



On the influence of load variations on lifetime and strength of wood

Nielsen, Lauge Fuglsang

Published in:

Proceedings of the International Conference on Integrated Approach to Wood Structure, Behavior and Applications

Publication date:

2006

Document Version

Early version, also known as pre-print

[Link back to DTU Orbit](#)

Citation (APA):

Nielsen, L. F. (2006). On the influence of load variations on lifetime and strength of wood. In *Proceedings of the International Conference on Integrated Approach to Wood Structure, Behavior and Applications* (pp. 95-103). DISTAF - Università degli Studi di Firenze.

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

On the influence of load variations on lifetime and strength of wood

Lauge Fuglsang Nielsen

Department of Civil Engineering
Technical University of Denmark

Abstract

To days recommendations for probability and reliability analysis of wood structures do not fully recognize the influence of wood microstructure and creep on the mechanical behavior of wood. As a consequence, certain important features in wood design cannot be considered properly. Ignoring the basic materials behavior of wood cannot be 'covered or replaced' by purely mathematical handling of problems without loss of credibility.

Some examples are considered in this note, which cannot be solved following present recommendations:

- The influence of load variations on lifetime.
- The influence of load history on recycle-strength (residual strength).

It is demonstrated in this paper, how the problems just mentioned can be solved from respecting wood as a damaged viscoelastic material, meaning that wood is a cracked (damaged) material with creep.

1. Introduction

Application of so-called k_{MOD} methods [e.g.1,2] on problems with respect to lifetime and residual strength has serious limits [3]. The concept of k_{MOD} factors¹⁾ being constants is based on theories, which are basically developed from constant load experiments. The k_{MOD} method is very non-reliable at higher load frequency variations. Application of the Palmgren-Miners rule [4,5] is also questionable. This rule does not properly consider load frequency when viscoelastic materials are considered [6].

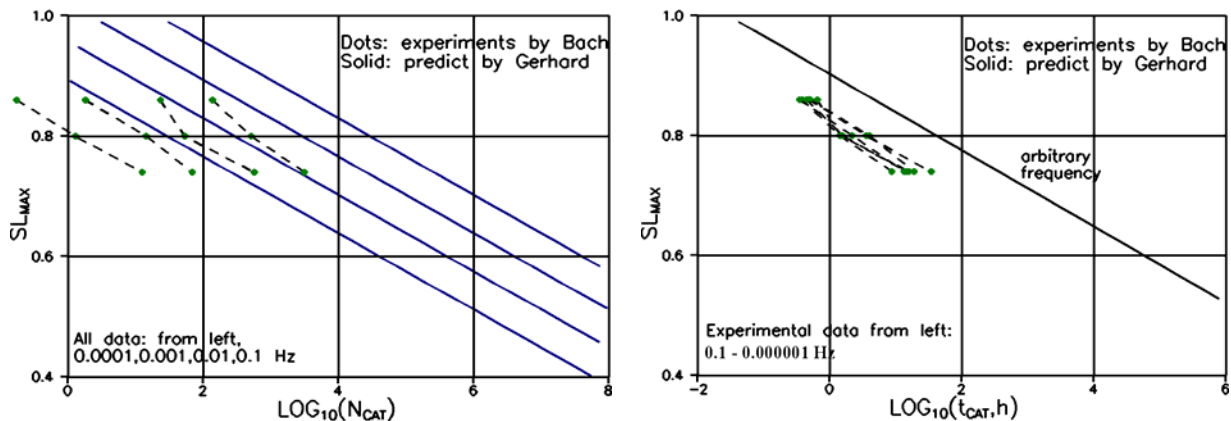


Figure 1. Lifetime (load cycles and time) of clear wood subjected to a block load history as defined in figure 4 between 0 and a maximum of SL_{MAX} (load relative to wood strength). Overestimated lifetime is a consequence of not considering crack closure effects, see main text.

The main reason, why present recommendations do not represent a sound basis for lifetime predictions of wood subjected to variable load is the fact that they do not consider energy dissipation appearing while changing from one load level to another (the phenomenon of crack closure). Recently, the quantitative consequences of disregarding this feature have been considered by the author in [7]. Overestimated lifetimes are typical consequences of such disregard.

An example of this feature is shown in Figure 1. The experimental lifetime data are the classical ones obtained by Bach [8] in tests exploring the influence of load level and frequency on time and load cycles to failure of wood subjected to varying load histories. The wood considered by Bach was clear

1) Widely spread concept of estimating long-term strength by multiplying short time strength with a codified factor, the so-called k_{MOD} factor.

wood specimens loaded in compression parallel to grain with a harmonic block load (see figure 4) shifting between 0 and a max load level of SL_{MAX} (load relative to strength).

The predictions presented in Figure 1 are reproduced from [7] where they are made by methods normally used in this context (Gerhard [9] and Barrett/Foschi [10,11]).

2. Viscoelastic lifetime prediction

It is demonstrated in this section, how lifetime predictions of wood can be improved significantly by considering wood as a damaged viscoelastic material – and furthermore get information of high importance with respect to residual (re-cycle) strength. As an extra advantage, solutions can be presented in a non-dimensional form such that they apply in general for a number of quality (FL) and viscoelastic (moisture) situations.

Basics

The basics of the authors DVM-theory (Damage Viscoelastic Material) presented in [12] and further developed in [e.g. 6,13,14] are the following:

- Damage in wood can be modeled by the Dugdale crack shown in Figure 2. The strength level (quality) of the wood considered is $FL = \sigma_{CR}/\sigma_L$ to be estimated from Figure 3. Traditional strength is σ_{CR} . Theoretical strength (no damage) is σ_L .
- The viscoelastic properties can be modeled by the Power-Law creep expression presented in Equation 1.

$$\text{Creep function : } C(t) = 1 + \left(\frac{t}{\tau}\right)^b \text{ with creep power } b \approx 0.2 - 0.3$$

$$\text{and relaxation time } \tau = \tau_{15} * 10^{(15 - u)/10} \text{ where } u(\%) \text{ is moisture content and} \quad (1)$$

$$\tau_{15} \approx 10 \text{ days is relaxation time at } u = 15\% \text{ for creep in damaged areas}$$

(somewhat dependent of wood considered)

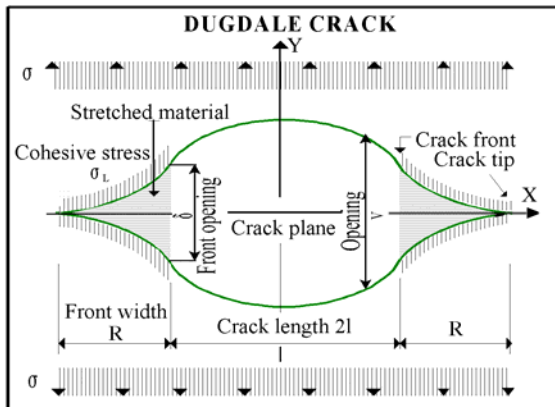


Figure 2. Damage model for wood. Damage ratio, $\kappa = l/l_0$, subsequently used is length of expanding crack l relative to initial crack length.

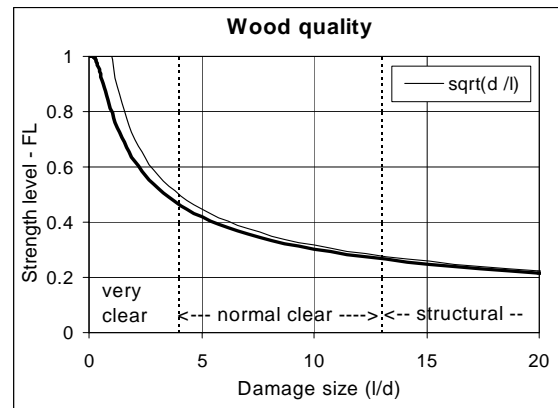


Figure 3. Wood quality estimated from damage size, l , relative to the damage nucleus $d = 0.3$ mm. Strength levels of $FL > 0.8$ can only be obtained improving the microstructure of wood by decreasing the size of the damage nucleus.

Lifetime prediction

The subsequent demonstration of DVM-predictions of wood lifetime is made by graphical presentations of results previously obtained by the author in [6,3] – and also presented in various working papers in the COST-E24 research project on ‘Reliability of Analysis of Timber Structures’ [15]. Specific versions of the theory have to be studied in publications referred to. Symbols used are summarized in the ‘List of Symbols’ at the end of this paper. Of special significance are the strength level FL previously defined – and the so-called fatigue parameters, $(C,M) = (3,9)$ introduced in [6]. Load level $SL =$

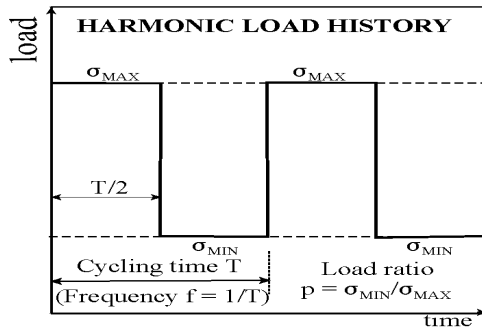


Figure 4. Harmonic block load.

σ/σ_{CR} is load relative to strength. The standard variable load history considered is the harmonic block load defined in Figure 4

An example of lifetime prediction is demonstrated in Figures 5 and 6. The experimental lifetime data are from Bach's work previously mentioned [8]. Predictions are made with creep and strength parameters $(b, \tau, FL) = (0.25, 1\text{day}, 0.4)$ and fatigue parameters $(C, M) = (3, 9)$. The two figures have to be compared with Figures 1 and 2.

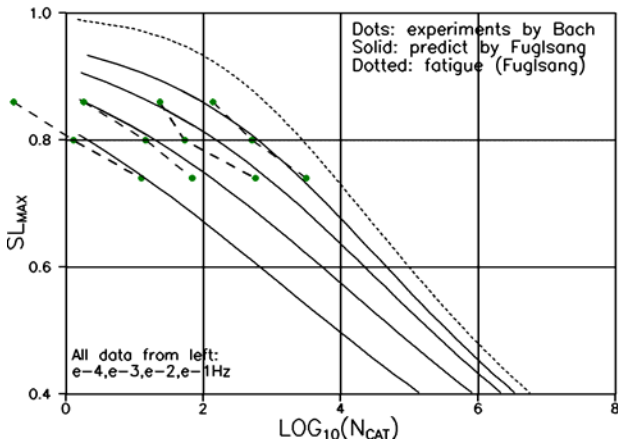


Figure 5. Number of cycles to failure predicted by [6] with crack closure effects considered.

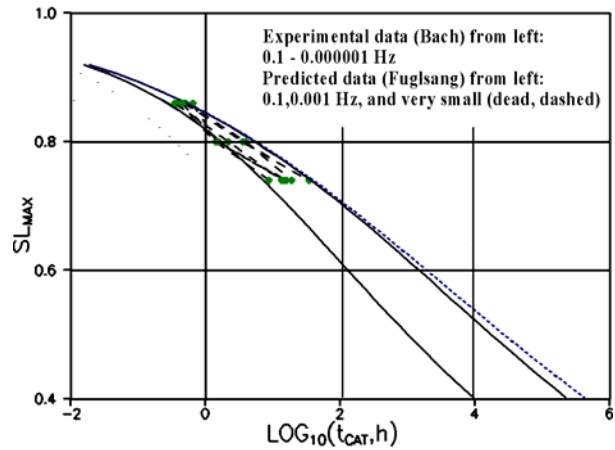


Figure 6. Time to failure predicted by [6] with crack closure effects considered.

3. Master graphs

As previously indicated, lifetime predictions can be made by general non-dimensional master graphs. Such are developed in [6] for any load, wood quality, FL (strength level), and creep relaxation time. The graphs shown in Figure 7 and 8 apply for a creep power of $b = 0.25$ and a load ratio of $p = 0$. As before, fatigue parameters are $(C, M) = (3, 9)$. Associated master graphs for re-cycle strength are shown in Figures 9 and 10.

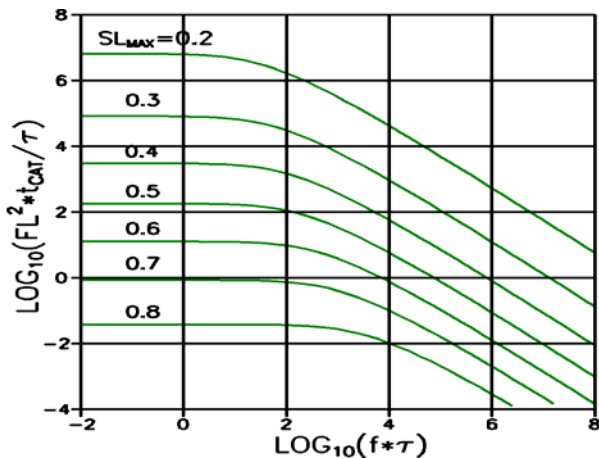


Figure 7. Master graph. Time to failure. Load variation $SL = 0 - SL_{MAX}$.

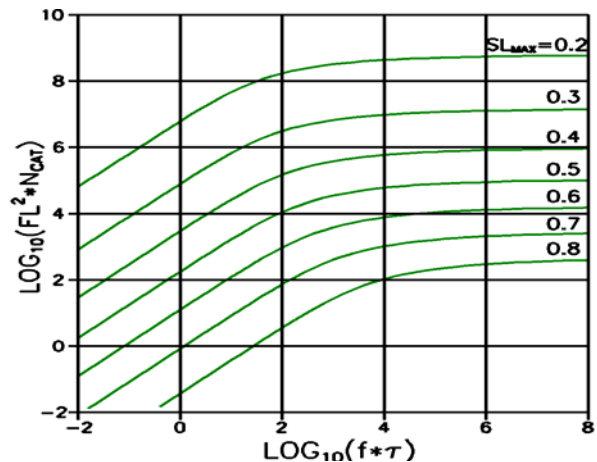


Figure 8. Master graph. Number of cycles to failure. Load variation $SL = 0 - SL_{MAX}$.

4. Design graphs

For practice the master graphs can be simplified [6] by combining the following constant load viscoelastic solutions and elastic fatigue solutions with a linear interpolation of these between the normalized frequencies $f^* \tau = 10$ and 10^5 when load ratio $p < 0.5$. (For $p > 0.5$. see [16]).

Dead load lifetime

$$\frac{d\kappa}{dt} = \frac{(\pi FL)^2}{8q\tau} \frac{\kappa SL^2}{[(\kappa SL^2)^{-1} - 1]^{1/b}} \quad \text{with} \quad q = \left[\frac{(1+b)(2+b)}{2} \right]^{1/b} \quad (\text{damage rate}) \Rightarrow \quad (2)$$

$$\frac{t_{CAT}}{\tau} = \frac{8q}{\pi^2 FL^2 SL^2} \int_0^{1/SL^2 - 1} \frac{x^{1/b}}{1+x} dx \quad (N_{CAT} = t_{CAT} / T = f * t_{CAT})$$

Dynamic (Elastic fatigue)

$$N_{CAT} = \frac{1}{G SL_{MAX}^2} \left[\frac{1 - SL_{MAX}^{M-2}}{(M-2) SL_{MAX}^{M-2}} - \frac{1 - SL_{MAX}^{M-4}}{(M-4) SL_{MAX}^{M-4}} \right] \quad \text{with} \quad G = \frac{CFL^2}{13} \left[\frac{1-p^2}{2} \right]^M \quad (3)$$

$$(t_{CAT} = N_{CAT} * T = N_{CAT} / f) \quad \text{fatigue parameters } (C, M) = (3, 9)$$

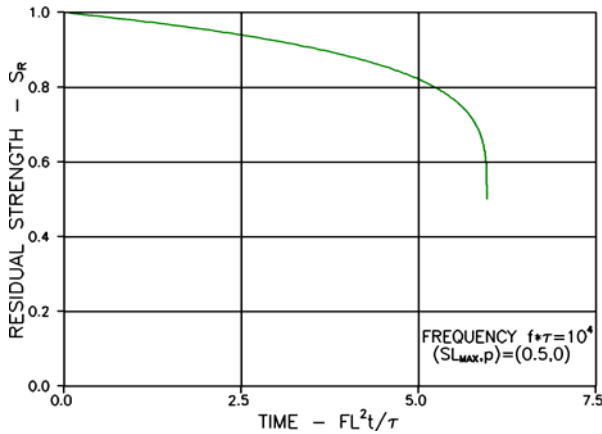


Figure 9. Master graph. Re-cycle strength as a function of time under variable load. Load variation $SL = 0 - 0.5$. Load frequency, $f\tau = 10^4$.

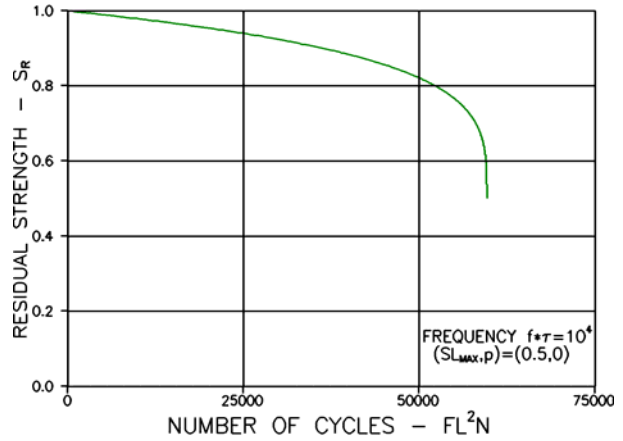


Figure 10. Master graph. Re-cycle strength as a function of number of load cycles. Load variation $SL = 0 - 0.5$. Load frequency, $f\tau = 10^4$.

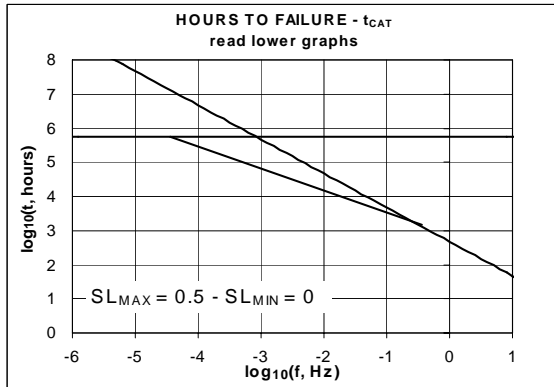


Figure 11. Design graph. Easy estimate of time to failure. Example: $SL_{MAX} = 0.5$, $p = 0$, $FL = 0.25$, $b = 0.20$. and $\tau = 3.2$ days ($u = 20\%$).

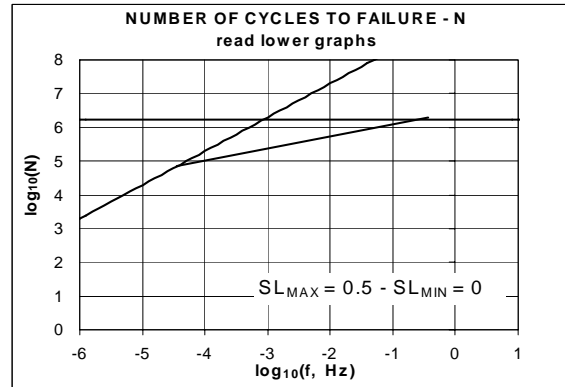


Figure 12. Design graph. Easy estimate of number of load cycles to failure. Example: $SL_{MAX} = 0.5$, $p = 0$, $FL = 0.25$, $b = 0.20$. and $\tau = 3.2$ days ($u = 20\%$).

5. Final remarks

Harmonic load variations have been assumed in this note. An important future research project is to develop a lifetime theory, which applies for more general variations (non-harmonic load histories such as sudden peak loads). It has been demonstrated in [17] that the DVM theory in [6] has the basic potentials to be further generalized for such loads. Figures 13 to 16, reproduced from [3,18], demonstrate some results obtained by a pilot theory being tested to predict residual strength of wood subjected to load histories caused by earthquakes.

With respect to the potentials of the DVM-theory should also be mentioned that research are presently being made [14] to generalize the results of the theory also to apply at variable moisture conditions. It is suggested that the influence of moisture variations very often can be considered by modifying the

creep properties of wood such that the Power-Law description in Equation 1 can be maintained without introducing complicated mechano-sorptive mechanisms. It is obvious that such approach will increase very much the practical applicability of the ‘non-dimensional’ master graphs presented in this article.

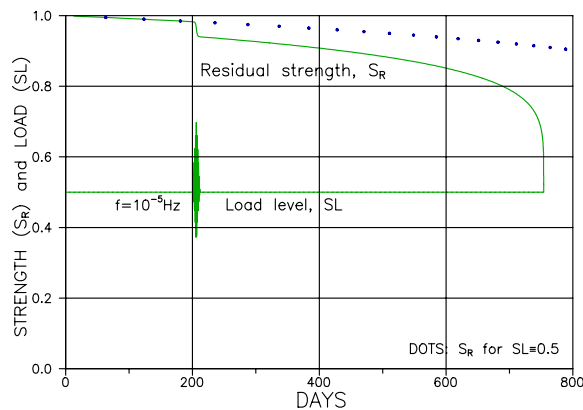


Figure 13. Lifetime and residual strength of wood, $(FL, b, \tau) = (0.4, 0.25, 1 \text{ day})$, loaded with $SL = 0.5 + 1.e-5 \text{ Hz}$ Pulse load at $t \approx 206$ days. The dots indicate residual strength if pulse load is absent.

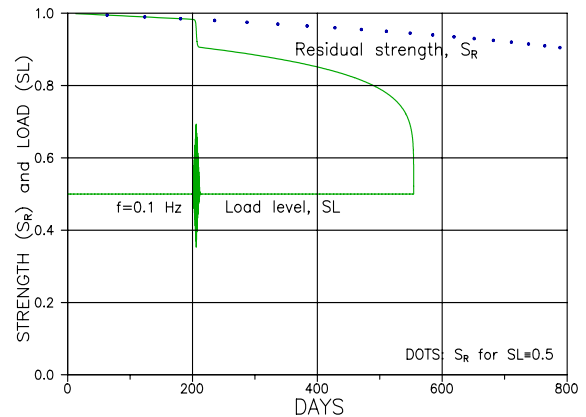


Figure 14. Lifetime and residual strength of wood, $(FL, b, \tau) = (0.4, 0.25, 1 \text{ day})$, loaded with $SL = 0.5 + 0.1 \text{ Hz}$ Pulse load at $t \approx 206$ days. The dots indicate residual strength if pulse load is absent.

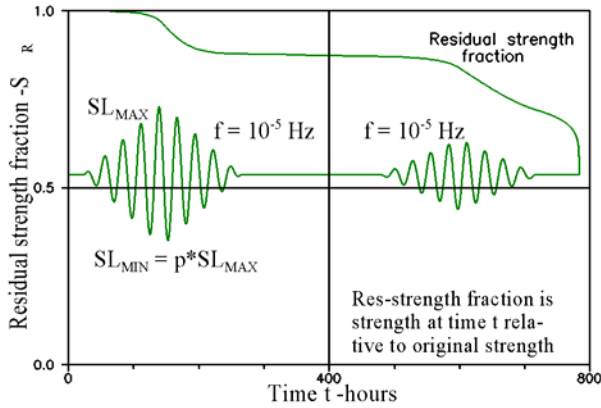


Figure 15. Residual strength and lifetime of wood subjected to load as indicated with $(FL, b, \tau) = (0.4, 0.25, 1 \text{ dav})$.

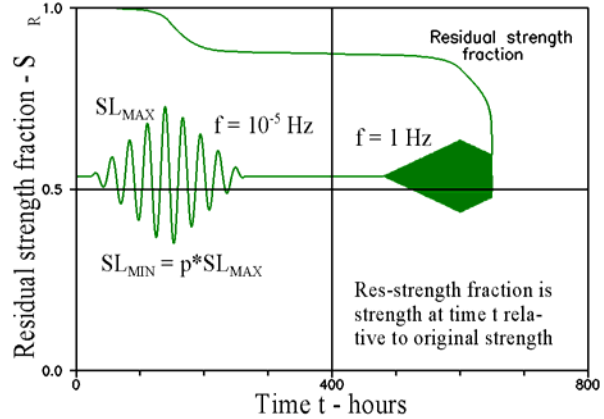


Figure 16. Residual strength and lifetime of wood subjected to load as indicated with $(FL, b, \tau) = (0.4, 0.25, 1 \text{ day})$.

Notations

Load and strength

Load level
Strength level (wood quality)
Residual strength
Load
Max load
Min load
Load ratio
Cyclic time
Frequency
Real strength at $t = 0$
Real strength at t
Theoretical strength (no damage)

Damage

Damage ratio (or just damage)
Immediate crack length
Initial crack length
Fatigue parameters in DVM model

$SL = \sigma / \sigma_{CR}$
 $FL = \sigma_{CR} / \sigma_L$
 $S_R = \sigma_{CR}(t) / \sigma_{CR}$
 σ
 σ_{MAX}
 σ_{MIN}
 $p = \sigma_{MIN} / \sigma_{MAX}$
 T
 $f = 1/T$
 σ_{CR}
 $\sigma_{CR}(t)$
 σ_L

$\kappa = 1/l_0$
 l
 l_0
 $(C, M) = (3, 9)$

Time and creep

Time in general	t
Relaxation time in creep	τ
Creep power	b
Time shift parameter	$q = (0.5(1 + b)(2 + b))^{1/b}$
Normalized creep function	$C = 1 + (t/\tau)^b$

Acknowledgement

The author appreciates very much the support he was given from the “Danish Research Agency, project no. 2020-00-0017” to write this paper and to present it at the ‘International Conference on Integrated Approach to Wood Structure, Behavior and Applications’, held in Firenze, May 14-17, 2006

Literature

1. Svensson, S., Thelandersson, S., and Larsen, H.J. (1999): ‘Reliability of timber structures under long term loads’, *Materials and Structures*, 32: 755-760.
2. Köhler, J. 2002: ‘Probabilistic modeling of duration of load effects in timber structures’, 4th International PhD Symposium in Civil Engineering, Technical university of Munich, 19.09.2002, Proceedings Vol.1: 317-325, Springer Düsseldorf.
3. Nielsen, L. Fuglsang (2004): ‘On the influence of crack closure on the strength estimates of wood’, *Holz als Roh- und Werkstoff*, 62: 81-87
4. Palmgren, A. (1924): ‘Die Lebensdauer von Kugellagern’, *VDI, Zeitschrift Verein Deutscher Ingenieur*, 68: 339-341.
5. Miner, M.A. (1945): ‘Cumulative damage in fatigue’, *Trans. ASTM* 67: A159-A164.
6. Nielsen, L. Fuglsang (2000): “Lifetime and residual strength of wood subjected to static and variable load”, Part I: Introduction and analysis and Part II: Applications and design”, *Holz als Roh- und Werkstoff*, 58: 81-90 and 141-152.
7. *Idem* (2002): ‘Models for damage accumulation in wood’, 3rd World Conference on Structural Control, 7-12 April 2002 in Como, Italy. Proceedings (Fabio Casciati, editor), Dept. Struct. Mech., University of Pavia, 2002.
8. Bach, L. (1975): “Frequency-dependent fracture under pulsating loading”. *Build. Mat. Lab., Tech. Univ. Denmark*, Tech. report 68(1979), (also presented at Forest Prod. Res. Society Annual Meeting 1975, Portland, Oregon, USA).
9. Gerhard, C.C.: "Time-related effects on wood strength: a linear cumulative damage theory", *Wood Science*, 3(1979), 139-144.
10. Barrett, J.D. and Foschi, R.O. (1978): "Duration of load and probability of failure in wood. Part I: modeling creep rupture", *Canadian Journal of Civil Engineering*, 4: 505-514.
11. Barrett, J.D. and Foschi, R.O. (1978): "Duration of load and probability of failure in wood. Part II: constant, ramp, and cyclic loadings", *Canadian Journal of civil Engineering*, 4: 515-532.
12. Nielsen, L. Fuglsang (1992): "DVM-analysis of wood" (Damaged Viscoelastic Material), Chapter 6 in Borg Madsen: "Structural Behavior of Timber", Timber Engineering Ltd., North Vancouver, B.C., Canada 1992.
13. *Idem* (1991): "Lifetime, Residual Strength, and Quality of Wood - and other viscoelastic materials". *Holz als Roh- u. Werkstoff*, 49: 451-455.
14. *Idem* (2005): ‘On the influence of moisture and load variations on the strength behavior of wood’, presented at the international conference on ‘Probabilistic models in timber engineering – tests, models, applications’ held in Arcachon, France 8 - 9 September 2005. Proceedings, ARBORA (Association for research on forestry and forest products in Aquitania, France).
15. COST-E24 project (2000-2005) (European COoperation in the field of Scientific and Technical research): ‘Reliability of Analysis of Timber Structures’.
16. Nielsen, L. Fuglsang: Download lifetime/life.xls from <http://www.mat-mek.dk> - and look at sheet lifevari.
17. *Idem* (1996): “Lifetime and residual strength of wood – subjected to static and variable load”, Report R-6(1996), Dept. Struct. Eng. and Materials, Tech. University of Denmark.
18. *Idem* (2001): “Lifetime and residual strength of wood subjected to static and variable load”, Lecture held at the COST E24 workshop in Coimbra, Mai, 2001, Overhead copies are available.
Idem (2001): “Lifetime and residual strength of wood subjected to various load variations”, Lecture held at the COST E24 workshop in Copenhagen, October 19-20, 2001, Overhead copies are available.