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Re-Analysis of Historical Data and Model Calibration of Duration of Load Effect on Structural Timber

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Abstract: The duration of load (DOL) effect in structure timber refers to the degradation of strength and stiffness that occurs under long-term continuous loading. This paper investigated the DOL effect in structure timber using DOL tests and DOL damage models. Based on the empirical-fitted formulae, the DOL coefficients were derived for three long-term sustained loads in bending, tension perpendicular to grain, and shear parallel to grain, and the results were compared and analyzed with the Madison equation, Gerhards model, Nielsen model, and Foschi and Yao model derivations to verify the applicability of the DOL empirical model and the three DOL damage models. The results show that based on the historical data of the DOL tests, the Madison empirical formula was found to be better applied to the derivation of DOL coefficients under the bending and tension perpendicular to grain long-term sustained loading, and the derivation of DOL coefficients under shear loading is not satisfactory. Among the three DOL damage models, the Foschi and Yao model was better than the Gerhards and Nielsen models for fitting the DOL test results under bending, tension perpendicular to grain, and shear parallel to grain. The DOL coefficients derived based on the Foschi and Yao model are more comparable to test results and resemble those derived from the Madison formula.

Keywords: structural timber; duration of load (DOL) effect; short-term test; long-term test; percentile matching method; model calibration

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Citation: Zhao, M.; Zhao, E.; Zhang, X.; Yue, Q. Re-Analysis of Historical Data and Model Calibration of Duration of Load Effect on Structural Timber. *Buildings* **2023**, *13*, 2073. https://doi.org/10.3390/buildings13082073

Academic Editor: Marco Corradi

Received: 11 July 2023
Revised: 4 August 2023
Accepted: 14 August 2023
Published: 15 August 2023

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1. Introduction

The deterioration of strength of structural timber under long-term loading is known as the duration of load (DOL) effect, however, the creep behavior refers to the development of deformation under long-term sustained loads [1–7]. In 1741, Buffon first discovered the DOL phenomenon in oak beams that had been under long-term bending loads, which led to the widespread recognition of the DOL effect as an important performance of structural timber [8,9]. A large number of DOL tests have been conducted on different species of structural timber to analyze the patterns of constants loads, including tension perpendicular to grain loads [10–18], bending loads [19–25], and shear loads [26–28] as well as the different factors that influence the DOL effect in structural timber, such as stress levels (SL) [15–17,27], climatic factors (moisture content and relative humidity) [13,21,22,24,29], and the geometric dimensions of the test specimen (small clear specimens, dimensional lumber, and structural lumber) [19,23,25,30,31]. The DOL effect and its adjustment to the design value of structural timber strength were studied based on the empirical fitting of experimental data, cumulative damage mechanics, or linear elastic fracture mechanics theory. The results of these studies have been incorporated into structural timber design codes, such as Eurocode 5: Design of timber structures—Part 1-1: General—Common rules and rules for buildings (EC5) [32], NDS-2015: National Design Specification for Wood Construction ASD/LRFD (NDS-2015) [33], and Canadian Standard Association: Engineering

Design in Wood (CSA O86) [34]. In these codes, the design value of structural timber is usually given based on specific loading conditions or "standard loading" conditions with a built-in DOL effect coefficient for various design conditions, such as permanent, long-term, medium-term, and other load durations. Therefore, it is fundamental to discuss the DOL effect on the strength and deformation of structural timber during the designed service life of structural timber and its components.

In the matter of the DOL effect, Wood [35] published the well-known Madison curve in 1947 that represents the relationship between the DOL effect and the time to failure of structural timber under different stress levels. Subsequently, Wood [36] and Pearson et al. [37,38] proposed similar empirical equations based on their respective long-term tests on various kinds of structural timber. It is worth noting that this document cannot provide a comprehensive review of all the published literature on the topic of DOL, and the literature focused on DOL tests was collected as much as possible for the purpose of subsequent re-analysis and model validation. Madsen [10] and Mindess et al. [11] both tested the DOL effect of tension perpendicular to grain loads on Canadian Douglas Fir. Mau [12] carried out a 70-day long-term test on Douglas Fir specimens. Aicher et al. [13] carried out DOL tests on 80 European spruce glulam beams subjected to bending and 180 glulam specimens subjected to tensile stress perpendicular to grain, which considered the effects of environmental factors, such as constant temperature and relative humidity, natural variation of humidity, and cyclic variation of humidity, on the DOL effect. Aicher et al. [14] conducted a group of DOL tests on solid wood specimens of European spruce, but no significant DOL effects were observed at the end of the tests. Recently, Kong [15] conducted DOL tests on Mongolian Scots pine (*Pinus sylvestris* var. *mongolica*) specimens subjected to tensile stress perpendicular to grain. Jin [16] and Zhu et al. [17] carried out short-term and long-term tests on small, clear specimens of Northeast China Larch glulam subjected to tension perpendicular to grain loading.

Concerning the DOL effect of bending loads, Madsen and Barrett [19] conducted bending DOL tests on different grades of dimensional lumber and showed that the DOL effect on Douglas Fir dimensional lumber was more severe than described by the Madison curve, and the DOL effect on high-quality structural timber was more severe than that on low-quality structural timber. Foschi and Barrett [20] conducted a DOL test of Hemlock dimensional lumber and showed that the DOL effect predicted by the Madison equation was more severe than the test results. Hoffmeyer et al. [21] studied the effects of climatic conditions and geometric dimensions on the DOL effect of laminated veneer lumber (LVL) and glulam beams. Gustafsson et al. [22] conducted long-term loading tests to investigate the DOL effect on glulam and LVL end-notched beams under constant and cyclic humidity. Gerhards [23] reviewed long-term tests of Select Structural (SS) and Grade No. 2 Douglas Fir dimensional lumber and found that the DOL effect on the dimensional lumber was more conservative than that predicted with the Madison equations, while the DOL effect was more severe on low-quality lumber than on high-quality lumber. Hoffmeyer et al. [24] published the final results of their 13-year study on DOL effects, which focused on the effect of moisture content on the DOL effect in structural timber subjected to constant bending loads. Zhu et al. [25] conducted short-term and long-term bending tests using No. 2 and No. 3 Grade Spruce–Pine–Fir (SPF) dimensional lumber as well as small clear specimens. Results showed no obvious DOL effect differences between high- and low-quality grade structural timber and between structural lumber and small clear specimens. Moreover, the DOL results obtained from the test were more consistent with those extrapolated with the Wood equation.

In terms of the DOL test research of shear loads, Spencer et al. [26] conducted a group of DOL tests on Canadian Douglas Fir specimens subjected to shear loads in 1986. The results of his study showed that the DOL effect predictions of the Madison curve were conserved. Larsson et al. [27] investigated the DOL effect on 80 specimens subjected to three degrees of shear loads ranging from 50−80% of the short-term load, which considered both shear loads perpendicular to grain and parallel to grain. The results showed that long-

term shear loads had a greater DOL effect compared to long-term bending loads. However, Gerhards [39] reviewed and re-analyzed data from the literature related to the effects of load-holding time and loading rate on the strength of structural timber and showed that the effect of loading rate on the strength of dry wood was most pronounced with tension perpendicular to grain, followed by compression parallel to grain, bending, and shear.

As DOL research was developing, scholars attempted to introduce damage state variables to express damage rate as a function of load history and damage state [40–42]. The damage evolution model for long-term constant loads was established based on the cumulative damage process simulated by subjecting structural timber under long-term loading conditions. From this, the time to failure (T_f) of structural timber or components was calculated. Gerhards et al. [43,44] proposed an exponential DOL cumulative damage model and calibrated it using DOL data from small, clear specimens and full-scale specimens. In 1978, based on Gerhards' model, Barrett and Foschi [45] proposed a DOL model (BF model) by introducing a second-order damage variable and adding a stress damage threshold, which allowed better prediction of the DOL effect. In 1986, Foschi and Yao [41,46] considered the influence of applied stress on the second-order term in the BF model and improved the BF model by increasing the model parameters to 4. Thereafter, the Foschi and Yao model was adopted by the National Standard of Canada, also known as the Canadian Model [16]. Nielsen [47–49] proposed a damage model for viscoelastic material based on viscoelastic fracture mechanics, which establishes relationships between the development of abstract damage and actual cracking by introducing the elastic modulus associated with the specimen into the Dugdale cracking model. The advantage of the Nielsen model lies in its clear and definite physical significance. However, the parameters of Nielsen model, such as the initial crack length and crack width, were obtained by fitting the test data and not by actual measurements, which greatly weakens its physical significance and thus limits its accuracy in simulating the DOL effect [16].

The DOL effect of wood directly affects the determination of its strength design value, however, the long-term test on wood is time-consuming and lacks a unified testing method. Therefore, it is quite necessary to review and re-analyze the historical data of the DOL test, which considers various factors, such as wood species, test conditions, loading types, etc. on the DOL effects, to reach a relatively universal conclusion. For this purpose, the empirical methods and damage models in design specifications, such as the Madison formula, Gerhards model, Nielsen model, and Foschi and Yao model, should also be well calibrated and discussed.

In the present paper, the DOL effect in structural timber was investigated in terms of DOL tests and DOL damage models through a re-analysis of historical data. The DOL tests and DOL damage models of structural timber were discussed. The impact of certain factors, such as the type of continuous load (tension, bending, and shear), specimen size, and climatic environment, on the DOL effects in structural timber were comprehensively analyzed. The DOL coefficient was obtained from the empirical formula fitting of different long-term tests and then compared with specification values. DOL data from various long-term tests were fitted with the recommended form of the empirical formula: $SR = a + b\lg(t)$ and then compared with the values in current codes. Three commonly used DOL models and their parameter estimation methods were studied and calibrated based on DOL test data to verify the applicability of the DOL damage models. The results of this study provide fundamental, theoretical, and experimental support for studies on the DOL effects in modern wood.

2. Basic Method

2.1. Short-Term Test

Results of short-term strength tests of structural timber can be regarded as random variables and can be expressed by means of mathematical statistics, such as the distribution function, strength quantile value, and coefficient of variation of test data. The determination of the mechanical properties of structural timber based on mathematical statistics is

achieved mainly with parametric and non-parametric estimation. The parametric method commonly uses normal distribution and Weibull distribution [9] as the distribution functions to determine the strength of structural timber. The non-parametric method does not consider the specific form of the distribution function. That is, if the $p \times 100$th quantile is calculated, and the measured short-term strength values of structural timber are arranged from lowest to highest, then the $p \times 100$th quantile is the strength of the i-th specimen. i is expressed as [9]:

$$i = p(n+1), \tag{1}$$

where n is the number of test specimens. If i is not an integer, the quantile value is determined using the linear interpolation of its two adjacent values.

It is worth noting that the parametric method needs to assume in advance that the sample obeys the given distribution function. However, if this assumption is not valid, the strength estimated based on the assumption will deviate. In contrast, the distribution function does not need to be assumed using the non-parametric estimation method, but the sample size needs to be considered. The results of non-parametric estimation are generally more conservative than those of parametric estimation. Furthermore, the short-term strength of structural timber is also closely related to factors such as structural timber species, moisture content, quality grade, and loading rate [50].

2.2. Long-Term Test

A special lever-loading device is usually used to deliver the load for long-term tests [21,24,25], as shown in Figure 1a. The aim of long-term tests is to obtain the time to failure T_f of the specimen under constant loads at a given level. The loading modalities used in DOL tests of structural timber described in the existing literature mainly include bending, tension parallel or perpendicular to grain, and shear, the static schemes of which are shown in Figure 1. Long-term loads are exerted as either constant loading or stepwise loading. For long-term tests with constant loads, the load is first exerted at a uniform loading rate K_s similar to that of short-term tests until the given load level is reached, after which the load is kept constant until the specimen fails [51]. The stress level of long-term test is usually determined according to the quantile values of the short-term strength test, here, the stress level (SL) means the value of the sustained stress applied to the specimen during the long-term test, including tension perpendicular to grain, bending, or shear stresses in the present paper. As discussed in Section 2.1, the short-term strength can be evaluated using cumulative distribution function (CDF), such as normal and Weibull distribution function. The 5th, 15th, or 30th quantile values of CDF of the short-term strength were commonly adopted as the sustained stress of long-term test. Therefore, it should be pointed out that the applied sustained stresses in the long-term test were relatively low stress levels calculated using the CDF of the short-term strength.

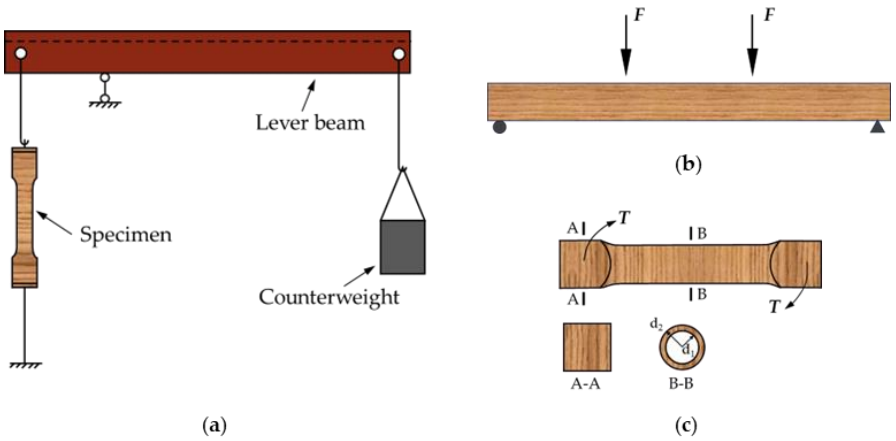


Figure 1. Sketch of the long-term test: (**a**) lever-loading device of tension perpendicular to grain [15]; (**b**) long-term test of bending [25]; and (**c**) long-term test of shear parallel to grain [26].

For long-term tests with stepwise loading, a low stress level is generally chosen for the initial loading in order to avoid sudden failure within the initial loading step [22]. Loading is continued for the given time T, then gradually increased step by step. The constant load is maintained in parts for the amount of time T until failure of the specimen occurs at whichever level of load. When determining the DOL effect using the stepwise loading method, it is generally believed that the duration of continuous low stress level loads do not affect the DOL effect at the high stress levels [13,21]. Therefore, the time to failure T_f of the test specimen only considers the duration of high stress level loads at which the specimen fails.

2.3. DOL Effect with Percentile Matching Method

The DOL effect is generally represented as a ratio of long-term strength to short-term strength [52]. Material strength is usually determined through destructive tests, but because damage to the material can only occur once, the same specimen cannot be tested in both short-term strength and long-term strength tests [25]. In this regard, it is impossible to accurately assess the DOL effect of the same specimen by means of experimentation. Therefore, the primary problem faced in DOL tests is determining short-term strengths that match long-term specimens from reasonable simplification or assumption for the calculation of the DOL effect coefficient. The development of DOL effect research has given rise to the mean or median method, the pair matching method, and the percentile matching method for the determination of short-term strength [53]. The test results always show a large variability in the strength of structural timber and large errors when the short-term strength of long-term specimens is determined using the mean or median method, which can usually be regarded as a simplified analysis method [53]. The pair matching method considers that two adjacent specimens have the same strength characteristics, and based on this, the pair matching specimens are tested separately in short-term and long-term tests, and the short-term strength of long-term specimens is determined. The pair matching method improves, to a certain extent, the accuracy of short-term strength matching but still does not overcome the problem of sample discreteness.

The percentile matching method proposed by Madsen [53] assumes that, under the premise that the samples come from a larger sample, structural timber specimens from the same source have the same strength distribution characteristics; the so-called Equal Rank Assumption and the strength matching relationship between long-term and short-term specimens can be established with the quantile values of the cumulative probability distribution of strength. There are two basic assumptions in the percentile matching method, that is (1) long-term strength and short-term strength have the same strength distribution characteristic, and (2) the magnitude of the short-term strength can be characterized by the length of time it can withstand the specified load level. Therefore, specimens that break first in the long-term test have a low corresponding short-term strength, while specimens that break later have a high corresponding short-term strength. For long-term tests involving N specimens, when the load level of the long-term test is taken as the i-quantile value of the short-term strength, theoretically, the failure of $i \times N$ specimens will occur when the load is increased from 0 to a given load level at the loading rate K_s, whilst $(1 - i) \times N$ specimens will complete the long-term test under the given constant loads. The quantile values of the test data in sample N can be obtained by arranging the specimens in the order in which they reached failure in long-term tests, and then the long-term strength of each specimen can be matched with the short-term strength using the same quantile values [12]. The DOL value can be calculated as the ratio of the long-term strength to its matching short-term strength, as shown in Figure 2. For example, the i-th failed specimen in the long-term test corresponds to a short-term strength of P_i, and the applied long-term stress level is q. Therefore, the stress ratio of the specimen is $SR_i = q/P_i$.

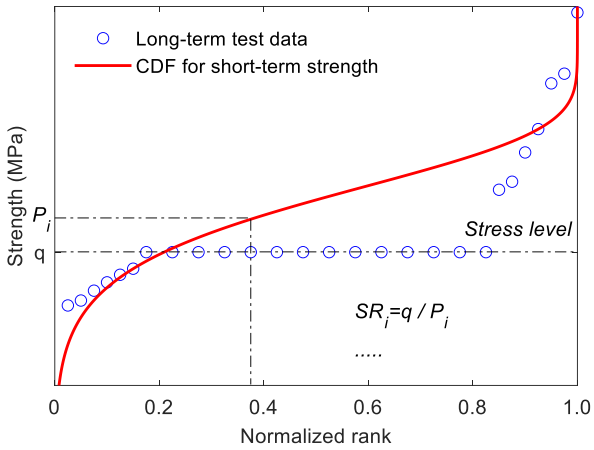


Figure 2. DOL calculation based on percentile matching method.

3. Duration of Load (DOL) Models

Wood et al. proposed the classic Madison equation to evaluate the DOL effect of structural timber based on the bending test of small, clear specimens. The method, used to analyze the DOL effect of structural timber under bending load, has been used for DOL tests up to now. The Madison equation was obtained using three control points, which are derived from the combined results of Elmendorf's impact loading test [54], Liska's ramp loading test [55], and Wood's long-term loading test. Madison equation can be expressed as follows [53]:

$$SR = 18.3 + 108.4T_f^{-0.0464}, \quad (2)$$

where SR denotes the stress ratio (%), and T_f denotes the duration of load in seconds. According to the Madison Equation (2), the strength of the structural timber after 10 years of constant load-holding would be 62% of the short-term strength. When only the results of Wood's long-term loading test in the Madison equation were considered, a fitting equation (Wood equation) was given as follows [36]:

$$SR = 90.4 - 6.3\lg(T_f), \quad (3)$$

where T_f denotes the duration of load in hours. According to Wood's Equation (3), the strength of structural timber after 10 years would be 59% of the short-term strength. In 1972, Pearson proposed a similar empirical equation based on Wood's research to estimate the DOL effect, and the formula is expressed as follows [37]:

$$SR = 91.5 - 7\lg(T_f), \quad (4)$$

where T_f denotes the duration of load in hours, and the strength of structural timber after 10 years according to Equation (4) would be 57% of the short-term strength.

In structural timber design codes, such as EC5, NDS-2015, and CSA O86, the DOL effect is represented by the adjustment coefficient K_{mod} of the design value of structural timber strength [56]. K_{mod} is directly related to factors such as the type of load and duration of load during the service life of the structure. In order to verify the DOL effects of different load combinations on the structural timber or components during its service life and to establish an adaptive reliability analysis method, researchers proposed different DOL damage models based on respective cumulative damage mechanics or linear elastic fracture mechanics and validated the models based on available short-term and long-term test data. At present, widely discussed DOL models include the Gerhards model [43,44], Foschi and Yao model [41,46], and Nielsen model [47–49], among which American and Canadian codes have adopted the former two models, respectively [57].

The general form of cumulative damage model can be defined by damage rate, as follows [16]:

$$\frac{d\alpha}{dt} = F(\tau, \alpha), \tag{5}$$

where α is the damage parameter, $\alpha = 0$ is the initial undamaged state, and $\alpha = 1$ is the fracture damage state; t is time, and $\tau(t)$ is the applied stress history. The general form of the damage model in Equation (5) indicates that the damage to a material or structure is not only related to the applied stress history but also to the degree of cumulative damage. When the damage evolution of the material is represented in an exponent, Equation (5) is expressed as:

$$\frac{d\alpha}{dt} = F_0\tau(t) + F_1\tau(t)\alpha + F_2\tau(t)\alpha^2 \ldots, \tag{6}$$

Gerhards et al. [43,44] considered only the first term on the right-hand side of Equation (6) in their study to model the cumulative damage of DOL in structural timber. The proposed Gerhards model is expressed as:

$$\frac{d\alpha}{dt} = \exp(-a + b\frac{S(t)}{f_s}), \tag{7}$$

where a and b are model parameters, f_s are short-term strengths, and $S(t)$ are stress loading histories.

Foschi and Yao [41,46] proposed a cumulative damage model for DOL considering the first two damage contributions on the right-hand side of Equation (6), which is expressed as:

$$\frac{d\alpha}{dt} = A[\frac{S(t)}{f_s} - \eta]^B + C[\frac{S(t)}{f_s} - \eta]^N \alpha, \tag{8}$$

where, A, B, C, and N are the model parameters, and η is the damage stress threshold, that is, damage will occur only when $S(t) - \sigma_0 f_s > 0$; otherwise, no damage occurs.

Based on the viscoelastic material damage theory, Nielsen et al. [47–49] treated structural timber as a cracking viscoelastic material, and by introducing time-dependent material parameters in the Dugdale cracking model, the proposed DOL fracture mechanics model was:

$$\frac{d\alpha}{dt} = \frac{(\pi \cdot FL)^2}{8q\tau} \frac{\alpha\left(\frac{S_c}{f_s}\right)^2}{\left(\left(\alpha\left(\frac{S_c}{f_s}\right)^2\right)^{-1} - 1\right)^{1/b}}, \tag{9}$$

where FL is the ratio of the short-term strength to the intrinsic strength of the non-cracked material; α is the ratio of the actual crack length to the initial crack length, $\alpha = 1$ indicates no damage, and $\alpha = (S_c/f_s)^{-2}$ indicates full damage. τ and b are the creep material parameters, and q is a function of the creep parameter of b, $q = [(b+1)(b+2)/2]^{1/b}$.

4. Model Calibration

4.1. DOL Effect Subjected to Bending

To verify the applicability of the empirical DOL equations, 12 groups of flexural DOL test results were collected from the existing literature, and the effects of structural timber species, specimen geometries, stress level, and moisture content on the bending DOL effect were considered. The basic parameters of long-term bending tests including Canadian Spruce–Pine–Fir (SPF) [25] and Norway spruce [24,58] are summarized in Table 1.

Table 1. Long-term test results of structural timber subjected to bending.

Materials	Loads	Geometric Dimensions (mm)	Percentile (%)	Stress Level (SL) (MPa)	Moisture Content (MC)
Canadian SPF	Bending	20 × 20 × 410	15	54.21	—
Canadian SPF	Bending	20 × 20 × 410	25	60.73	—
Canadian SPF	Bending	38 × 140 × 2820	15	29.07	—
Canadian SPF	Bending	38 × 140 × 2820	25	33.05	—
Canadian SPF	Bending	38 × 140 × 2820	15	21.54	—
Canadian SPF	Bending	38 × 140 × 2820	25	25.61	—
Norway spruce	Bending	44 × 95 × 1800	5	26.50	20%
Norway spruce	Bending	44 × 95 × 1800	5	26.50	Variable
Norway spruce	Bending	44 × 95 × 1800	5	28.20	11%
Norway spruce	Bending	44 × 95 × 1800	15	31.40	20%
Norway spruce	Bending	—	5	—	—
Norway spruce	Bending	—	15	—	—

According to the percentile matching method, after determining the short-term strength corresponding to the long-term test to calculate the bending DOL effect, the long-term loading stress ratio of the tested specimen was calculated and labeled as the y-axis, and the logarithm of the time to failure T_f of the long-term test specimen was labeled as the x-axis to illustrate the DOL effect in semi-logarithmic coordinates. The flexural DOL effect results listed in Table 1 were fitted using the empirical equation $SR = a + b\lg(t)$ and were compared to the Madison curve, as shown in Figures 3 and 4.

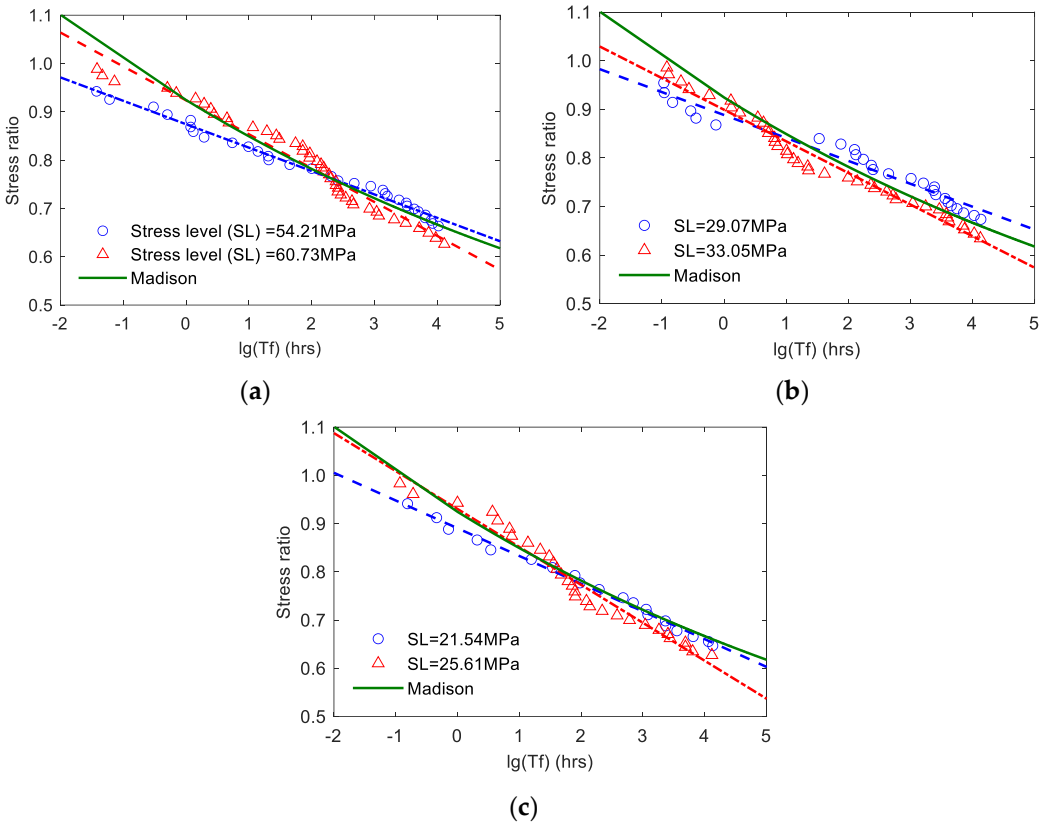


Figure 3. Fitting of flexural DOL effect of Canadian SPF: (**a**) Canadian SPF, small, clear specimen; (**b**) Canadian SPF, No. 2 dimensional lumber; and (**c**) Canadian SPF, No. 3 dimensional lumber.

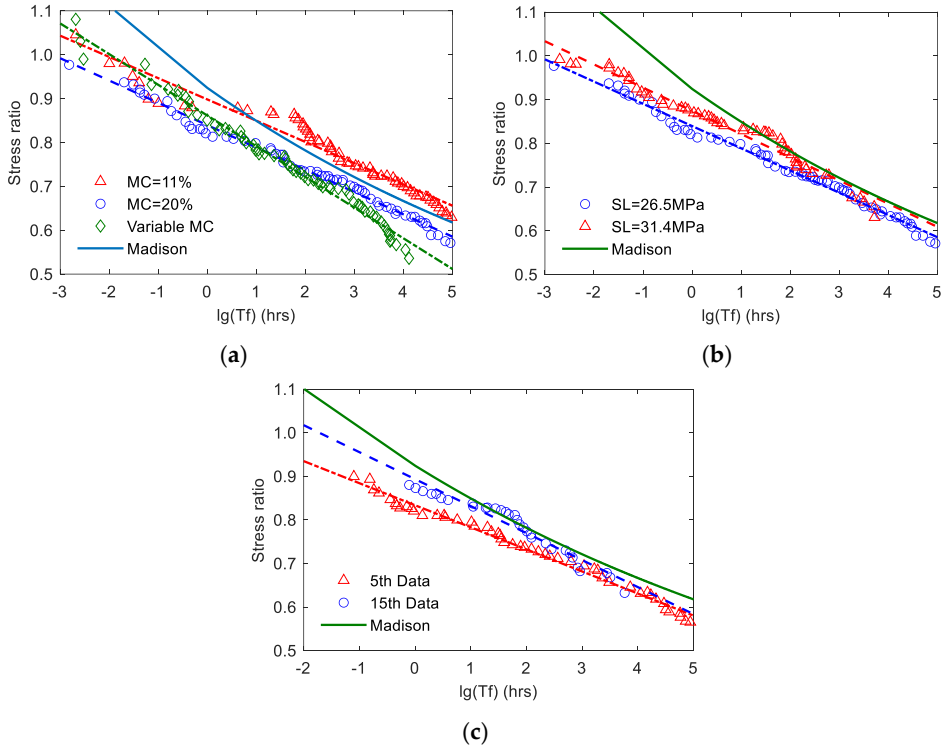


Figure 4. Fitting of flexural DOL effect of Norway spruce: (**a**) Norway spruce with three moisture contents (MC); (**b**) Norway spruce, MC = 20%; and (**c**) Norway spruce, dimensional lumber.

It should be noted that clear wood means the timber specimens that are free of defects and are commonly used to study the physical and mechanical properties of the timbers. The clear wood used for testing is called small, clear specimen. Dimensional lumber refers to the specimen with a specified nominal cross-section, and it is classified into four grades of SS, No. 1, No. 2, and No. 3 according to the NDS-2015. Canadian Spruce–Pine–Fir is composed of several kinds of tree species: Spruce, Pine, and Fir, which have extremely similar physical properties and are collectively called Canadian SPF.

The figures indicate that the fitted DOL effect curves subjected to bending under different conditions correlate well with the Madison curve. According to the empirical fitting formula for the results of the 12 groups of flexural DOL tests in Figures 3 and 4, the calculated values of the DOL effect after 10 years of constant load-holding ranged from 0.52 to 0.66, with a mean value of 0.6, agreed with the result of 0.62 calculated from the Madison formula, indicating that the Madison formula predicts the flexural DOL effect well.

The results of eight groups of flexural DOL tests were used to verify the three DOL models—the Gerhards model, the Nielsen model, and the Foschi and Yao model—as mentioned in Chapter 3. The model parameters in the three models were estimated based on the maximum likelihood estimation method, as shown in Table 2. The DOL test results were also compared with the prediction results of three DOL models and analyzed the predictive ability of different DOL models against the bending DOL effect, as shown in Figure 5. Madison curves are also shown in the figure for comparative analysis.

Table 2. DOL model parameters subjected to bending.

Materials	Stress Level (SL) (MPa)	Gerhards	Foschi and Yao			Nielsen	
		B	B	C	N	b	τ
Canadian SPF	21.54	41.08	17.12	1.760	4.063	0.237	76.61
Canadian SPF	25.61	37.36	93.94	317.9	4.911	0.489	25.32
Canadian SPF	54.21	38.76	13.81	3.83×10^{-4}	9.05×10^{-4}	0.196	142.1
Canadian SPF	60.73	36.25	43.96	39.47	4.457	0.436	38.27

Table 2. *Cont.*

Materials	Stress Level (SL) (MPa)	Gerhards	Foschi and Yao			Nielsen	
		B	*B*	*C*	*N*	*b*	τ
Canadian SPF	29.07	44.77	18.51	0.053	2.453	0.214	236.9
Canadian SPF	33.05	37.35	33.14	6062	7.771	0.411	16.93
Norway spruce	26.50	42.00	14.84	0.071	2.354	0.204	48.43
Norway spruce	31.40	46.81	22.33	2.211	3.319	0.367	17.50

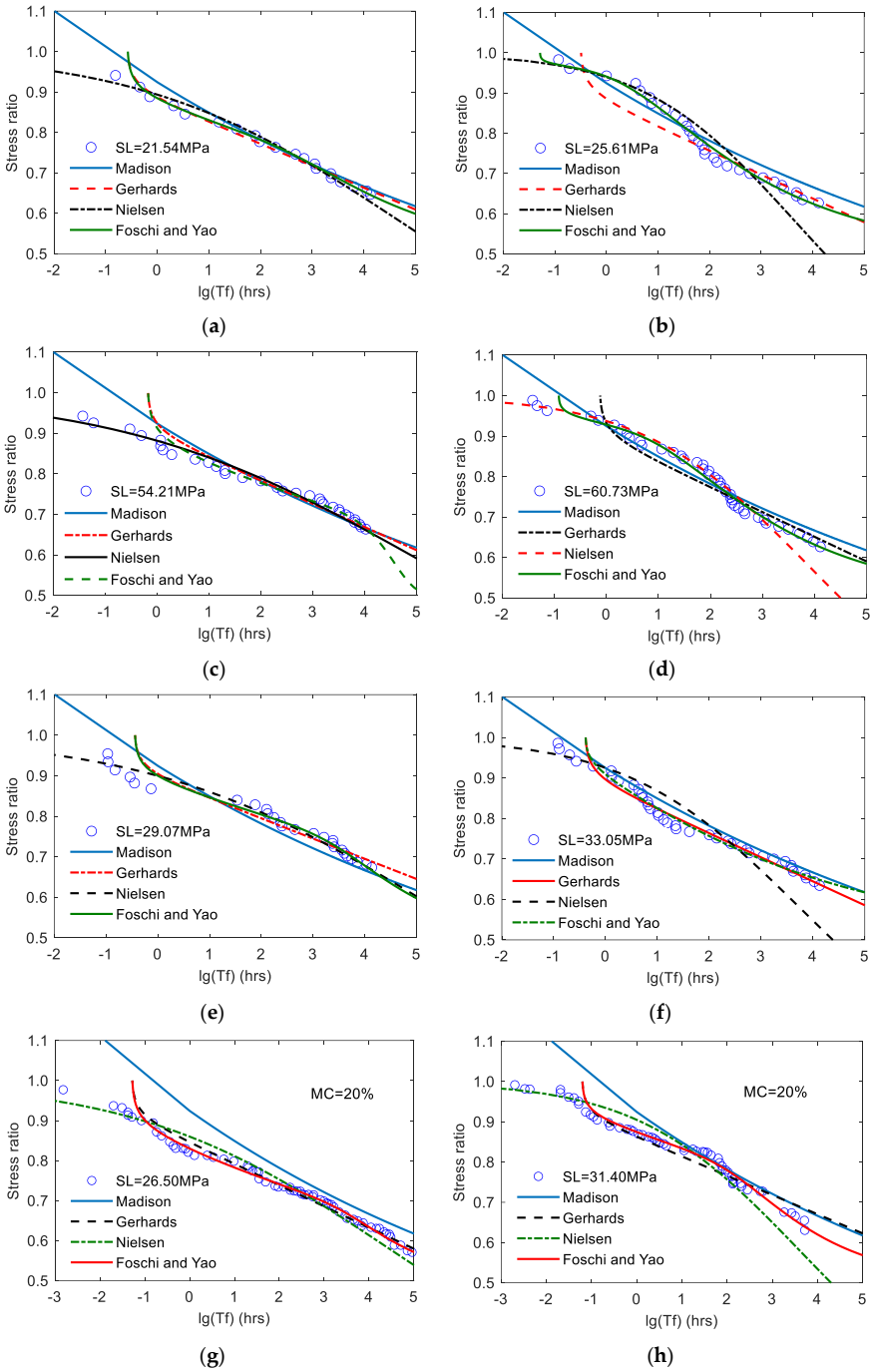


Figure 5. Fitting DOL model subjected to bending: (**a**) Canadian SPF, SL = 21.54 MPa; (**b**) Canadian SPF, SL = 25.61 MPa; (**c**) Canadian SPF, SL = 54.21 MPa; (**d**) Canadian SPF, SL = 60.73 MPa; (**e**) Canadian SPF, SL = 29.07 MPa; (**f**) Canadian SPF, SL = 33.05 MPa; (**g**) Norway spruce, SL = 26.50 MPa; and (**h**) Norway spruce, SL = 31.40 MPa.

From Figure 5, the Gerhards model and the Foschi and Yao model fit the bending DOL effect results better, while the Nielsen model differs significantly from the Gerhards model and the Foschi and Yao model in the shape of the curve. The Nielsen curve as a whole exhibits a middle-upper convex shape and does not produce a good fit. Based on the DOL model parameters determined with the maximum likelihood estimation method, the three DOL models were used to calculate the strength after 10 years of constant load-holding, and the calculated bending DOL coefficients are shown in Table 3.

Table 3. DOL coefficients subjected to bending.

Materials	Stress Level (SL) (MPa)	Gerhards	Nielsen	Foschi and Yao	Fitting
Canadian SPF	21.54	0.62	0.56	0.61	0.61
Canadian SPF	25.61	0.59	0.41	0.59	0.54
Canadian SPF	54.21	0.62	0.60	0.53	0.63
Canadian SPF	60.73	0.60	0.44	0.58	0.58
Canadian SPF	29.07	0.65	0.60	0.60	0.65
Canadian SPF	33.05	0.59	0.44	0.62	0.58
Norway spruce	26.50	0.58	0.55	0.58	0.60
Norway spruce	31.40	0.63	0.43	0.57	0.62
Average	—	0.61	0.50	0.59	0.60

From Table 3, the mean values of flexural DOL coefficients calculated based on the Gerhards model, Nielsen model, and Foschi and Yao model are 0.61, 0.50, and 0.59, respectively. Among them, the derived results of Gerhards model and Foschi and Yao model agree with the empirical formula $SR = a + b\lg(t)$ and the Madison formula. When the constant load-holding period of 10 years is taken as the time to failure to calculate the DOL coefficient, the prediction results given by Nielsen model are conservative compared with Gerhards model and Foschi and Yao model due to the middle-upper convex shaped fitting curve of the Nielsen model. Overall, the Gerhards model and the Foschi and Yao model predicted the bending DOL effect better than the Nielsen model.

4.2. DOL Effect Subjected to Tension Perpendicular to Grain

The DOL effect of structural timber under tension perpendicular to grain loading conditions has become a popular research topic in the study of DOL effect. Based on the results of 10 groups of tension perpendicular to grain DOL tests, this section conducts the fitting and model verification of tension perpendicular to grain DOL coefficients. The applicability of tension perpendicular to grain DOL effect in different models is also compared and analyzed. Table 4 provides basic information, including long-term tension perpendicular to grain strength tests for Northeast China Larch [17], Douglas Fir [12], and Mongolian Scots pine [15].

Table 4. Long-term test results for structural timber subjected to tension perpendicular to grain.

Materials	Loads	Geometric Dimensions (mm)	Percentile	Stress level (SL) (MPa)
Northeast China Larch	Tension perpendicular to grain	30 × 50 × 100	5	1.27
Northeast China Larch	Tension perpendicular to grain	30 × 50 × 100	15	1.49
Northeast China Larch	Tension perpendicular to grain	30 × 50 × 100	30	1.90
Douglas Fir	Tension perpendicular to grain	25 × 25 × 152	—	1.56
Douglas Fir	Tension perpendicular to grain	25 × 25 × 152	—	1.91
Douglas Fir	Tension perpendicular to grain	25 × 25 × 152	—	2.47
Douglas Fir	Tension perpendicular to grain	130 × 130 × 305	—	0.86
Douglas Fir	Tension perpendicular to grain	130 × 130 × 305	—	0.95
Douglas Fir	Tension perpendicular to grain	130 × 130 × 305	—	1.16
Mongolian Scots pine	Tension perpendicular to grain	30 × 50 × 100	34	1.80

The tension perpendicular to the grain DOL test results were fitted using the equation $SR = a + b\lg(t)$ and compared with the Madison formula, as shown in Figure 6.

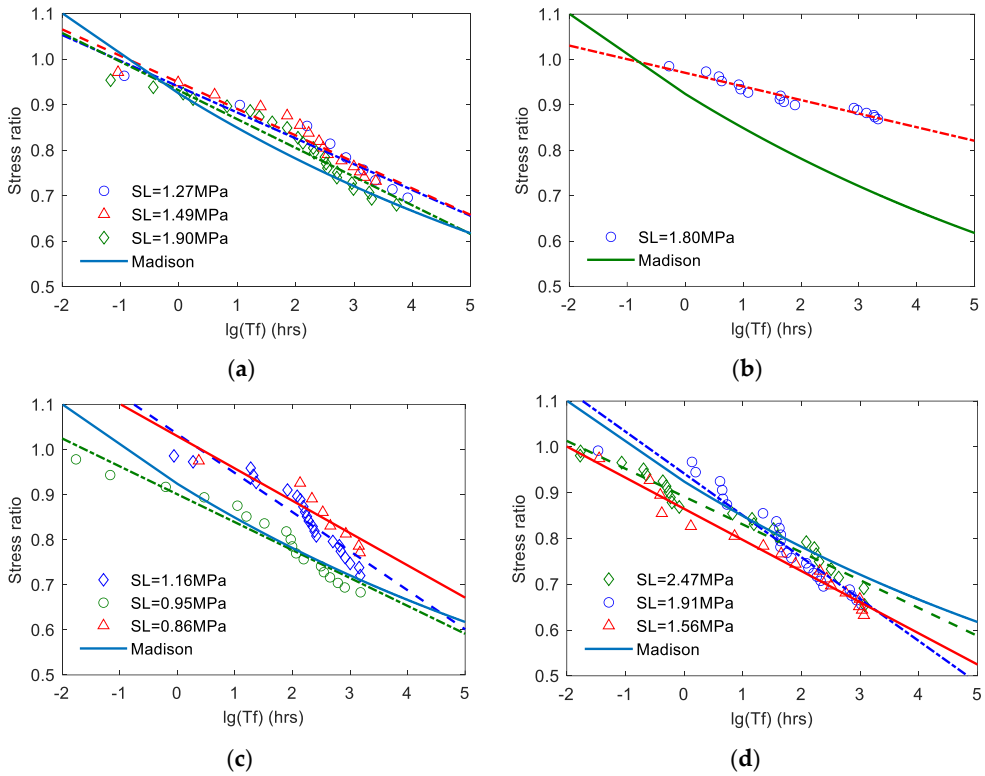


Figure 6. Fitting of tension perpendicular to grain DOL effect: (**a**) Northeast China Larch; (**b**) Mongolian Scots pine; (**c**) Douglas Fir (25 × 25 × 152 mm); and (**d**) Douglas Fir (130 × 130 × 305 mm).

The applicability of the Madison formula for the tension perpendicular to grain DOL effect has been shown to vary in different structural timber species. For the DOL effect of the Northeast China Larch at the three stress levels in Figure 6a, the Madison formula agrees with the experimental results. However, the plots for the DOL test results of the Mongolian Scots pine in Figure 6b all lie above the Madison curve, and the DOL coefficients derived from the Madison formula are on the conservative side compared to the test results. The DOL test results for Douglas Fir in Figure 6c are similar to those for the Mongolian Scots pine. Furthermore, when comparing Figure 6c,d, it can be seen that for Douglas Fir, the size influences the DOL coefficient of the structural timber, with larger sizes being more affected by the sustained action of the long-term load.

Table 5 shows the estimated model parameters of the Gerhards model, Nielsen model, and the Foschi and Yao model using the maximum likelihood estimation method based on the results of 10 groups of tension perpendicular to grain DOL tests. The fitted curves of the three DOL models are shown in Figure 7. The Madison curve is also shown in the figure for comparative analysis.

Table 5. Parameters of DOL model for tension perpendicular to grain test.

Materials	Stress Level (SL) (MPa)	Gerhards	Foschi and Yao			Nielsen	
		b	*B*	*C*	*N*	*b*	*τ*
Mongolian Scots pine	1.80	138.7	765.9	3.73×10^7	19.22	0.373	2914
Northeast China Larch	1.90	57.63	51.69	10.17	3.939	0.325	78.29
Northeast China Larch	1.49	67.65	92.59	87.70	5.606	0.376	128.6
Northeast China Larch	1.27	63.27	91.91	84.02	5.701	0.318	238.2
Douglas Fir	1.16	72.18	410.6	23.56	3.253	0.953	34.46
Douglas Fir	0.95	55.22	48.26	15.93	3.673	0.378	21.95

Table 5. *Cont.*

Materials	Stress Level (SL) (MPa)	Gerhards	Foschi and Yao			Nielsen	
		b	*B*	*C*	*N*	*b*	τ
Douglas Fir	0.86	85.51	234.2	1.494	2.159	0.753	104.4
Douglas Fir	2.47	50.57	27.95	1.386	2.539	0.479	7.340
Douglas Fir	1.91	47.02	265.4	228.9	3.554	0.831	4.881
Douglas Fir	1.56	43.34	19.67	0.513	1.979	0.384	6.317

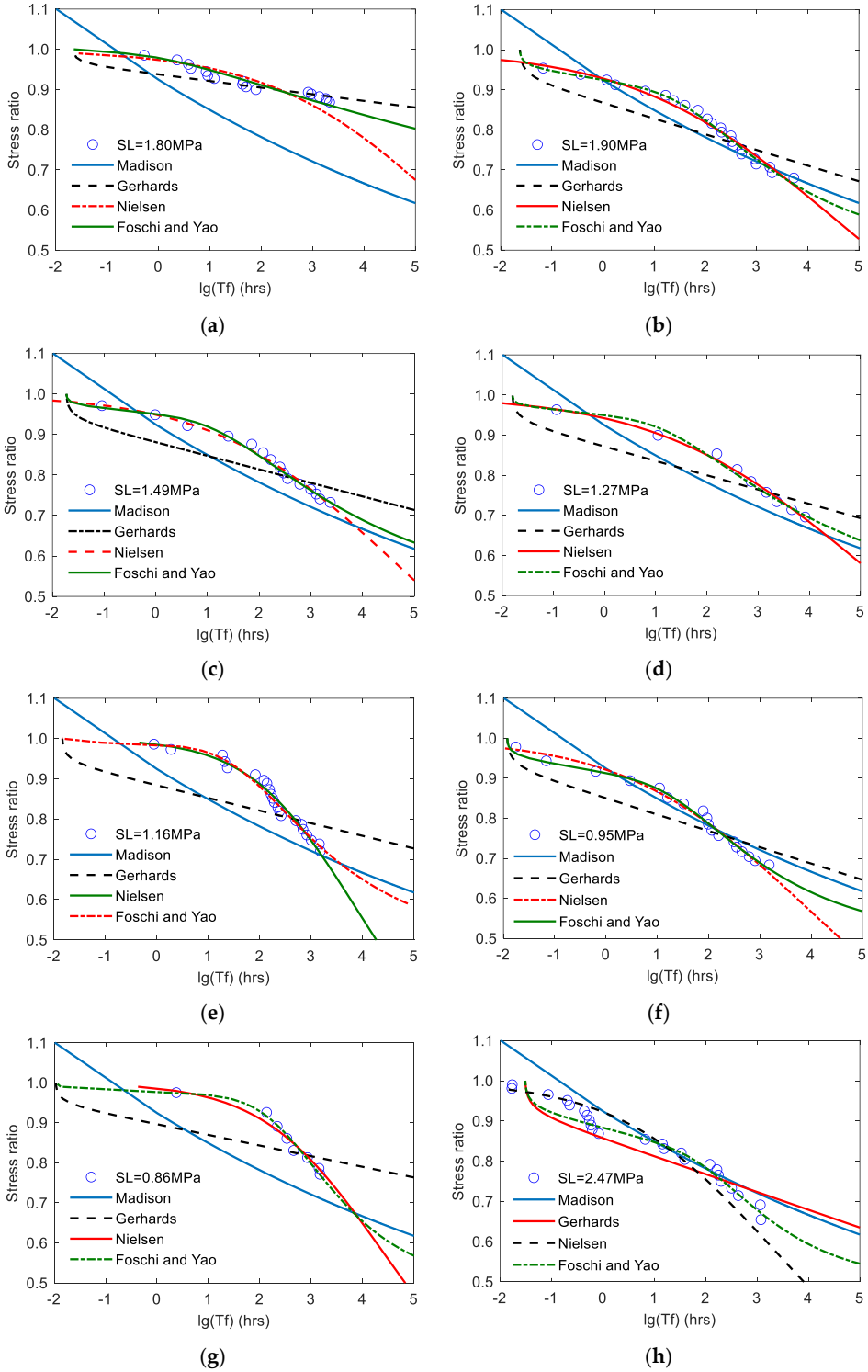
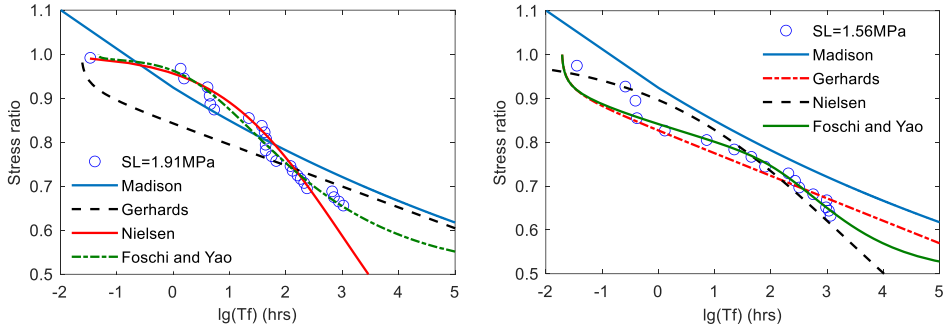


Figure 7. *Cont.*



(**i**) (**j**)

Figure 7. Fitted DOL models of tension perpendicular to grain strength: (**a**) Mongolian Scots pine, SL = 1.80 MPa; (**b**) Northeast China Larch, SL = 1.90 MPa; (**c**) Northeast China Larch, SL = 1.49 MPa; (**d**) Northeast China Larch, SL = 1.27 MPa; (**e**) Douglas Fir, SL = 1.16 MPa; (**f**) Douglas Fir, SL = 0.95 MPa; (**g**) Douglas Fir, SL = 0.86 MPa; (**h**) Douglas Fir, SL = 2.47 MPa; (**i**) Douglas Fir, SL = 1.91 MPa; and (**j**) Douglas Fir, SL = 1.56 MPa.

From the fitting results in Figure 7, the Foschi and Yao model produces the best fit for the tension perpendicular to grain DOL test results, followed by the Nielsen model, while the Gerhards model produces an unsatisfactory fit. Both the Foschi and Yao model and the Nielsen model display middle-upper convex shaped curves. Based on the Gerhards model, for the Nielsen model and Foschi and Yao model for tension perpendicular to grain strength of structural timber determined with parameter estimation, the DOL coefficients for tension perpendicular to grain strength after 10 years of constant load-holding were calculated and shown in Table 6.

Table 6. DOL coefficients for tension perpendicular to grain.

Materials	Stress Level (SL) (MPa)	Gerhards	Nielsen	Foschi and Yao	Fitting
Mongolian Scots pine	1.80	0.85	0.68	0.82	0.82
Northeast China Larch	1.90	0.68	0.53	0.59	0.62
Northeast China Larch	1.49	0.72	0.55	0.64	0.66
Northeast China Larch	1.27	0.69	0.59	0.64	0.66
Douglas Fir	1.16	0.73	0.38	0.59	0.61
Douglas Fir	0.95	0.65	0.46	0.57	0.60
Douglas Fir	0.86	0.76	0.49	0.57	0.68
Douglas Fir	2.47	0.64	0.37	0.55	0.59
Douglas Fir	1.91	0.61	0.27	0.55	0.49
Douglas Fir	1.56	0.57	0.40	0.53	0.53
Average	—	0.69	0.47	0.61	0.63

As shown in Table 6, the calculated mean values of DOL coefficients are 0.69 for the Gerhards model, 0.47 for the Nielsen model, and 0.61 for the Foschi and Yao model, and the mean value of DOL coefficient based on the empirical formula fit is 0.63. From the above-calculated DOL coefficients, the mean value of DOL coefficients derived from the Foschi and Yao model is analogous to the experimental results and is close to the value of 0.62 calculated from the Madison formula.

4.3. DOL Effect Subjected to Shear Parallel to Grain

Spencer et al. [26] investigated the DOL effect tests of Douglas Fir lumber with dimensions of 65 mm × 65 mm × 590 mm subjected to shear parallel to grain loading, in which DOL tests were carried out at three stress levels of 5.50 MPa, 7.30 MPa, and 8.30 MPa, respectively.

The results of the shear DOL tests from the previous literature were fitted using the empirical formula $SR = a + b\lg(t)$ and plotted against the Madison curve for analysis, as shown in Figure 8.

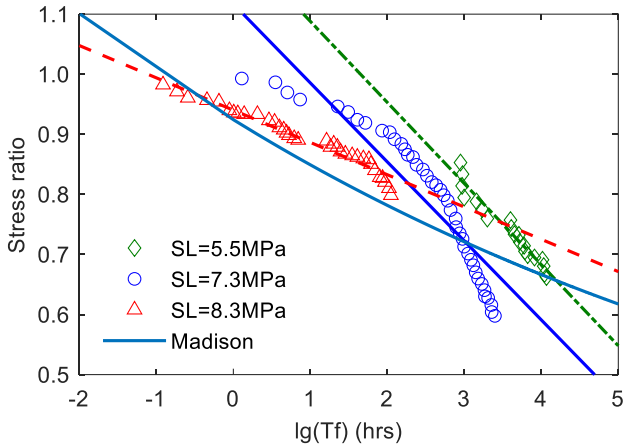


Figure 8. Fitting Douglas Fir DOL effects subjected to shear.

As shown in Figure 8, the shear DOL test results subjected to shear parallel to grain under different stress levels are quite different, and the fitting results with empirical formula are different from Madison formula. The DOL coefficients calculated from the DOL test results for the SL = 8.30 MPa condition are analogous to those derived from Madison formula, while the DOL coefficients for the 5.50 MPa and 7.30 MPa stress level conditions are significantly lower than those calculated from the Madison formula.

Based on the above three groups of DOL results, the maximum likelihood estimation method was used to estimate the parameters of the three DOL models, and the model parameters of the Gerhards model, Nielsen model, and Foschi and Yao model under continuously applied shear load were obtained, as shown in Table 7.

Table 7. DOL model parameters for shear test.

Materials	Stress Level (SL) (MPa)	Gerhards	Foschi and Yao			Nielsen	
		b	*B*	*C*	*N*	*b*	*τ*
Douglas Fir	5.50	54.49	412.4	2.494	2.408	0.701	237.8
Douglas Fir	7.30	44.12	104.2	0.257	0.694	1.654	19.97
Douglas Fir	8.30	69.82	66.58	1134	7.629	0.496	35.17

For the DOL effect under shear loading, the simulation results of the three DOL models are shown in Figure 9. For comparative analysis, the Madison curve is also shown in the figure.

As shown in Figure 9, the shear DOL test data exhibit clear middle-upper convex shaped curves, the Foschi and Yao model and the Nielsen model produced better fits, and the Gerhards model did not produce a good fit. The calculated DOL coefficients based on the three DOL models for 10 years of constant load-holding are shown in Table 8.

Table 8. DOL coefficients for Douglas Fir shear test.

Stress Level (SL) (MPa)	Gerhards	Nielsen	Foschi and Yao	Fitting
5.50	0.68	0.51	0.59	0.56
7.30	0.61	0.28	0.51	0.47
8.30	0.75	0.43	0.66	0.67
Average	0.68	0.41	0.59	0.57

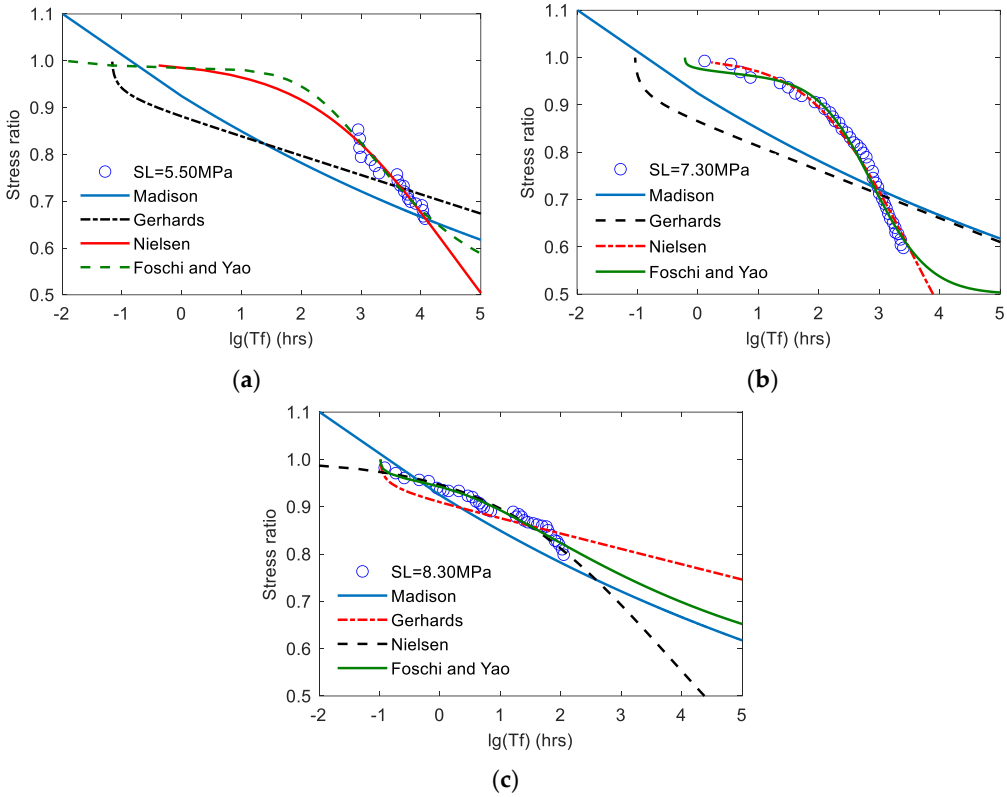


Figure 9. Fitting of DOL model for shear test: (**a**) Douglas Fir with SL = 5.50 MPa; (**b**) Douglas Fir with SL = 7.30 MPa; and (**c**) Douglas Fir with SL = 8.30 MPa.

As seen in Table 8, the mean values of shear DOL coefficients derived from the Gerhards model, Nielsen model, and Foschi and Yao model are 0.68, 0.41, and 0.59, respectively, and the mean value of the shear DOL coefficient derived based on the fitted empirical formula fitting is 0.57. The Foschi and Yao model is superior to the Gerhards and Nielsen models in predicting the shear DOL effect.

It should be highlighted that that the actual value of DOL effect is indeed affected by the moisture content of the specimens and testing conditions. However, it is clearly difficult to consider these factors in actual structural design practice, which prefers to adopt a more simplified approach. For example, the value of DOL coefficient is taken as a deterministic reduction value of 0.72 in standard of wood structure design of China GB 50005-2017. It is worth noting that based on the re-analysis results in the present paper, the fitted mean values of the DOL coefficients are 0.60, 0.63, and 0.57 for bending, tension perpendicular to grain, and shear long-term tests, respectively. Evaluating the mean value of the DOL coefficient indicates that there is no significant difference in DOL coefficients regardless of the test conditions and wood species and other test details. This DOL coefficient for shear load appears to be relatively small, which may be due to the small size of the data sample. Furthermore, the test results were found to coincide well with that calculated using the Gerhards model and Foschi and Yao model. In the NDS-2015, the DOL coefficient for the residential load condition (10 years) was taken as 0.625. The recommended value also seemed to be consistent with the experimental results. However, it must be declared that the effect of moisture content, loading speed, and other details on DOL effect of wood still need to be studied in the future.

5. Summary and Conclusions

This paper reviews and re-analyzes the DOL test results of structural timber in previous research and fits the DOL test results under three long-term sustained loads, such as bending, tension perpendicular to grain, and shear based on the empirical equation

$SR = a + b\lg(t)$. The DOL coefficients for 10 years of constant load-holding were also calculated, and the results were compared and analyzed with the Madison empirical formula, the Gerhards model, the Nielsen model, and the Foschi and Yao model to verify the applicability of the Madison formula and the three DOL damage models. The summary and conclusions are as follows:

(1) For the short-term strength of different woods, including Douglas Fir, Norway spruce, Canadian SPF, etc., both the 2-P Weibull distribution and the normal distribution were used to achieve an accurate fit of their short-term strength distribution characteristics to provide a theoretical basis for determining the short-term strength in long-term tests using the percentile matching method. Moreover, factors such as wood type, specimen geometry, loading rate, and moisture content significantly affect the short-term strength distribution characteristics and DOL effect;

(2) The Madison empirical formula proposed by Wood based on the comprehensive results of impact testing, ramp loading test, and long-term loading test can be better applied to the calculation of DOL coefficients for structural timber under long-term continuous bending and tension perpendicular to grain loading. The DOL coefficients for bending and tension perpendicular to the grain of timbers are 0.60 and 0.63 extrapolated based on empirical formulas, respectively, which have a well agreement with the DOL coefficient of 0.62 derived from Madison's empirical formula.

(3) The three DOL damage models have different simulation effects on the long-term sustained effects of different types of loads. For the bending DOL effect, the calculated results of the Gerhards model and the Foschi and Yao model agree with the results derived from the empirical formula and the Madison formula, while the calculated results for the Nielsen model are conservative. For the tension perpendicular to grain and shear DOL effects, the DOL coefficients derived from the Foschi and Yao model are analogous to the experimental results and are close to those derived from the Madison formula.

This work summarizes the historical data of the DOL data and calculates the DOL coefficients through empirical fitting and model calibration, which is necessary for understanding the DOL effect on wood as a whole. However, the limitations of this work need to be emphasized as follows. The historical documents considered a variety of influencing factors on the DOL effect of wood, such as wood species, moisture content, loading states, loading speeds, and others. However, the specific effect of these factors on DOL were not discussed in detail and still need further study. Furthermore, the DOL effect on wood has been widely studied; however, modern wood structures are commonly constructed using engineered wood products (EWPs), and the DOL effect on EWPs still need investigation in the future.

Author Contributions: Conceptualization, X.Z.; methodology, E.Z. and X.Z.; validation, E.Z.; investigation, E.Z. and Q.Y.; resources, M.Z.; data curation, M.Z.; writing—original draft preparation, M.Z.; writing—review and editing, E.Z. and Q.Y.; supervision, X.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (No. 52038006), the Major Scientific & Technological Innovation Projects of Shandong Province, P. R. China (No. 2021CXGC011204), and the Jinan Science and Technology Bureau (NO. 202228057).

Data Availability Statement: Data will be made available upon request.

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

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