LONG TERM STRENGTH OF SPRUCE SOLID WOOD AT TRANSVERSE TENSION LOADING

ZEITSTANDFESTIGKEIT VON FICHTEN-VOLLHOLZ BEI TRANSVERSALER ZUGBEANSPRUCHUNG

RESISTANCE A LONG TERME DE EPICEA EN TRACTION TRANSVERSALE

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SUMMARY

The paper reports on ramp load and duration of load (DOL) tests of spruce solid wood subjected to tension loading perpendicular to grain. The long-term tests were performed at constant climate conditions of 20°C and 65% relative humidity. The DOL tests aimed at a so far not existing proof whether the long term decrease of tension strength perpendicular to grain follows the so-called Madison curve, as assumed today, although this relationship has been derived for bending parallel to grain. At the given conditions the expected typical influence of duration of load on strength of wood could not be proven here. The latter fact is explained qualitatively by stress redistribution due to anisotropic creep-compliances.

ZUSAMMENFASSUNG

Im vorliegenden Aufsatz wird über Versuche zur Kurz- und Dauerstandfestigkeit von Fichtenvollholz bei Zugbelastung rechtwinklig zur Faserrichtung berichtet. Die Zeitstand-Versuche wurden unter konstanten Klimabedingungen bei 20°C und 65% Luftfeuchtigkeit durchgeführt. Die Dauerstandversuche zielten darauf ab, den bisher nicht existierenden empirischen Beweis zu erbringen, ob sich die Querzugfestigkeit sich unter Einwirkung von Dauerlasten gemäß der Madison-Kurve abmindert. Letzteres wird bisher angenommen, obwohl die Beziehung für Biegung parallel zur Faserrichtung abgeleitet wurde. Unter den gegebenen Randbedingungen ließ sich der für Holz ansonsten typische Einfluß der Belastungsdauer auf die Festigkeit nicht nachweisen. Dies wird qualitativ durch Spannungsumlagerungen auf Grund anisotroper Kriech-Nachgiebigkeiten erklärt.

RESUME

Cet article rapporte des essais sur la resistance à court et long terme de l'épicea en traction perpendiculaire. Les essais a long terme ont été conduits sous un environment maintenu constant de 20°C et 65% d'humidité relative. Les essais à long terme avaient pour but de montrer que la resistance en traction perpendiculaire décroissait sous la charge selon la relation connue sous le nom de 'Courbe de Madison'. Cette relation empirique communément admise aujourdhui, a été établie à partir d'essais en flexion parallele au fil. Dans les conditions réalisées, l'effet attendu de la durée de charge n'a pas été observé. Une explication qualitative est proposée basée sur l'hypothèse d'une redistribution des contraintes due à l'anisotropie de fluage du materiau.

KEYWORDS: Long term strength, tension perpendicular to grain, spruce solid wood, effect of anisotropic creep

1. INTRODUCTION

The duration of load effect of wood comprising the combined effects of accumulated time of loading, load level and climate conditions on strength is one of the most important characteristics of the material wood.

Since the first systematic investigations [Wood, 1947] resulting in todays DOL master curve, the so-called Madison relationship, numerous investigations with clear wood and structural lumber were performed. Milestones were i. a. laid by [Barrett et al., 1978; Madsen, 1992; Morlier et al., 1998].

The question may be posed whether the duration of load effect is an intrinsic material property of structural timber irrespective of mode of loading. A simple answer is given in Eurocode 5: Design of timber structures, saying 'yes'. Looking deeper into the problem and bearing in mind the anisotropic constitutive law, it might be supposed that there are differences in loading modes parallel and perpendicular to fibre direction. In case of the latter load-grain configuration the globally cylindrical material law, dependant on size and sawing pattern, induces a highly inhomogeneous stress and strain state even in uniaxial tension tests.

This paper presents the results of an extensive investigation on the DOL effect in transverse tension loading of spruce solid wood at constant climate conditions performed in the frame of a European research project. It is revealed that the Madison curve does not apply to the specifically regarded configuration.

2. MATERIAL

The investigated material was spruce (picea abies) from a single stand in Southern Sweden. The specimens comprised 25 boards with a cross-section of 45×195 mm and lengths between 4000 and 5000 mm. In order to classify the material with respect to density and stiffness parallel to grain the boards were cut to 2 m length. For these boards MOE was determined via bending vibration.

The volume and dimensions of the actual test volume within the specimen (see below Fig. 1a, b) were chosen according to European standard [EN 1193] as $V = 0.000567\ m^3$ and $h = 180$ mm, $b = 45$ mm, $l = 70$ mm, respectively. The test volumes contained no visible defects such as knots and resin pockets, i. e. conformed to so-called clear wood. The material was stored at 20°C, 65% RH until ramp-load testing respectively start of DOL tests.

In order to obtain well matched test samples for ramp-load tests ($n = 45$ specimens) and the long term tests in three different climates (each with 15 specimens)[1] the entity of all test volumes was split into six MOE-classes. Each MOE class extended over a range of 1 GPa; the MOE means of each class were 9.5, 10.5, 11.5, 12.5, 13.5 and 14.5 GPa. The respective specimen numbers of the four collectives were determined randomly from the different MOE classes.

[1] here only the results of the tests in constant climate 20°C, 65% RH are presented.

3. SPECIMENS

Preliminary tests on tension strength perpendicular to the grain of solid wood were conducted according to [EN 1193] and to more detailed procedures stated in [Ehlbeck et al., 1994].

Yet, the described load transfer mechanism via intermediate wooden blocks of spruce with grain direction *parallel* to load direction turned out to be rather inapt for the case of solid wood. The vast majority of preliminary test specimens failed in the glue-line between intermediate blocks and the actual test volumes, the reason therefore being still too high stiffness differences between test volume and adhered load transferring on-gluings.

It was thus necessary to develop an improved specimen with a smaller stiffness difference between intermediate wooden blocks and test volume. It should be stated that a sole necking of the spruce volume, suitable for many other materials, is no solution to the problem due to inhomogenities and stochastic micro-defect distribution. Figures 1 a and b illustrate the realized specimen configurations, slightly different for ramp load and DOL tests, consisting of a spruce test volume and two intermediate on-gluings with grain direction perpendicular to load direction. As tension strength of beech in direction perpendicular to the grain is only about two times higher than strength of spruce, the load transferring beech on-gluings had to be necked. In the case of short term tests (Fig. 1a) the beech on-gluings were directly connected to steel grips and thereby to the test machine. In case of the long term tests (Fig. 1b) additional spruce blocks (on-gluings 2) with grain direction parallel to load direction were adhered to the beech on-gluings. The end-grain faces of the on-gluings 2 were adhered to steel plates incorporating centrically a screw hole serving for screwed and hinged fixations to the DOL rig. The steel to wood adhesion was performed by means of a two component Polyurethane adhesive; in order to increase the interface capacity two steel rods were adhered parallel to grain direction and fixed to the steel plates.

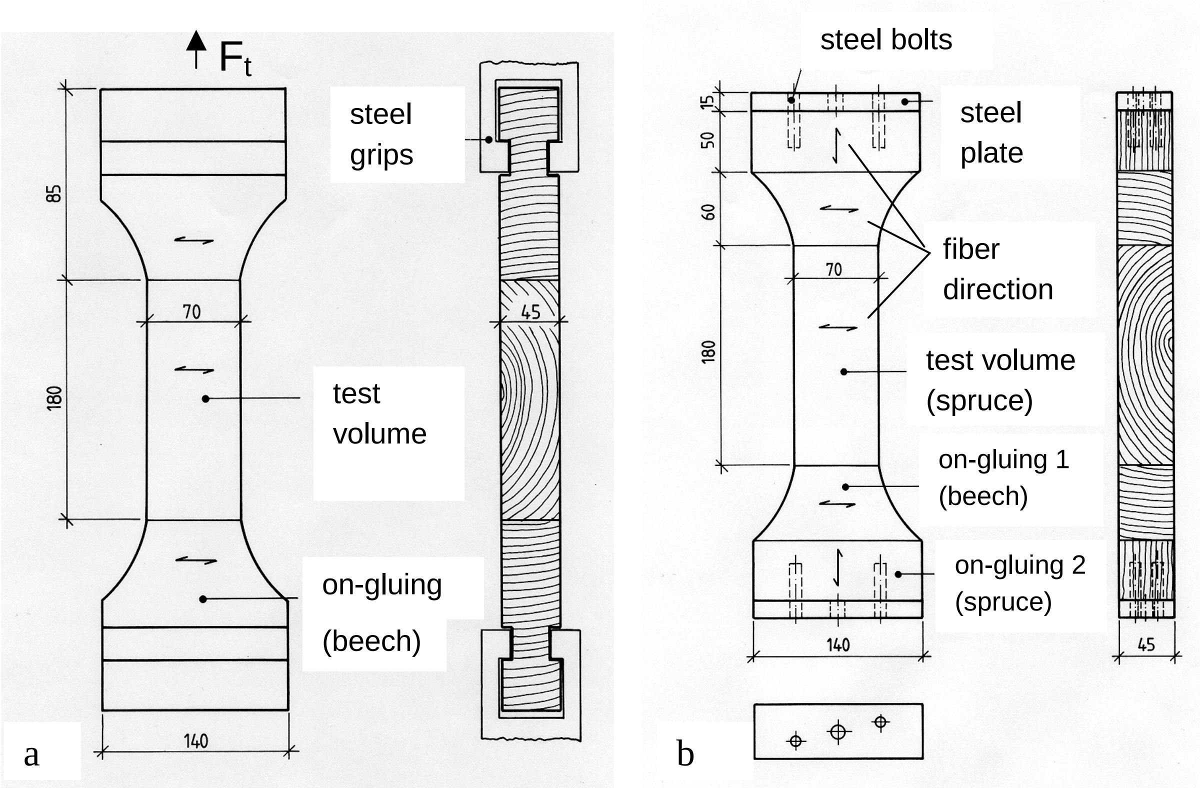

Fig. 1a, b. *Sketches of developed specimen built ups slightly different for ramp load and long-term testing*
a) ramp load specimen *b) DOL specimen*

4. RAMP LOAD TESTS

All 45 ramp load tension tests were performed according to [EN 1193] in stroke control at a constant cross-head speed of 0.8 mm / min. The majority of failures (75%) obtained with the special specimen configuration described above was located near mid-height (h/2) of the specimens. The rest of the specimens failed close to or partly in the interface between test volume and on-gluings. Figure 2 shows the results of the ramp-load tests as cumulative frequency distribution vs. strength perpendicular to grain altogether with a fitted Gauss distribution. Other fit approximations (lognormal and 3parameter Weibull) give almost equal fit results. The mean strength (± standard deviation) and the coefficient of variation were $f_{t,\,90} = 2.16 \pm 0.393$ N/mm^2, C.O.V. = 18.1%, The minimum and maximum values were 0.999 and 2.96 N/mm^2.

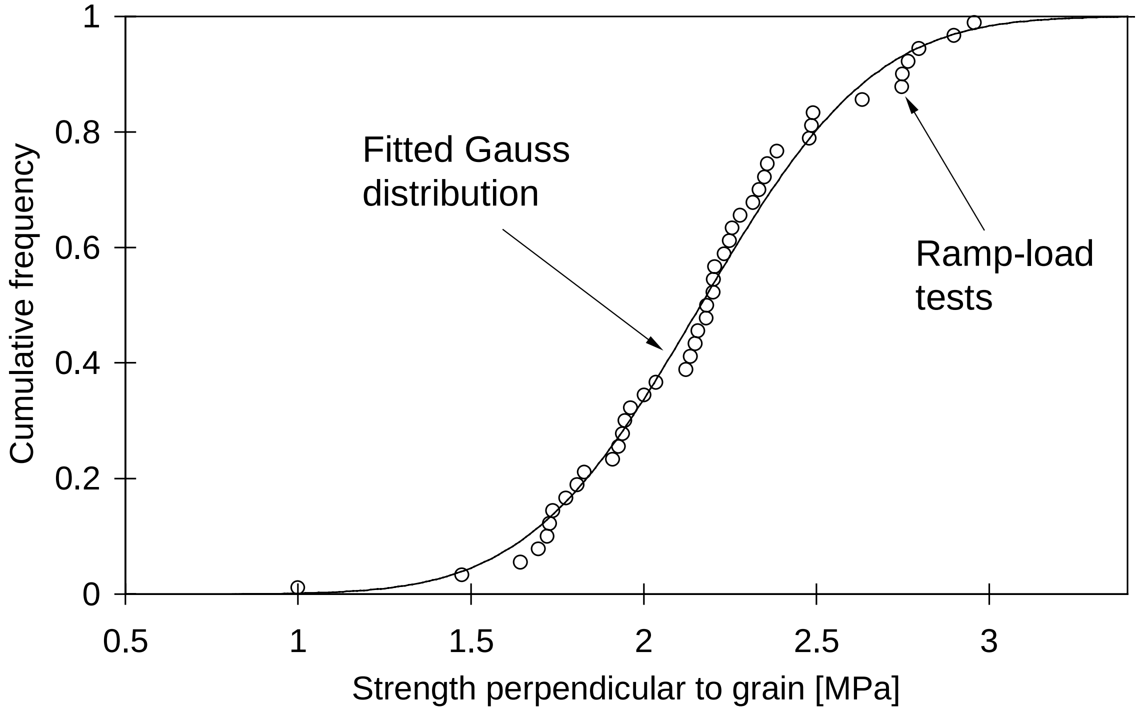

Fig. 2. *Cumulative frequency distribution of ramp-load strength perpendicular to grain altogether with a fitted Gauss distribution.*

5. LONG TERM TESTS

5.1 Test set-up and loading regime

The long-term loads were applied via a lever principle and hanging dead loads. Figure 3 shows the realised test set-up in the climate chamber. The loading regime consisted in a stepwise increase of the applied load with a step length of 28 days. The applied tension stress of the first step was chosen as 1.404 N/mm^2 representing a stress level SL of 65% relative to the mean ramp-load strength value. The sucessive equal load increments were set to 0.108 N/mm^2 representing 5% of $f_{t,\ 90,\ ramp}$ resp. 7.7% increases of the first load level.

The initial load was applied via a screw driven load table lowered at constant speed until the dead load in the bucket at the lever arm end was free of support. For the load increments penny shaped steel shred was poured cautiously into the buckets.

The times to failure of the individual specimens were registered by electrical switches activated in case of fracture.

Fig. 3. *Photograph of realised long-term test set-up in the climate chamber*

5.2 Results

Table 1 contains a compilation of the most important results of the DOL tests, being long term strength, time to failure from beginning of the test and time to failure within respective load step. Further, density and MOE of the boards where the specimens were cut from are given.

Table 1. *Compilation of most important DOL results; further MOEs from bending vibration tests and individual densities are given*.

Specimen No.	Board No.	sequential order of failure	No. of load-step	Long-term strength $f_{t,90}$ [MPa]	time to failure from begin of test [h]	time to failure from begin of load step [h]	Density ρ_{12} [kg/m^3]	MOE acc. to bending vibration [MPa]
1	1b	1	3	1.62	1349.2	8.1	416	10.8
2	2a	3	5	1.84	2862.3	174.3	446	13.7
3	4a	11	9	2.27	5745.7	369.7	476	13.7
4	8a	2	4	1.73	2610.3	594.3	450	12.0
5	9b	5	7	2.05	4037.7	12.8	434	10.0
6	10a	9	8	2.16	4970.0	266.0	480	14.4
7	11a	13	10	2.38	6081.8	33.8	410	9.8
8	11b	7	8	2.16	4700.1	20.1	417	11.8
9	12b	15	11	2.48	7253.7	533.7	492	11.4
10	18a	14	11	2.48	6779.8	59.8	459	10.8
11	18a	4	5	1.84	3229.6	541.6	459	10.8
12	20a	8	8	2.16	4740.7	60.7	476	12.2
13	20a	10	8	2.16	5320.8	616.8	476	12.2
14	18a	12	10	2.38	6048.0	4.8	461	10.8
15	23a	6	7	2.05	4430.5	398.5	478	14.8

Figure 4 visualises the evolution of the failures along the time axis of the stepped loading regime. It can be seen that the first failure occured shortly after the beginning of load step 3 with a nominal stress level of 75 %. The 8th specimen, i.e. the 50% fractile specimen, failed at load step 8 at a nominal stress level of 100%. The last failures were observed at nominal stress levels of 115% within 11th load step. Thus the DOL test lasted for almost one year despite of the stepped loading regime.

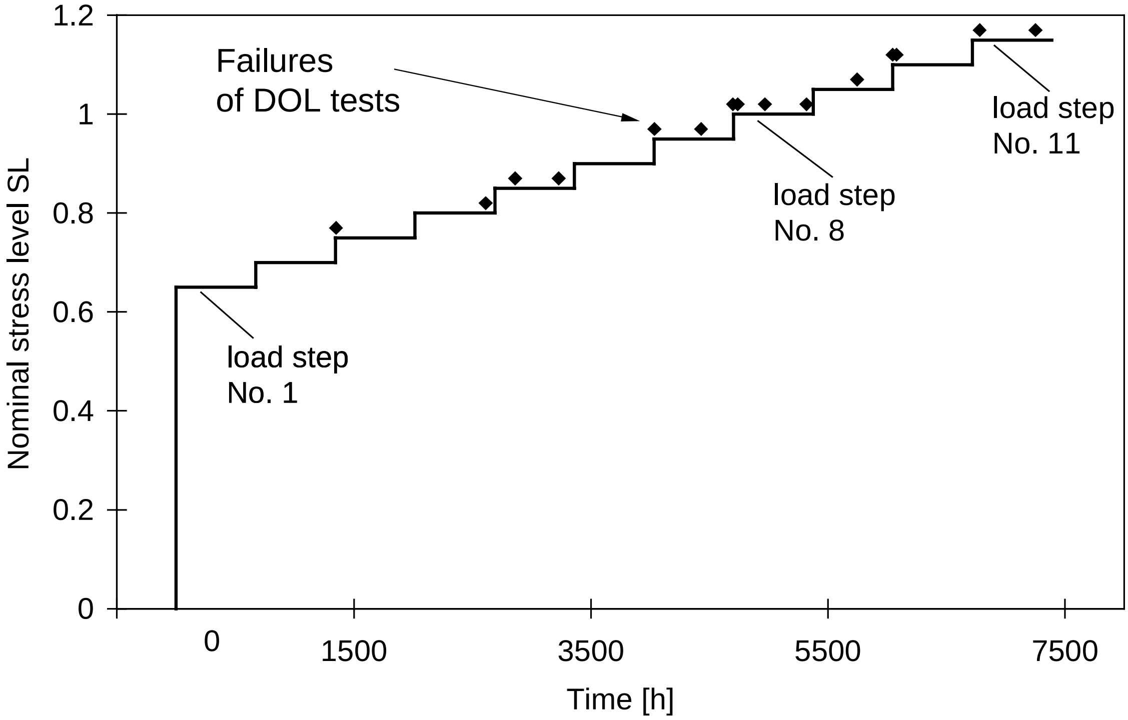

Fig. 4. *Times to failure along load history with increased stepped nominal stress levels*

The DOL stress level of 100% of the median specimen (50% fractile) forwards the non expected result being that no strength reduction is obtained at the 50% fractile level. In order to find out whether the latter observation holds true for the whole range of strength values the strength distributions of ramp load and DOL tests were compared. Figure 5 gives the cumulative frequencies of ramp load and DOL results revealing the nearly perfect coincidence of both distributions; only in the upper branch of the distribution some slight decrease of strength may be assumed.

In other words almost no DOL effect was observed for solid wood subjected to transverse tension loading at constant climate conditions of 20°C and 65% RH.

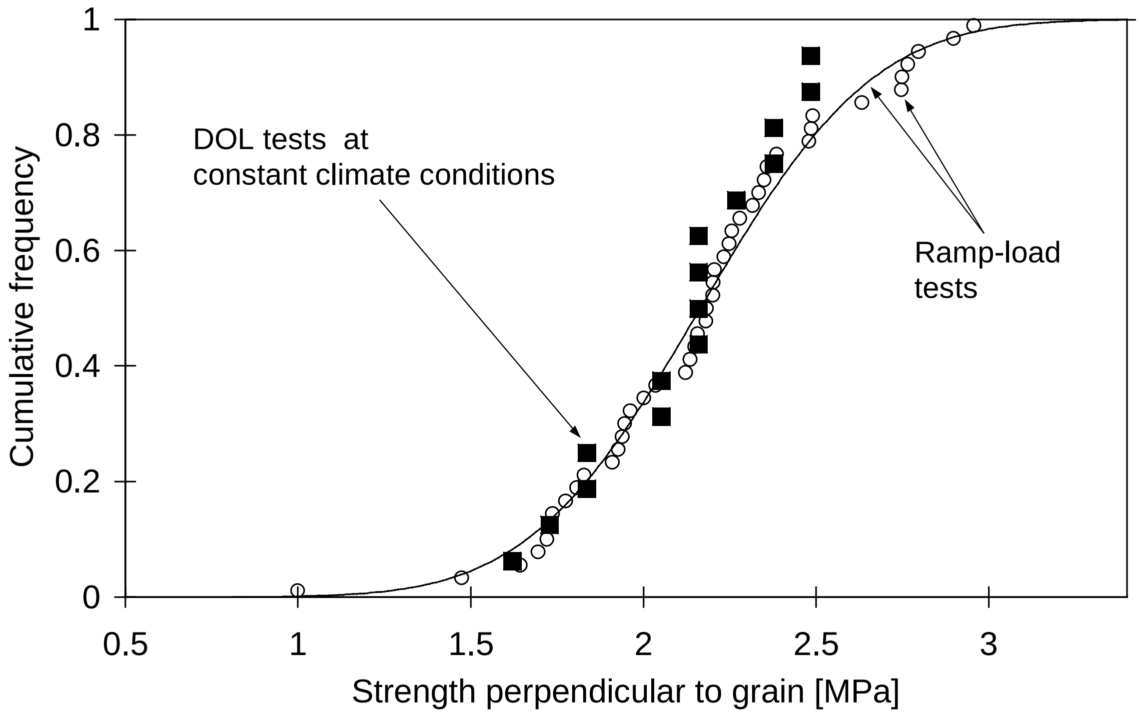

Fig. 5. *Cumulative frequency of strength perpendicular to grain in DOL tests at constant climate conditions of 20°C / 65% RH; also given are the results and the fitted distribution of the ramp load tests.*

The almost lacking DOL effect is most clearly demonstrated in Fig. 6 where the 'ranked' stress levels are plotted vs. logarithmic time scale. Within the ranking procedure the strengths of the DOL specimens are related to ramp load strengths of equal cumulative failure frequency what results in a set of individual stress levels for all specimens. In detail, the ramp load strength for a given frequency has to be taken from a fitted strength distribution, here being a normal distribution. In the case of the median of the distribution, the nominal stress level coincides with the individual stress level. Figure 6 additionally shows the DOL effect normally supposed for clear wood specimens ('Madison curve') respectively for glulam as experienced in [Aicher et al., 1998]. The linear behaviour with a slope of about –6.3 in the semi-logarithmic plot of stress level vs. time to failure is supposed to be a typical characteristic of wood and wood based materials. However, solid wood, at least of the used size and species, subjected to tension load perpendicular to grain obviously does not exhibit this feature.

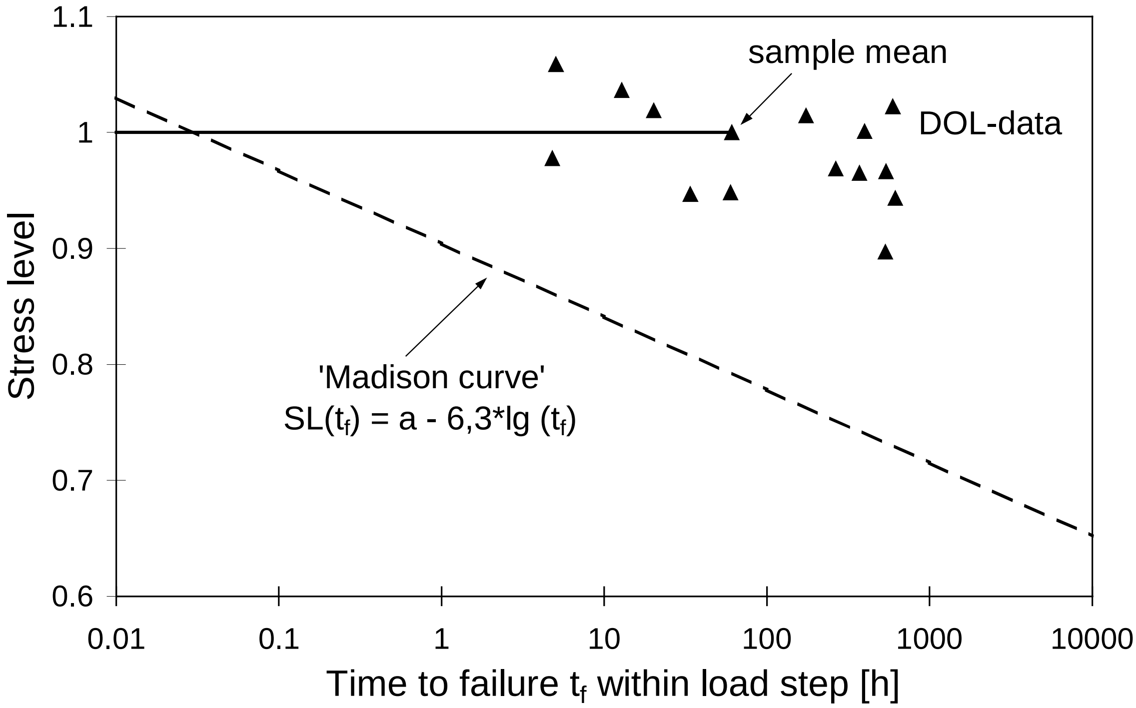

Fig. 6. *Individual failure stress levels vs. time to failure within failure load steps; additionally given is the Madison curve, i .e. the expected DOL behaviour of wood*

In this paper the observed unexpected phenomenon will only be explained by means of qualitative argumentation.

The main mechanism of the effect may be described as a combination of relaxation effects with polar anisotropy within the transversal (radial-tangential) plane of wood. Results of recent studies have shown that effective off-axis stiffness is varying considerably in the cross-section of a board due to the so-called shear coupling effect [Aicher et al., 1996; Aicher et al., in press]. The elastic compliance parallel to load direction is 4 to 5 times higher in the sections where the angle between the annual rings and the load direction is about 45 degrees (close to the board edges) as compared to sections where direction of load and tangential on-axis direction (near board width) coincide. In the last mentioned paper it is also proven, both numerically and empirically, that in the 45°-sections the off-axis Poisson ratios reach values of about 0.9 to 1.

That these facts, being well understood for elastic performance, hold true analogously for the creep behaviour is qualitatively revealed by Fig. 7 showing the typical deformation shape of the DOL specimens. Highly remarkable is that the so-called ‘right’ specimen edge being the edge oriented closer towards pith bows convexly although a tension load is applied. However, the ‘bow’ results from the extreme lateral contraction caused by elastic and even more by creep deformation parallel to direction of applied load in combination with the high value of off-axis Poisson ratio.

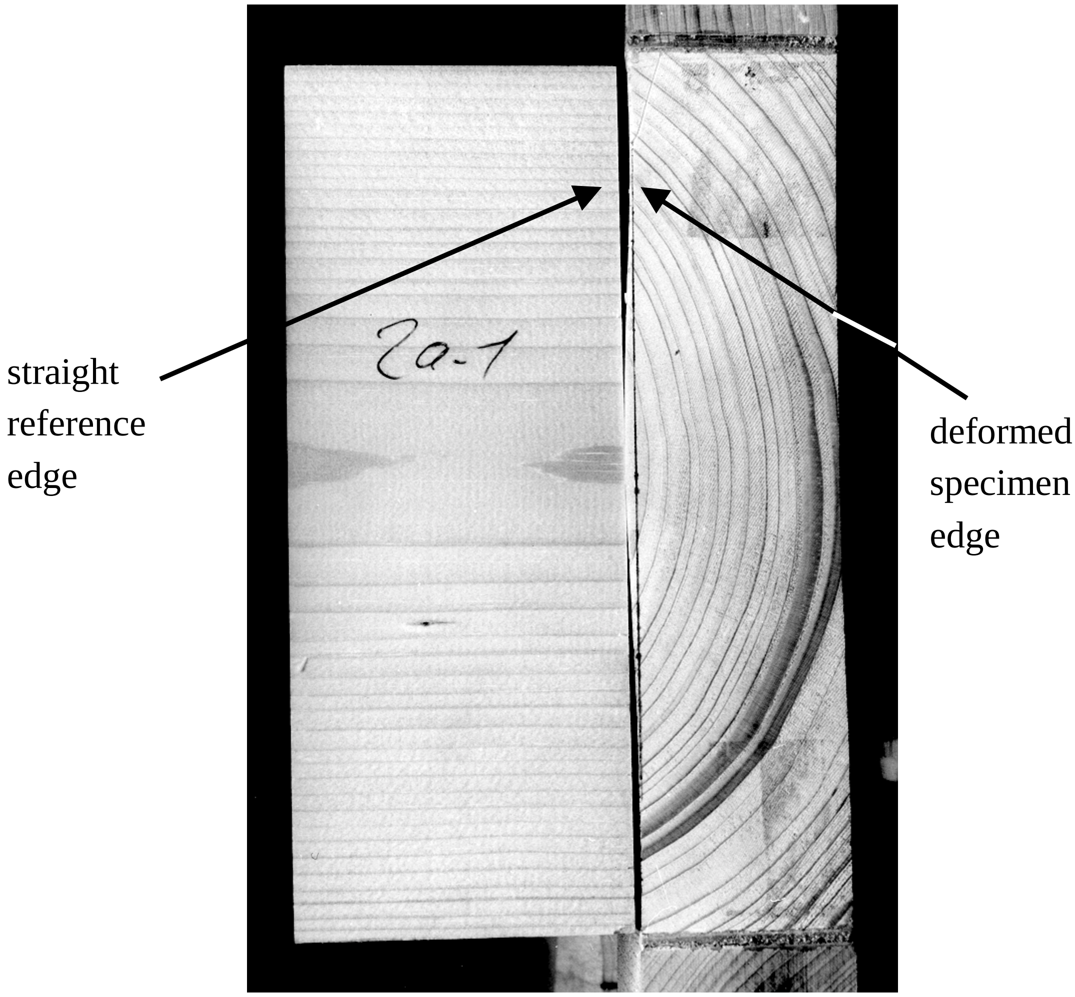

Fig. 7. *Typical deformation shape of investigated spruce specimens long-term loaded in tension perpendicular to grain.*

If the observed deformation shapes result from pronouncedly higher creep in the 45°-sections there is a considerable redistribution of stresses within the whole cross-section leading to a more smooth and thereby less damaging stress distribution. Thus stress relaxation and redistribution counteract the material degradation being responsible for strength loss due to sustained loading. The results of the presented work show that both processes seem to be in a balance for the chosen time scale, specimen volume, species, boundary and climate conditions.

6. CONCLUSIONS

The performed duration of load (DOL) tests with spruce solid wood loaded in tension perpendicular to grain at constant climate conditions of 20°C and 65% relative humidity forwarded an absolutely unexpected result: almost no duration of load effect was observed compared to a well matched ramp-load test series. The explanation for this material-specimen behaviour consists in the effect of cylindrical anisotropy and off-axis loading which results in a pronounced stress redistribution within the specimen. The mentioned anisotropy is most pronounced for creep deformations resulting in a remarkable change of the rectangular specimen shape.

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