the strain rate is reduced to a minimum and becomes nearly constant. In tertiary creep, the strain rate increases exponentially with stress, and is associated with damage. Under relative small stress, creep increases linearly as stress levels increase and stays within the primary and secondary region. According to Schaffer (1972), "Wood behaves non-linearly over the whole stress-level range, with linear behavior being a good approximation at low stress. Because of this nearly linear responses at low levels of stress, Boltzmann's superposition principle applies to stress-strain behavior for stresses up to 40% of short time behavior." The experiments of Schaffer's indicate that within certain limits of stress and at constant MC and temperature wood can be treated as a linear viscoelastic material. This finding was later verified by other studies (Bažant 1985; Foudjet and Bremond 1989; Hering and Niemz 2012; Massaro and Malo 2019a; Nakai and Grossman 1983). Youngs et al. (1957) conducted compression creep tests perpendicular to grain of red oak under various stress levels at 28 °C (82 °F). Hoyle et al. (1985) tested Douglas-fir in bending at constant room temperature and low MC at different levels of applied stress, below 50% of clear wood ultimate bending strength. Jong and Clancy (2004) compared wood creep in an hour under two different load levels, 6 and 8 MPa (870 and 1160 psi). Hunt (2004) analyzed the data of Gressel's 8 years wood creep bending test, concluding that there can be no creep limit in a constant environment (Gressel 1984). Creep can reach tertiary stages due to stress levels and load durations which are over certain limit values. Liu (1993) analyzed bending samples under different applied stress level ranges from 4 to 60% of the rupture strength of Scots pine. The experimental results show tertiary creep deflections and the associated failure points.

Temperature is also a contributing factor to material behavior. Higher temperature decreases the elastic modulus of wood (Bach 1968). It is also found that increasing of temperature accelerates the creep deformation and creep rate. King (1961) compared creep curves of Hoop pine from 21 to 27 °C (75 to 80 °F) under different levels of stress, and confirmed this effect. Davidson (1962) conducted bending tests to study the influence of temperature of wood by using six species subjected to temperatures ranging from 20 to 60 °C (68 to 140 °F). Similarly, Kingston and Budgen (1972) concluded from bending and compression tests in the range of 20 to 50 °C (68 to 122 °F) that temperature had a obvious effect on wood creep. Experiments by Jong and Clancy (2004) show that an increase in temperature increases the creep with the temperature ranges from 20 to 100 °C (68 to 212 °F).

One of the most important factors in wood behavior is MC and changes thereof. As mentioned previously, shrinkage in wood occurs when the moisture level drops. However MC also affects creep behavior. Water in wood acts as a plasticizer, in effect decreasing the viscosity; increases in MC will lead to increases in creep compliance (Schniewind 1968). For example, in bending, total deformation and creep rate have been found to increase with increasing moisture content (Bodig and Jayne 1982; Fridley et al. 1991; Hering and Niemz 2012; Schniewind 1968). Armstrong and Kingston (1960) found that the increase in deformation of initially saturated wood is much greater than in initially dry wood (Armstrong 1962). It is also shown that MC exhibits larger influence on wood creep than temperature (Hsieh and Chang 2018). The larger effect of MC on creep was also observed in tensile tests of Norway spruce (Engelund and Salmén 2012).

As mentioned, mechano-sorptive creep defines the response produced by the combination of mechanical influence and moisture adsorption, which cannot be predicted from each effect separately (Grossman 1976). It was proposed that changes in the MC of the wood while under load markedly influenced both creep-rate and total creep, which indicates that mechano-sorptive effects will results in failure under lower stresses or in shorter time (Armstrong and Kingston 1960; Armstrong 1972). This phenomenon is supported by a large number of experiments (Armstrong and Christensen 1961; Bodig and Jayne 1982; Fridley et al. 1992; Mårtensson 1994; Toratti 1991; Zhou et al. 1999). Experimental results also indicate that the deflection of a loaded beam which is taken through one or more cycles of humidity increases far beyond the deflection of beams loaded after they have been conditioned to either of the extreme moisture levels (Hunt 1999). Additional results indicate that mechano-sorptive creep is exacerbated in directions perpendicular to the grain compared to the longitudinal direction (Ranta-Maunus 1993).

In addition to stress and environmental conditions, other factors such as species and material structure play a role in creep. These factors are more difficult to isolate. For example, in construction, often only a species group such as Douglas-Fir-Larch is specified, for which general properties are provided. However due to variation in the microstructure of different tree species the instantaneous deformation and total creep may vary, and thus cannot be considered independently of species. Foudjet and Bremond (1989) conducted 14 day bending tests of four tropical hardwoods under room temperature, at less than 35% of stress at failure and with constant MC. The creep function curve shows similar trends between species, but different absolute values. Similar results are found in other studies (Kingston and Budgen 1972; Tissaoui 1996).

Wood is also divided into early- and late wood, according to the time within the life cycle during which the cells were grown. The main factor which determines the different properties of the early and late wood is the structure within the cell wall, defined by the microfibril angle (MFA). This angle is a consequence of the need for higher flexibility in young saplings, compared to the stiff trunks of grown trees. Experiments suggest that in the region of small MFA, the creep deformation becomes much smaller (Kojima and Yamamoto 2004; Roszyk et al. 2010). As the tree grows, the MFA decreases, which means that early wood creep is larger than that of late wood (Hunt 1999).

2 Materials and Methods

2.1 Data collection

As noted above, variable environmental conditions were not considered for this study. Thus, to build the database, only experiments which were conducted under constant environmental conditions were considered viable. They were then filtered based on realistic engineering requirements. Humidity, temperature, and loading should reflect values typical in mass timber projects. Thus, the requirements for data include: room temperature (20–25 °C or 68–78 °F), a small range of equilibrium moisture content (8–15% is the typical range for structures in service), and relatively low stress levels (under 40% of ultimate strength or modulus of rupture). MFA was not taken into account as it is generally not measured in experimental creep studies.

The database includes 12 different tree species (from multiple continents), loaded in bending, tension, and compression in the longitudinal direction. Time spans ranged from 4 h to a maximum of 450 days. One major drawback of available data was the lack of long-term studies, as previously mentioned. Though one study was found which included tests over 10 years, the data was unavailable (Gressel 1984). This is a serious limitation on the predictive capabilities of the compliance function.

Nakai and Grossman (1983) tested bending specimen with the size 15 × 15 × 800 mm (0.6 × 0.6 × 7.8 in) under four different load levels corresponding to 17, 33, 50, and 67% of the modulus of rupture, as tested by the authors with matching material. (The modulus was not provided by the authors; table values for the species are Jarrah: 110 MPa (16 ksi), Mountain Ash: 98 MPa (14.1 ksi), and Hoop Pine: 85 MPa (12.3 ksi).) However, only the data at 17 and 33% of the modulus of rupture were taken into the database, to comply with the initial assumption of linear behavior. Hoyle et al. (1985) conducted bending tests of Douglas-fir beams under stress levels of 8.61 MPa (1250 psi), 13.1 MPa (1900 psi), 17.9 MPa (2600 psi), and 21.7 MPa (3150 psi) with 10 × 10 × 488 cm (4 in × 4 in × 16 ft) specimens. Foudjet and Bremond (1989) performed bending creep tests of four different species for a 600 mm (23.5 in) span with various width and depth to resist shear force. Fridley et al. (1992) showed one typical compression test results with specimens 5 × 5 × 365 cm (2 in × 4 in × 12 ft) in size under a stress level 5% of the static strength. Bond (1993) conducted tension and compression tests under stress levels equal to 20–25% ultimate strength, with a specimen size of 1.25 × 1.25 × 30.5 cm (1/2 × 1/4 × 12 in.) and 1.25 × 1.25 × 10 cm (1/2 × 1/2 × 4 in.) respectively. Liu (1993) grouped bending tests according to elastic modulus. Experimental results with load levels under 45% of the ultimate tensile strength were used in the database. Tissaoui (1996) tested tension and compression creep for a specimen size of 1.25 × 1.25 × 30.5 cm (1/2 × 1/4 × 12 in.) and 1.25 × 1.25 × 10 cm (1/2 × 1/2 × 4 in.) respectively for southern pine and yellow poplar. Hering and Niemz (2012) conducted three groups of bending tests under MCs at 8.1, 15.5, and

23.2%. The two low MC tests were averaged and used in the database. Note also that different papers plotted experimental results either averaged or as individual test curves. For consistency all curves of identical temperature, stress, etc. per study were averaged within the database. A summary of the papers collected into the database, as well as experimental conditions and test methods therein, is presented in Table 1.

After the studies were filtered, the data was converted to a consistent format. Researchers generally focused on different aspects of the results, and so data might be presented as deflection, relative deflection, strain, relative strain, compliance, or relative compliance. All data was converted into compliance with the assumption $J_0 = 1/E_0$, where J_0 is the instantaneous elastic strain caused by $\sigma = 1$, and E_0 is the elastic modulus. The specimen are all slender beams and only parallel-to-grain experiments are taken into account. It is therefore reasonable to ignore Poisson's effect and assume a one-dimensional problem. Some papers also do not provide elastic modulus; in this case elastic modulus values were assumed according to the species. Figure 1 displays compliance vs. log of time for the experimental data.

2.2 Creep models

Whilst any empirical equation may be used, some have been found to be more relevant than others for creep compliance, particularly in wood. Three equations were considered in this study, based on a review of the literature:

Table 1: Experimental database.

	Species	Class	Temperature (°C)	MC (%)	Loading	Time	Elastic modulus (GPa)
Bond 1993	Southern Pine	S	25	12	Tension	4 h	–
	Southern Pine	S	20	9	Tension	16 h	–
	Southern Pine	S	20	12	Tension	16 h	–
Liu 1993	Scots Pine	S	23	11.9	Bending	65 d	13.4
	Scots Pine	S	23	11.9	Bending	105 d	13.6
	Scots Pine	S	23	11.9	Bending	60 d	14
	Scots Pine	S	23	11.9	Bending	65 d	14.5
	Scots Pine	S	23	11.9	Bending	20 d	15.8
	Scots Pine	S	23	11.9	Bending	450 d	16.7
	Scots Pine	S	23	11.9	Bending	30 d	16.7
	Scots Pine	S	23	11.9	Bending	125 d	17
	Scots Pine	S	23	11.9	Bending	450 d	18.2
	Scots Pine	S	23	11.9	Bending	75 d	18.2
Hoyle 1984	Douglas-fir	S	21	12	Bending	400 h	11.2
	Douglas-fir	S	21	12	Bending	400 h	10.9
	Douglas-fir	S	21	12	Bending	400 h	11.4
	Douglas-fir	S	21	12	Bending	400 h	12.8
Tissaoui 1996	Southern Pine	S	20	12	Tension	125 d	–
	Yellow Poplar	S	20	12	Tension	125 d	–
	Yellow Poplar	S	20	12	Compression	125 d	–
	Southern Pine	S	20	12	Compression	125 d	–
Soltis 1989	Douglas-fir	S	22	9	Compression	160 d	11.4
	Beech	H	20	8.1	Bending	7 d	–
Foudjet and Breamond 1989	Azobe	H	20	12	Bending	11 d	20.7
	Azobe	H	20	12	Bending	11 d	20.7
	Movingui	H	24	11.8	Bending	11 d	10
	Movingui	H	24	11.8	Bending	11 d	10
	Movingui	H	24	11.8	Bending	11 d	10
	Sapeli	H	19	15	Bending	12 d	8.3
	Sapeli	H	19	15	Bending	12 d	8.3
	Sapeli	H	19	15	Bending	12 d	8.3
	Tali	H	25	12.7	Bending	17 d	14.7
	Tali	H	25	12.7	Bending	17 d	14.7
Nakai and Grossman 1983	Jarrah	H	25	12	Bending	180 d	14.9
	Jarrah	H	25	12	Bending	180 d	14.9
	Mountain Ash	H	25	12	Bending	180 d	17.4
	Mountain Ash	H	25	12	Bending	180 d	17.4
	Hoop Pine	S	25	12	Bending	180 d	18.1

The species classification "hardwood" and "softwood" are represented by "H" and "S", respectively.

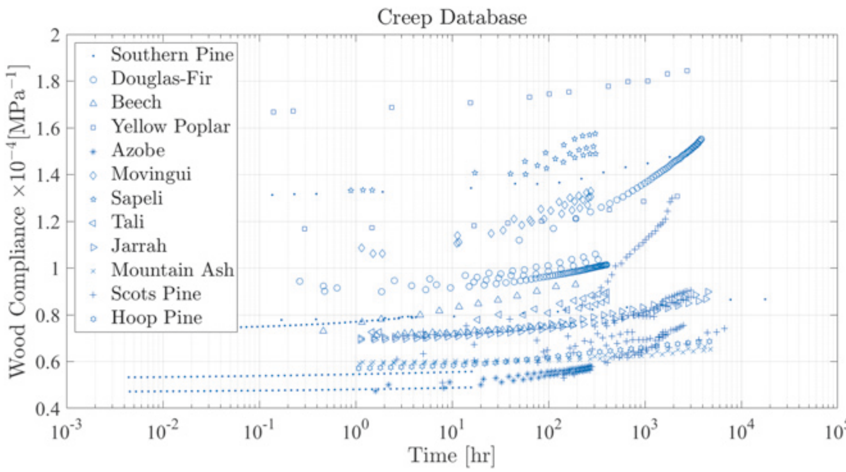

Figure 1: Creep data with instantaneous compliance.

$$J(t) = c + a\left(\frac{t}{t_0}\right)^b \tag{1}$$

$$J(t) = c + a_0 \log\left(\frac{t+1}{t_0}\right) \tag{2}$$

$$J(t) = c + a_1 \log\left(\frac{t+1}{t_0}\right) + a_2\left[\log\left(\frac{t+1}{t_0}\right)\right]^2 \tag{3}$$

where t_0 is 1 h, the same units as t, and a_0, a_1, a_2, a, c and b are empirical constants (Holzer et al. 1989). For Eq. (1), (2), and (3), t is the time of loading, and the constant c corresponds to the instantaneous compliance $J_0 = 1/E_0$, as previously mentioned. Note that these equations are only applicable to constant-load histories (Fridley et al. 1992).

King (1961) developed Eq. (2) to fit tension experimental result for domestic and tropical species. Bach (1968) conducted tension tests of hard maple for 1,000 min and fitted data using Eq. (3). Schniewind and Barrett (1972) conducted tensile creep tests in the radial-longitudinal and tangential-longitudinal planes of Douglas-fir at 10% MC and used the form of Eq. (1) as model function to fit tests. Gressel (1984) fitted existing experimental data from 10 year creep tests using Eq. (1). Hoyle et al. (1985) implemented Eq. (1) based on experimental results from bending Douglas-fir beams. Bond (1993) used Eq. (1) to fit tension and compression creep test of pine and yellow poplar.

2.3 Optimization and fitting

For fitting the compliance functions, an unbiased statistical evaluation of weighted least square method was used. The algorithm was devised by Bažant and associates to handle the spurious effects of non-uniform data distribution. This has consistently plagued time-related data sets for concrete responses due to a greater amount of short term data (Bažant and Baweja 2000; Rasoolinejad et al. 2019). It is clear that for the current database, the majority of data points concentrate in early time periods. Thus, the data for each curve was divided by intervals of equal size in log scale, $\log \Delta(t_i) = \log(t_{i+1}) - \log(t_i) = 1$, $i = 1, 2, 3 \ldots n$. The number of intervals, n, was defined such that each interval has a similar number of data points, m_i. The points are weighted based on Eq. (4). This method was also adopted in Pathirage et al. (2019). The weights, $\overline{w}$, for each interval were calculated as follows,

$$\overline{w} = \sum_{i=1}^{n} \frac{1}{m_i} \tag{4}$$

$$w_i = \frac{1}{m_i \overline{w}}$$

where the w_i is the *ith* interval weight.

Once weights are obtained, the weighted standard deviation, s, may be computed as follows,

$$s = \sqrt{\frac{N}{N-P}\frac{\overline{w}}{n}\sum_{i=1}^{n} w_i \sum_{j=1}^{m}\left(Y_{ij} - y_{ij}\right)^2} \tag{5}$$

The error (or residual) $e = Y_{ij} - y_{ij}$ is regarded as the error of predictions where Y_{ij} is the experimental results and y_{ij} is the numerical prediction of compliance as a function of time. N is the total number of data points. P is the number of parameters (e. g., Three for power law fitting). The multiplier $N/(N-P)$, used to avoid a bias, is close to one because the value for N is much larger than P. This multiplier is necessary primarily to prevent the variance of regression errors of the database, which has a finite number N data points, from being smaller than the variance of a theoretical database where $N \to \infty$. Additionally, only a set of P data points can be fitted exactly without error (Bažant and Li 2008). The weighted mean value for experimental data is $\bar{y}$, s is defined as the overall weighted standard error of numerical predictions per curve, and $\bar{s}$ is the overall weighted deviation of all the data.

$$\bar{s} = \sqrt{\frac{N}{N-P}\frac{\overline{w}}{n}\sum_{i=1}^{n} w_i \sum_{j=1}^{m}\left(Y_{ij} - \bar{y}\right)^2} \tag{6}$$

where

$$\bar{y} = \frac{\overline{w}}{n}\sum_{i=1}^{n} w_i \sum_{j=1}^{m} y_{ij} \tag{7}$$

With s, $\bar{y}$, and $\bar{s}$, the unbiased coefficient of variation, $\omega_n = s/\bar{y}$, and the coefficient of determination, $r^2 = 1 - s^2/\bar{s}^2$, can be computed for each curve to identify the goodness of fit. The nonlinear regression fitting results are presented in Table 2 in detail for Eq. (1). After an analysis

Table 2: Parameter fitting results of $J(t) = c + a\left(\frac{t}{t_0}\right)^b$.

	$a \times 10^{-11}[Pa^{-1}]$	$b\,[-]$	$c \times 10^{-11}[Pa^{-1}]$	R^2	ω_n
Bond 1993	0.438	0.283	7.265	0.997	0.001
	0.241	0.145	5.215	1.000	0.000
	0.155	0.162	4.651	1.000	0.000
Liu 1993	0.012	0.698	5.007	0.999	0.022
	0.361	0.297	3.835	0.981	0.013
	0.428	0.310	5.463	0.999	0.023
	0.194	0.287	5.560	0.999	0.011
	0.008	0.858	6.051	0.999	0.020
	0.932	0.147	4.914	0.915	0.026
	0.012	0.677	6.268	0.984	0.008
	0.581	0.230	5.380	0.994	0.017
	0.871	0.271	5.464	0.968	0.049
	0.067	0.591	7.065	0.988	0.023
Hoyle 1984	0.178	0.359	8.937	0.993	0.004
	0.138	0.401	9.246	0.989	0.005
	0.112	0.408	8.946	0.990	0.004
	0.194	0.286	7.788	0.969	0.006
Tissaoui 1996	0.123	0.347	13.09	0.994	0.004
	0.052	0.445	11.64	0.996	0.003
	0.376	0.213	16.43	0.994	0.003
	0.627	0.089	7.207	1.000	0.006
Soltis 1989	0.865	0.245	8.956	1.000	0.001
Stefan 2012	0.125	0.311	6.973	0.971	0.004
Foudjet and Bremond 1989	0.279	0.271	4.400	0.997	0.003
	0.276	0.255	4.657	0.995	0.003
	0.998	0.212	9.488	0.996	0.004
	0.837	0.258	9.592	0.994	0.006
	0.883	0.243	9.899	0.996	0.005
	0.171	0.419	13.12	0.992	0.004
	0.224	0.402	13.09	0.995	0.004
	0.546	0.304	12.75	0.994	0.005
	1.274	0.120	5.920	0.987	0.006
	1.025	0.167	6.169	0.999	0.002
Nakai and Grossman 1983	0.271	0.245	6.588	1.000	0.002
	0.431	0.210	6.490	1.000	0.002
	0.040	0.332	5.856	1.000	0.001
	0.049	0.324	5.914	1.000	0.001
	0.913	0.105	4.707	0.993	0.005
Average	0.396×10^{-11}	0.315	7.633×10^{-11}	0.991	0.0124

of the results, some abnormal values of parameters were removed, for instance when the value for c was much smaller than the inverse of the elastic modulus.

The overall unbiased coefficient of variation ω was found based on the individual curve unbiased coefficient of variation ω_n, such that $\omega = \sqrt{(\omega_1^2 + \omega_2^2 + \omega_3^2 + \cdots + \omega_N^2)/N}$. Here n represents the individual curve and $N = 39$, the total number of curves in the database.

3 Results and discussion

Functions Eq. (1), (2), and (3) were optimized and fitted by using each curve in the database. The root mean square of the unbiased coefficient of variation for each function is shown in Table 3. As one can see, Eq. (1) is associated with the smallest overall coefficient of variation.

A select comparison of a single curve is shown in Figure 3a, which clearly shows an unreasonable fit of Eq. (2). In agreement with previous fitting studies, the present work shows that the power law model (Eq. (1)) is the most suitable for long term wood creep. Parameters a, b, and c are constrained to be greater than 0, where c is expected to be close to the instantaneous compliance value $1/E_0$. The parameter probability density functions (pdf) are shown in Figure 2a and c. The pdf distribution was fitted to Gaussian, Weibull, exponential, and lognormal distributions. It was

Table 3: Unbiased coefficient of variation per compliance function.

	Equation (1)	Equation (2)	Equation (3)
ω	0.0125	0.0260	0.0170

found that the lognormal distribution fits most reasonably, which agrees with previous studies (Schaffer 1972). The mean, standard deviation (σ), and coefficient of variation (ω_P) of each parameter per the entire database are given in Table 4.

Figure 3b shows the relationship between c and $1/E_0$, where the value for c is obtained from fitting experimental results and the elastic modulus E_0 is given either in the experimental study (cross markers) or assumed according to the species (circle markers). The dash line shows $c = 1/E_0$. It can be see that the fitted parameter c is generally slightly lower than the elastic modulus. In testing it is impossible to measure the instantaneous compliance, as there will always be some creep behavior involved between the time of loading and the time of the first measurement, so the fitting result for c is expected, in general, to be smaller than $1/E_0$.

Figure 3c presents the experimental data adjusted by removing the value of parameter c from each curve, representing relative compliance. Eq. (1) with mean parameter values for a and b is shown for comparison. The individual parameter values per curve are presented in Table 2. Whilst the agreement with a power law compliance function may indicate creep behavior tending to an asymptotic rate, no definite conclusions can be derived without more long-term data. However, the statistical distribution of parameters can be used to define an envelope of certainty for expected creep values. The high standard of deviation shows that there is a possibility for creep shortening much larger than twice that of the instantaneous elastic deformation.

In realistic conditions, the MC of buildings in service is considered within 8–15%, but it is often difficult to ascertain the exact values. Therefore, it is practical to collect data only within this range for the wood creep database, but to make no distinction between them. To support this assumption, the fitted parameters were analyzed for trends regarding MC, where values for a and b were averaged per MC. No trends were observed for either parameter within the 8–15% range. Thus, although it is known that higher moisture increases wood creep, the low range considered

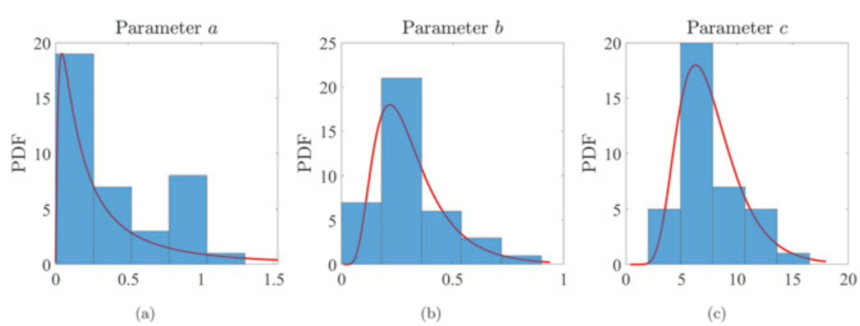

Figure 2: PDF distribution for fitted parameters.

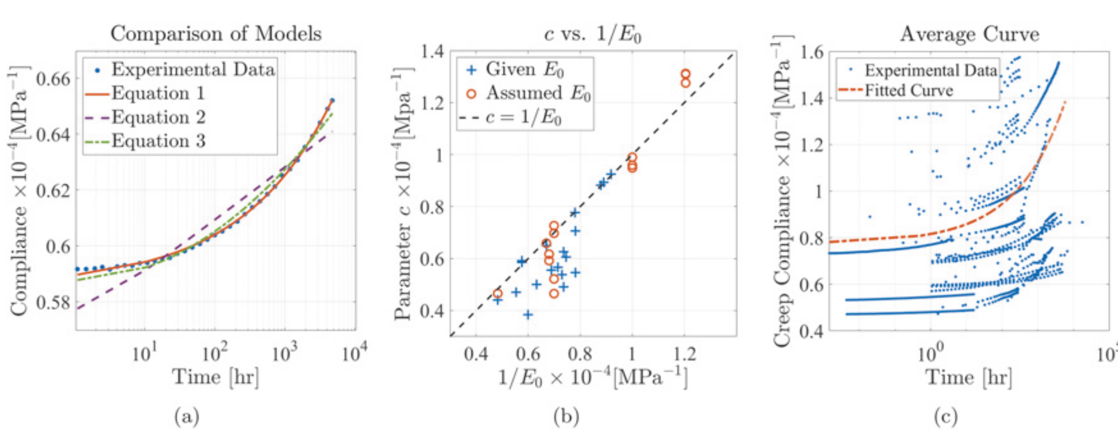

Figure 3: (a) Mountain Ash curve from Nakai and Grossman 1983 comparing fittings for all three functions. (b) Relationship between c and $1/E_0$. (c) Fitting all data using average parameter values.

Table 4: Statistical values for power law model parameters.

Parameter	Mean	σ	ω_P
a [Pa^{-1}]	0.396×10^{-11}	0.356×10^{-11}	0.899
b [–]	0.315	0.165	0.525
c [Pa^{-1}]	7.633×10^{-11}	3.020×10^{-11}	0.396

in this database does does not strongly influence wood creep and may be neglected, for constant environmental conditions.

The database includes both hardwood and softwood, and additional analysis was performed with respect to species classification versus parameters a and b. There was a trend for higher creep parameter values in softwoods, however, due to the low number of species considered (seven hardwoods and five softwoods) no strong conclusions may be drawn.

4 Conclusion

A database for wood creep under constant environmental conditions was created for the study of long term deformations under sustained loads. Based on the results obtained in this study the following conclusions can be drawn:

(1) The power law model for constant environmental conditions fits individual experimental curves better than logarithmic functions.
(2) The parameters for the power law model were found to be lognormally distributed, which confirms earlier studies.
(3) The y-axis intercept parameter c and an independently obtained elastic modulus were compared and the results show good agreement, with c values trending linearly with $1/E_0$, but lower on average, as expected due to the effect of short term creep.
(4) A lack of long term data hinders the ability to develop a robust prediction model. Instead an envelope approach should be taken to determine limits on creep deformations.

Further extrapolation of prediction models based on this database should be performed to determine a method for use in structural design. Future work is also planned to expand the database to include experiments with with loading perpendicular to grain and variable moisture conditions. Future inclusion of mechano-sorptive creep will be critically important for application in engineering, as changing humidity and temperature are known to be significant causes of creep.

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References

Abrahamsen, R. (2017). *Mjøstårnet-construction of an 81 m tall timber building*. International House Forum.
ACI (2008). *209.2R-08: Guide for modeling and calculating shrinkage and creep in hardened concrete*. American Concrete Institute.
Armstrong, L. (1962). The effect of moisture content of wood under stress. Aust. J. Applied Sci. 13:257–276.
Armstrong, L. (1972). Deformation of wood in compression during moisture movement. Wood Sci. 5:81–86.
Armstrong, L. and Christensen, G. (1961). Influence of moisture changes on deformation of wood under stress. Nature 191: 869. https://doi.org/10.1038/191869a0.
Armstrong, L. and Kingston, R. (1960). Effect of moisture changes on creep in wood. Nature 185: 862. https://doi.org/10.1038/185862c0.
Bach, L. (1968). Nonlinear mechanical behavior of wood in longitudinal tension. Forest Prod. J. 18: 60–66. https://doi.org/10.14359/20203.
Bažant, Z.P. and Baweja, S. (2000). Creep and shrinkage prediction model for analysis and design of concrete structures: Model b3. ACI Spec. Publ. 194: 1–84.
Bažant, Z.P. and Li, G.H. (2008). Unbiased statistical comparison of creep and shrinkage prediction models. ACI mater. J. 105: 610–621.
Bažant, Z. (1985). Constitutive equation of wood at variable humidity and temperature. Wood Sci. Technol. 19: 159–177.
Bodig, J. and Jayne, B.A. (1982). *Mechanics of wood and wood composites*, Vol. 712. Van Nostrand Reinhold.
Bond, B.H. (1993). *Development of tension and compression creep models for wood using the time-temperature superposition principle*. Ph.D. thesis, Virginia Tech.
Bond, B.H., Loferski, J., Tissaoui, J., and Holzer, S. (1997). Development of tension and compression creep models for wood using the time-temperature superposition principle. Forest Prod. J. 47: 97.
Davidson, R. (1962). The influence of temperature on creep in wood. Forest Prod. J. 12: 377–381.
Engelund, E.T. and Salmén, L. (2012). Tensile creep and recovery of norway spruce influenced by temperature and moisture. Holzforshung 66: 959–965. https://doi.org/10.1515/hf-2011-0172.
Foudjet, A. and Bremond, C. (1989). Creep of four tropical hardwoods from cameroon. Wood Sci. Technol. 23: 335–341. https://doi.org/10.1007/BF00353249.
Fridley, K.J., Tang, R., and Soltis, L.A. (1991). Moisture effects on load-duration behavior of lumber. part i. effect of constant relative humidity. Wood Fiber Sci. 23: 114–127.
Fridley, K.J., Tang, R., and Soltis, L.A. (1992). Creep behavior model for structural lumber. J. Struct. Eng. 118: 2261–2277. https://doi.org/10.1061/(ASCE)0733-9445(1992)118:8(2261).
Fridley, K.J., Tang, R., and Soltis, L.A. (1992). Moisture effects on load-duration behavior of lumber. part ii. effect of cyclic relative humidity. Wood Fiber Sci 24 (1): 89–98.

Gressel, P. (1984). Prediction of long-term deformation-behavior from short-term creep experiments. Holz Roh Werkst. 42: 293–301.
Grossman, P. (1976). Requirements for a model that exhibits mechano-sorptive behaviour. Wood Sci. Technol. 10: 163–168. https://doi.org/10.1007/BF00355737.
Grossman, P. and Kingston, R. (1954). Creep and stress relaxation in wood during bending. Aust. J. Appl. Sci. 5: 403–417.
Hassani, M.M., Wittel, F.K., Hering, S., and Herrmann, H.J. (2015). Rheological model for wood. Comput. Method Appl. M 283: 1032–1060. https://doi.org/10.1016/j.cma.2014.10.031.
Hering, S. and Niemz, P. (2012). Moisture-dependent, viscoelastic creep of european beech wood in longitudinal direction. Eur. J. Wood Wood Prod. 70: 667–670. https://doi.org/10.1007/s00107-012-0600-4.
Holzer, S.M., Loferski, J.R., and Dillard, D.A. (1989). A review of creep in wood: Concepts relevant to develop long-term behavior predictions for wood structures. Wood Fiber Sci. 21: 376–392.
Hoyle, R.J., Griffith, M.C., and Itani, R.Y. (1985). Primary creep in douglas-fir beams of commercial size and quality. Wood Fiber Sci. 17: 300–314.
Hsieh, T.Y. and Chang, F.C. (2018). Effects of moisture content and temperature on wood creep. Holzforschung 72: 1071–1078. https://doi.org/10.1515/hf-2018-0056.
Hubler, M., Wendner, R. and Bažant, Z. (2015). Comprehensive database for concrete creep and shrinkage: Analysis and recommendations for testing and recording. ACI Mater. J. 112: 547–558. https://doi.org/10.14359/51687452.
Hunt, D.G. (1999). A unified approach to creep of wood. Proc. Royal Soc. London. Series A: Math., Phys. and Eng. Sci. 455: 4077–4095. https://doi.org/10.1098/rspa.1999.0491.
Hunt, D.G. (2004). The prediction of long-time viscoelastic creep from short-time data. Wood Sci. Technol. 38: 479–492. https://doi.org/10.1007/s00226-004-0244-6.
Jong, F. and Clancy, P. (2004). Compression properties of wood as functions of moisture, stress and temperature. Fire Mater. 28: 209–225. https://doi.org/10.1002/fam.859.
King, E.G. (1961). Time-dependent strain behavior of wood in tension parallel to the grain. For. Prod. J. 11: 156–165.
Kingston, R. and Budgen, B. (1972). Some aspects of the rheological behaviour of wood part iv: Non-linear behaviour at high stresses in bending and compression. Wood Sci. Technol. 6: 230–238. https://doi.org/10.1007/BF00351580.
Kojima, Y. and Yamamoto, H. (2004). Effect of microfibril angle on the longitudinal tensile creep behavior of wood. Wood Sci. 50: 301–306. https://doi.org/10.1007/s10086-003-0565-3.
Lehne, J. and Preston, F. (2018). *Making concrete change: Innovation in low-carbon cement and concrete*. Technical report, Chatham House.
Liu, T. (1993). Creep of wood under a large span of loads in constant and varying environments. Holz Roh Werkst. 51: 400–405. https://doi.org/10.1007/BF02628237.
Massaro, F.M. and Malo, K.A. (2019a). Long-term behaviour of norway spruce glulam loaded perpendicular to grain. Eur J Wood Wood Prod 77: 821–832.
Massaro, F.M. and Malo, K.A. (2019b). Modelling the viscoelastic mechanosorptive behaviour of norway spruce under long-term compression perpendicular to the grain. Holzforschung 73: 715–725. https://doi.org/10.1515/hf-2018-0218.
McLain, R. and Steimle, D. (2017). *Accommodating shrinkage in multi-story wood-frame structures*. WoodWorks.
Mårtensson, A. (1994). Mechano-sorptive effects in wooden material. Wood Sci. Technol. 28: 437–449. https://doi.org/10.1007/BF00225463.
Mukudai, J. (1983). Evaluation of linear and non-linear viscoelastic bending loads of wood as a function of prescribed deflections. Wood Sci. Technol. 17: 203–216. https://doi.org/10.1007/BF00372319.
Nakai, T. and Grossman, P. (1983). Deflection of wood under intermittent loading. Wood Sci. Technol. 17: 55–67. https://doi.org/10.1007/BF00351832.
NDS 2017 (2017). *National design specification for wood construction*. American Wood Council.
Ozyhar, T., Hering, S., and Niemz, P. (2013). Viscoelastic characterization of wood: Time dependence of the orthotropic compliance in tension and compression. J. Rheol. 57: 699–717. https://doi.org/10.1122/1.4790170.
Pathirage, M., Bentz, D., Luzio, G.D., Masoero, E., and Cusatis, G. (2019). The onix model: a parameter-free multiscale framework for the prediction of self-desiccation in concrete. Cement Concrete Comp. 103: 36–48. https://doi.org/10.1016/j.cemconcomp.2019.04.011.
Pentoney, R. and Davidson, R. (1962). Rheology and the study of wood. Forest Prod. J. 12: 243–248.
Ranta-Maunus, A. (1993). Rheological behaviour of wood in directions perpendicular to the grain. Mater. Struct. 26: 362–369. https://doi.org/10.1007/BF02472962.
Rasoolinejad, M., Rahimi-Aghdam, S., and Bažant, Z.P. (2019). Prediction of autogenous shrinkage in concrete from material composition or strength calibrated by a large database, as update to model b4. Mater. Struct. 52: 33. https://doi.org/10.1617/s11527-019-1331-3.
Ross, R.J. (2010). Wood handbook: wood as an engineering material. Forest Prod. J.
Roszyk, E., Moliński, W., and Jasińska, M. (2010). The effect of microfibril angle on hygromechanic creep of wood under tensile stress along the grains. Wood Res.-Slovakia 55: 13–24.
Schaffer, E. (1972). Modeling the creep of wood in a changing moisture environment. Wood Fiber Sci. 3: 232–235.
Schniewind, A.P. (1968). Recent progress in the study of the rheology of wood. Wood Sci. Technol. 2: 188–206. https://doi.org/10.1007/BF00350908.
Schniewind, A.P. and Barrett, J. (1972). Wood as a linear orthotropic viscoelastic material. Wood Sci Technol. 6: 43–57. https://doi.org/10.1007/BF00351807.
Tissaoui, J. (1996). *Effects of long-term creep on the integrity of modern wood structures*. Ph.D. thesis, Virginia Tech.
Toratti, T. (1991). *Creep of wood in varying environment humidity part i: Simulation of creep*. Laboratory of Structural Engineering and Building Physics.
Willebrands, O. (2017). *Differential vertical shortening in timber-concrete high-rise structures*. Master's thesis, Delft University of Technology.
Youngs, R.L. (1957). The perpendicular-to-grain mechanical properties of red oak as related to temperature, moisture content, and time. Forest Prod. J.: 2079.
Zhou, Y., Fushitani, M., Kubo, T., and Ozawa, M. (1999). Bending creep behavior of wood under cyclic moisture changes. Wood Sci. 45: 113–119. https://doi.org/10.1007/BF01192327.