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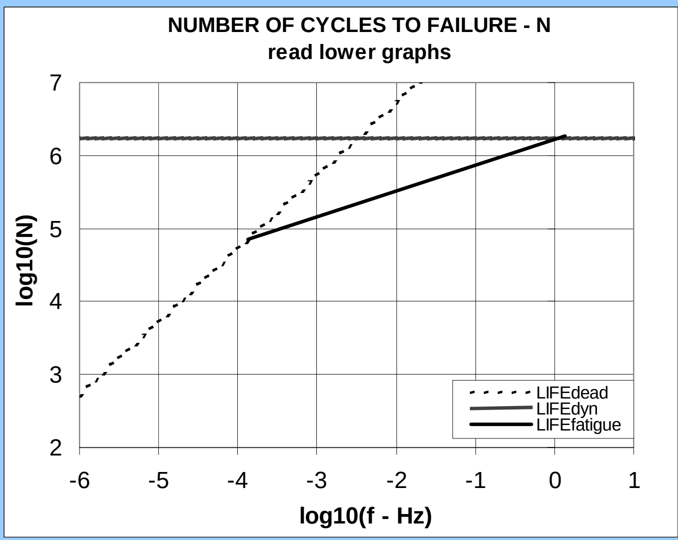
The influence of moisture- and load variations on the fatigue behavior of wood

Lauge Fuglsang Nielsen



Predicted number of load cycles to fatigue failure. Wood quality, FL = 0.25. Variable load level, SL = 0 - 50%. Variable surface moisture content, u_S *= 11% - 20%.*

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Abstract: It is demonstrated in this paper that the influence of moisture- and load variations on lifetime and residual strength (re-cycle strength) of wood can be considered by theories previously developed by the author. The common, controlling factor is creep, which can be modified very easily by introducing a special moisture dependent relaxation time in the well-known Power-Law creep expression.

Because basic failure mechanisms in wood are invariant with respect to loading modes, it is suggested that a number of methods used in design of wood structures can be generalized/simplified to apply irrespective of loading modes and moisture conditions. Reliability studies may become more 'reliable' as the result of recognizing property distributions to be related.

Keywords: Moisture variation, load variation, Power-Law creep, lifetime, fatigue, residual strength (re-cycle strength).

1. INTRODUCTION

The intension of this paper is to simplify the models used in practical design of wood structures. The models should be based on the fewest possible real basic mechanical parameters for classification of (damage) structure and viscoelasticity.

The specific examples considered in this paper is lifetime of wood as influenced by moisture- and load variations. It is demonstrated in this paper that lifetime under these actions can be considered by the same damage mechanisms, which have been established previously for constant moisture conditions, see [1]. We do not need two different failure mechanisms. One is enough: Damages expand in a solid, the viscoelastic properties of which changes because of moisture variations.

The format of the paper presented is that of an operational summary of property predictions made by the author's DVM-theory (Damaged Viscoelastic Material) presented/developed in [1,2,3]. (Recently the most important prediction formulas have been summarized in [4]). The text of the paper is rather brief. Only very few theoretical explanations are presented. Such must be studied in the original papers just mentioned and in some further references listed at the end of the paper. The list of symbols – also at the end of the paper – should be frequently consulted.

1.1 Material properties

Creep

The viscoelastic behavior of wood can be very well described by the so-called Power-Law (normalized) creep expression presented in Equation 1. The expression is quantified by the constant creep power b (of magnitude 1/3 – 1/5) - and the relaxation time τ, which depends on a homogeneously distributed moisture content of u(%) as indicated. Time is denoted by t.

$$C = 1 + \left(\frac{t}{\tau}\right)^b \quad \textit{with relaxation time} \quad \tau = \tau_{15} * 10^{(15-u)/10} \quad \textit{where} \qquad (1)$$

$$\tau_{15} \approx \begin{cases} 10^4 - 10^5 \textit{ days for bulk creep} \\ 10 \textit{ days for creep in damaged areas, cracks} \end{cases} \quad \textit{is relaxation time at } u = 15\%$$

Quality

Wood quality is defined as immediate strength, σ_{CR}, relative to theoretical strength, σ_L. We introduce the symbol, FL = σ_{CR}/σ_L, for strength level (or wood quality) which can be estimated from Figure 1.

Remark: It is noticed that strength levels analytically considered in this paper are FL < 1/3, which covers most wood in practice. For analysis of wood with higher strength levels a few modifications have to be introduced, see [4].

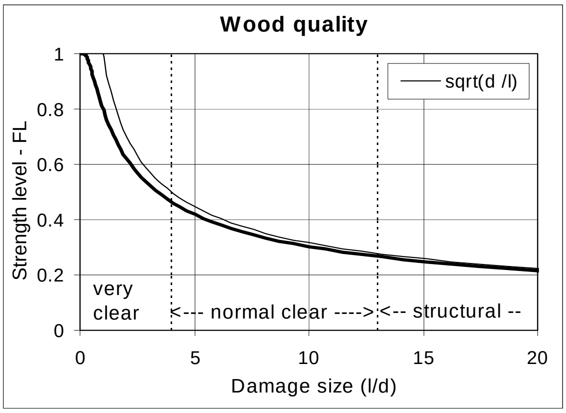

Figure 1. *Wood quality estimated from damage size, l, relative to the damage nucleus (inherent defect) d = 0.3 mm.*

2. LIFETIME AT CONSTANT MOISTURE

Lifetime expressions for wood at constant moisture conditions are presented in the following sections. Symbols used are explained in the list of symbols at the end of this paper. Of special interest are the load level, SL = σ/σ_{CR}, which is load applied relative to strength. The symbol, κ, used is damage ratio, which is immediate (time dependent) damage size (ℓ) relative to its initial size (ℓ_o).

2.1 Constant load

At constant load, lifetime of wood can be predicted by the following Equation 2*, which expands as shown in Equation 3 for wood with special creep powers.

* The damage rate expression applies also for variable loads as long as positive rates are predicted.

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

$$\frac{t}{\tau} = (1/SL^2 - 1)^{1/b} + \frac{8q}{\pi^2 FL^2 SL^2}\int_{1/(\kappa SL^2)-1}^{1/SL^2-1}\frac{x^{1/b}}{1+x}dx \quad (damage - time\ relation) \qquad (2)$$

$$\frac{t_{CAT}}{\tau} = (1/SL^2 - 1)^{1/b} + \frac{8q}{\pi^2 FL^2 SL^2}\int_{0}^{1/SL^2-1}\frac{x^{1/b}}{1+x}dx \quad (lifetime,\ \text{where } \kappa = \kappa_{CR} = 1/SL^2)$$

$$\frac{t_{CAT}}{\tau} = \mu^{1/b} + \frac{1}{(FL*SL)^2}\begin{cases} 3.06*\left[\frac{\mu^3}{3} - \frac{\mu^2}{2} + \mu - log(\mu+1)\right] & b = \frac{1}{3} \\ 3.17*\left[\frac{\mu^4}{4} - \frac{\mu^3}{3} + \frac{\mu^2}{2} - \mu + log(\mu+1)\right] & b = \frac{1}{4} \\ 3.25*\left[\frac{\mu^5}{5} - \frac{\mu^4}{4} + \frac{\mu^3}{3} - \frac{\mu^2}{2} + \mu - log(\mu+1)\right] & b = \frac{1}{5} \end{cases} \quad with \quad \mu = \frac{1}{SL^2} - 1 \qquad (3)$$

For κ expanding from 1 to the critical damage ratio $\kappa_{CR} = 1/SL^2$ the second term in Equation 2 can be used to determine residual strength (re-cycle strength), $S_R = \sigma_{CR}(t)/\sigma_{CR} = 1/\sqrt{\kappa}$

Important: We notice that all expressions are fully dimensionless with respect to strength, load, and time. Some results illustrating this feature are shown in Figures 2 and 3.

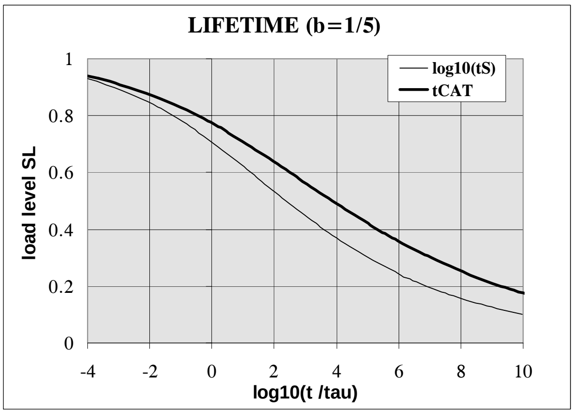

Figure 2. *Non-dimensional prediction of lifetime for wood of quality, FL = 0.25.*

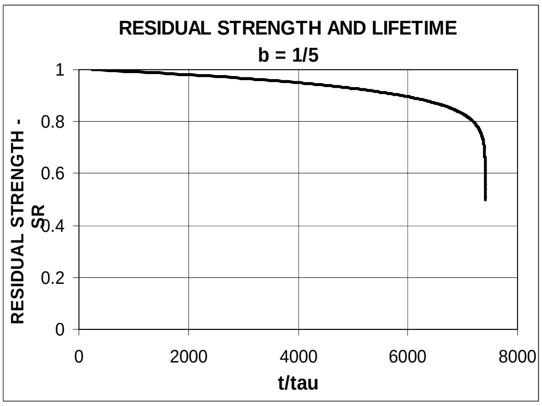

Figure 3. *Non-dimensional prediction of residual strength for wood of quality FL = 0.25.*

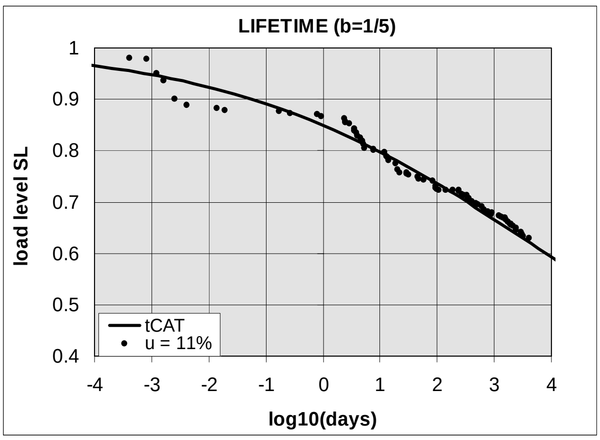

Figure 4. *FL = 0.25, τ = 25.4 days. u ≡ 11%. Experimental data: P. Hoffmeyer [5,6].*

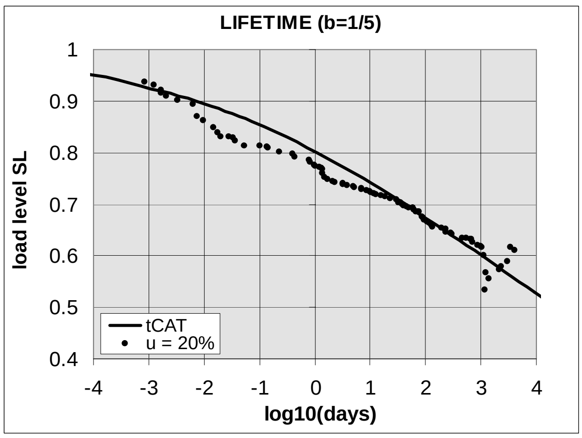

Figure 5. *FL = 0.25, τ = 3.20 days. u ≡ 20%. Experimental data: P. Hoffmeyer [5,6].*

Real results with real quantites of strength, load, and lifetime are compared in Figures 4 and 5 with experimental data obtained by Hoffmeyer in his work [5,6] on failure of wood as influenced by moisture and duration of load. The results of a residual strength analysis based on the Hoffmeyer moisture data (u ≡ 20%), are presented in Figure 6.

2.2 Variable load (fatigue)

Lifetime solutions for wood subjected to harmonic loads are developed in [1] following the energy dissipation in damaged areas (cracks) as it develops with time. Two mechanisms are involved: A creep mechanism and a crack closure mechanism. Catastrophic failure occurs when the total dissipation becomes critical. Some results from the analysis in [1] are shown in Figures 8 - 11. The theory developed is strongly justified by various experiments – such as presented in Bach [7] and MacNatt [8,9] – see Figures 10 and 11.

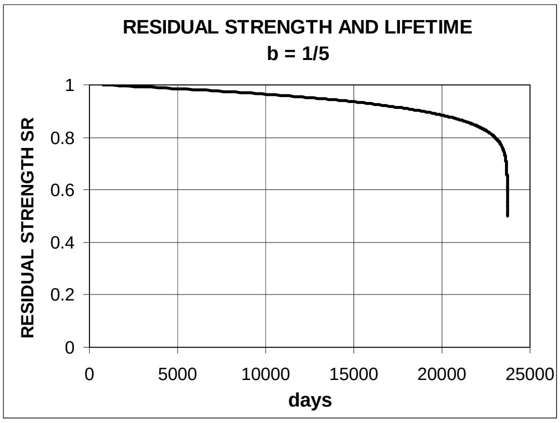

Figure 6. *Residual strength for wood of quality FL = 0.25. Moisture content u = 20% (τ = 3.2 days). Load is SL = 0.5*

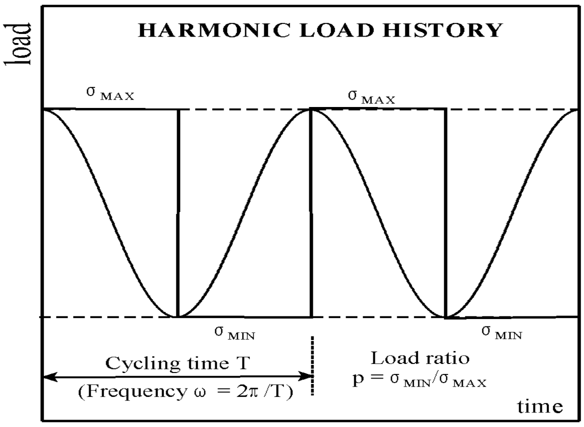

Figure 7. *Variable load considered. (In analysis square wave load is assumed).*

We notice that the, graphical, presentations shown in Figures 8 and 9 (FL = 0.2, b = 0.2), can be used for any wood quality and relaxation time (constant moisture content).

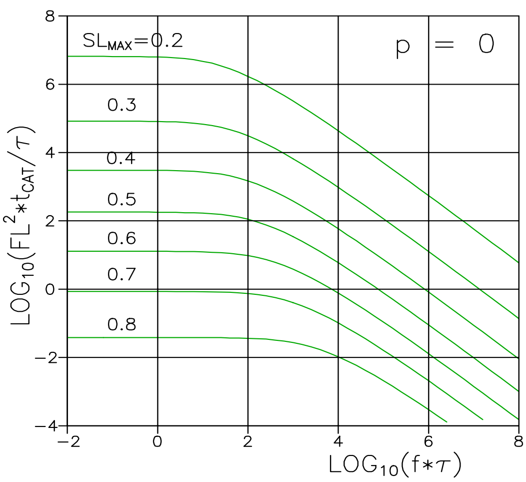

Figure 8. *Normalized time to failure, accurate analysis with fatigue parameters (C,M) = (3,9)*

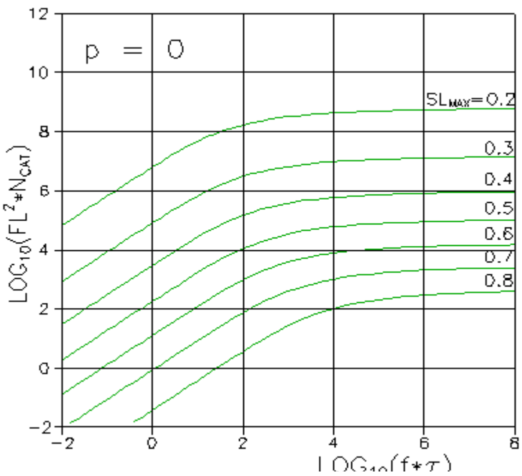

Figure 9. *Number of load cycles to failure, accurate analysis with fatigue parameters (C,M) = (3,9).*

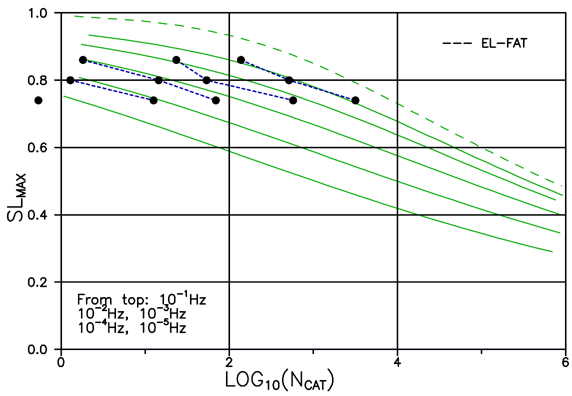

Figure 10. *Fatigue of spruce compressed parallel to grain with p = 0. Experimental data from [7]. Elastic fatigue indicated is predicted lifetime at very high frequencies.*

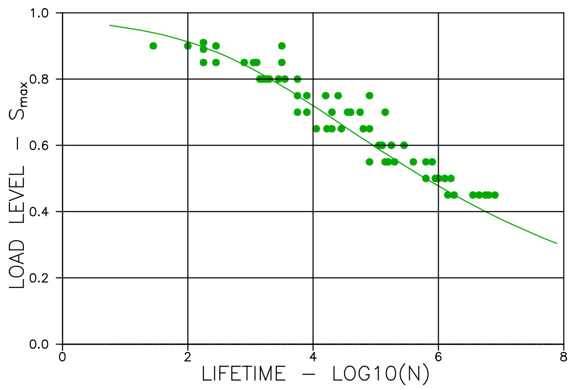

Figure 11. *Lifetime of particleboards and hardboards loaded in tension and interlaminar shear with (p,f) = (0.1,15 Hz). Experimental data from [8,9].*

Design graphs

It is observed from the master graphs shown in Figures 8 and 9 that lifetime can practically be described as elastic fatigue at non-dimensional load frequencies $f^*\tau > 10^5$ – and as deadload lifetime at frequencies $f^*\tau < 10$. In a transition area $10 < f^*\tau < 10^5$ both creep and elastic fatigue mechanisms are active. Easy safe estimates for load ratios, $p < 0.5$, can be made as shown in Equation 5 and demonstrated in Figures 12 and 13, (for higher load ratios the transition area has to be shifted to the right [1]). So-called fatigue parameters (C,M) = (3,9) are used throughout the paper.

$$\text{Elastic lifetime analysis:} \begin{cases} N_{CAT} = \dfrac{1}{G SL_{MAX}^2}\left[\dfrac{1-SL_{MAX}^{M-2}}{(M-2)SL_{MAX}^{M-2}} - \dfrac{1-SL_{MAX}^{M-4}}{(M-4)SL_{MAX}^{M-4}}\right] \quad \text{with } G = \dfrac{CFL^2}{13}\left[\dfrac{1-p^2}{2}\right]^M \\ t_{CAT} = N_{CAT} * T = N_{CAT}/f \end{cases} \tag{4}$$

$$\textit{Viscoelastic lifetime analysis for } p < 0.5 \begin{cases} \textit{dead load (Eq. 2) when } f\tau < 10 \\ \textit{elastic fatigue (Eq. 4) when } f\tau > 10^5 \\ \textit{straigth line log-log interpolation when } 10 < f\tau < 10^5 \end{cases} \tag{5}$$

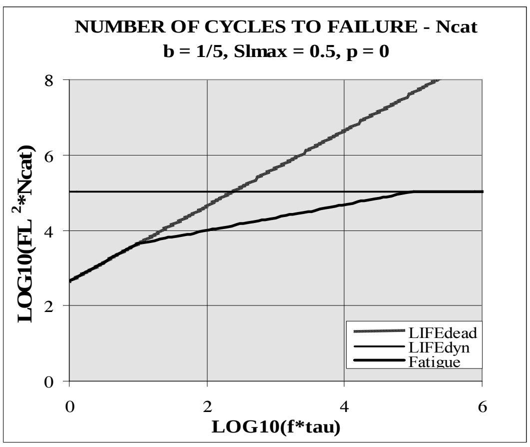

Figure 12. *Non-dimensional presentation of number of cycles to failure (lower graphs). Frequency of loading is f.*

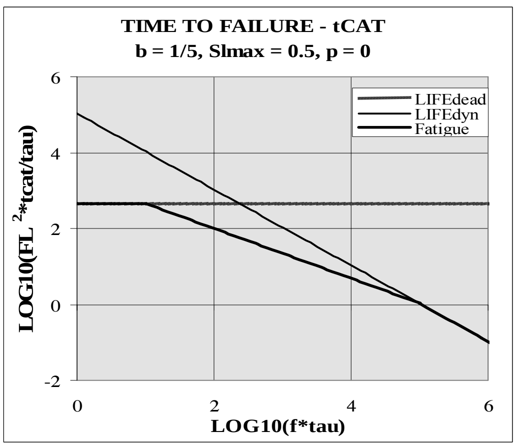

Figure 13. *Non-dimensional presentation of time to failure (lower graphs). Frequency of loading is f.*

3. LIFETIME AT VARIABLE MOISTURE

3.1 Generalized creep

Moisture variation and distribution

The moisture distribution in a cross-section of a wood beam is described with the following expressions suggested in [10] with α *being a so-called moisture flow relaxation time*. u_S and u_C are moisture content on the surface and in the middle part of a cross-section respectively.

$$\left.\begin{array}{ll}\textit{Moisture on surface of cross-section:} & u_S = u_S(t) \\ \textit{Moisture in middle parts of cross-section:} & u_C = u_C(t)\end{array}\right\} \quad \frac{du_C}{dt} = \frac{u_S - u_C}{\alpha} \tag{6}$$

$$\begin{array}{l} \textit{general:} \quad \Delta u_{C(n)} = \frac{1}{\alpha}\left(u_{S(n)} - u_{C(n)}\right)\Delta t_{(n)} \quad ; \quad u_{C(n)} = u_{C(n-1)} + \Delta u_{C(n)} \\ \textit{harmonic:} \begin{cases} u_S = u_{AV} + \Delta u_S sin(\omega t) \quad \Rightarrow \quad u_C = u_{AV} + \Delta u_C sin(\omega t - \delta) \\ \textit{with } \omega = \frac{2\pi}{T} \quad , \quad \Delta u_C = \frac{\Delta u_S}{\sqrt{1+(\alpha\omega)^2}} \quad \textit{and} \quad \delta = artan(\alpha\omega) \end{cases} \\ \textit{constant:} \quad u_C = u_S = u \end{array} \tag{7}$$

The moisture history used by Hoffmeyer in his lifetime experiments [5,6] has been simulated as shown in Figure 14 using the following parameters: Moisture loading: u_{AV} = 15.5%, Δu_S = 4.5%, T = 56 days. Moisture relaxation time: α = 5 days.

Creep

The hypothesis is suggested in [10] that creep of wood subjected to a variable moisture history can be expressed by the following modified Power-law expression where *K is a so-called moisture modification factor*.

$$\begin{array}{l} \underline{\textit{In general:}} \\ \frac{dC}{dt} = \frac{b}{t}\left(\frac{t}{\tau}\right)^b \quad \textit{with relaxation time} \quad \tau = \tau_{15} * 10^{[15-(u_C+u_S)/2]/10 - ABS(u_C - u_S)/K} \\ \Rightarrow C \cong 1 + \left(\frac{t}{\tau_{REG}}\right)^b \quad \textit{with relaxation time } \tau_{REG} \textit{ determined by regression} \end{array} \tag{8}$$

The creep rate suggested is the same, which applies for the Power-law expression in Equation 1 – with time dependent relaxation time, however. For harmonic moisture variation the Power-Law creep expression determined by the latter expression in Equation 8 has a high fit quality to the creep function determined by the former expression. Thus, for such variations the conclusion can be made that the concept of Power-Law creep can be kept with a modified relaxation time τ_{REG}.

The creep functions shown in Figure 15 have been predicted according to Equation 8. The basic moisture histories assumed are those used by Hoffmeyer [5,6]. A moisture modifiation factor of K = 2 has been estimated. At u = 11%, 20%, and variable 11-20% relaxation times of τ = 25.4 days, τ = 3.2 days, and τ_{REG} = 0.85 day respectively were predicted by Equations 7 and 8.

Remarks: It is noticed that Equation 8 predicts creep to increase with abs(u_C -u_s) as a 'driving force' – and that Equations 1 and 8 become identical when moisture conditions are constant. The creep functions predicted (see Figure 15) consider real creep relevant for viscoelastic analysis. They represent smoothened, averaged mechano-sorptive creep functions as this phenomenon is observed in e.g. [5,11,12,13,14].

It is recognized that the moisture distribution model described above is rather crude, and has to be refined in further research. In the present paper, however, it fulfills its purpose: To demonstrate how moisture variations provoke increasing creep of wood – and decreasing lifetime. The model contains two parameters which have to be justified experimentally: The moisture flow relaxation time, α, and the moisture modification factor, K.

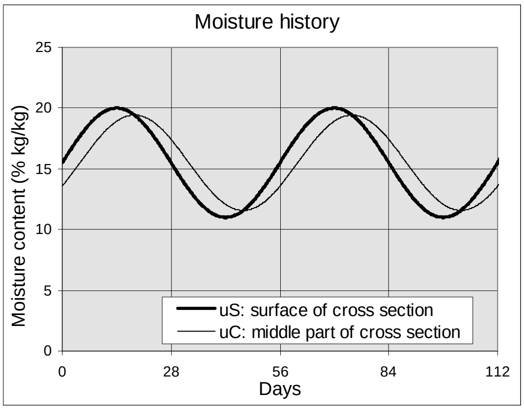

Figure 14. Sinus description of surface moisture variation u_{MIN} - u_{MAX} = 11 ↔ 20% used by P. Hoffmeyer [5,6].

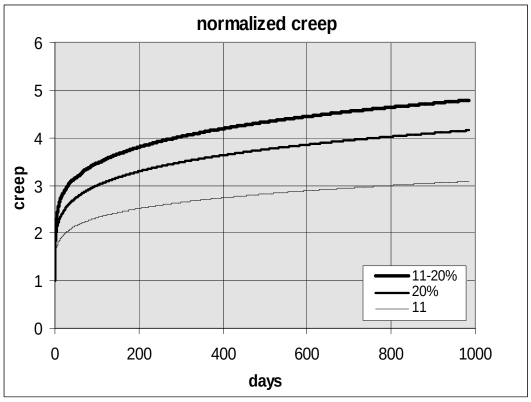

Figure 15. Predicted normalized creep (in damaged areas) for constant and variable moisture histories used in [5,6].

Generalization of analysis with respect to moisture

The observation made in Section 3.1 with respect to Power-Law descriptions is very important in the analysis of wood behavior as influenced by moisture variations: It means that the analysis of wood properties based on constant moisture content can be generalized to apply also for harmonically varying ambient moisture conditions. Examples are demonstrated in the following sections.

3.2 Constant load

Lifetime Equation 3 (b = 1/5) has been used to 'predict' the varying moisture experimental data obtained by Hoffmeyer in [5,6]. The results are shown in Figure 16 with a relaxation time of τ = 0.85 day determined as described in Equation 8. Consistent residual strength data predicted by the second term in Equation 2 are presented in Figure 17.

3.3 Load history versus moisture history

The simultaneously agreement between theoretical predictions and the experimental results obtained by Hoffmeyer, see Figures 4, 5, and 16, for different moisture histories supports the idea that the basic damage mechanism (propagating cracks) 'invented' to explain the lifetime behavior of wood subjected to constant moisture conditions – applies also at variable moisture conditions with relaxation time modified as suggested in Equations 7 and 8.

This generalization can be extended to apply also for variable loads. In principles the creep mechanisms act in similar ways in theories developed for constant and variable loads [1].

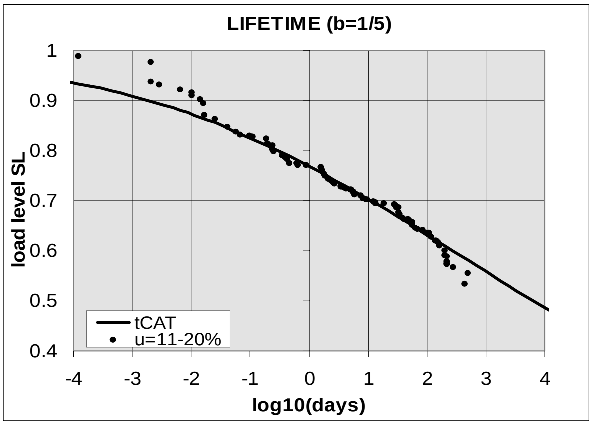

Figure 16. FL = 0.25; τ = 0.85 days. u = 11 ↔ 20%. Experimental data: P. Hoffmeyer [5,6].

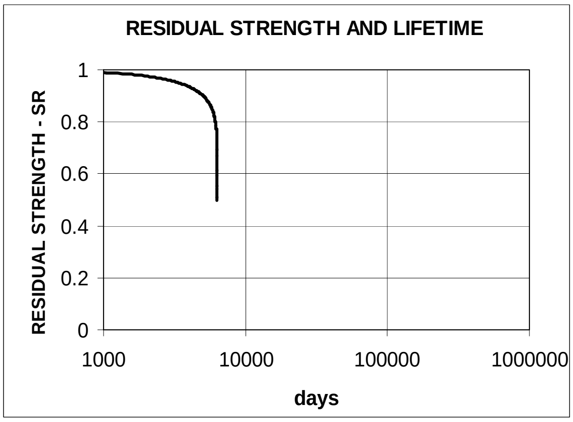

***Figure 17.** Residual strength and lifetime of wood (FL = 0.25). Load level is SL = 0.5. Power-Law creep with relaxation time, τ = 0.85 days (11 ↔ 20%), and a creep power of b=1/5.*

3.4 Variable load (fatigue)

The observations made in Section 3.3 are now utilized to predict fatigue strength of wood subjected to both variable load and variable moisture. Some results of such analysis are presented in Figures 18 – 21.

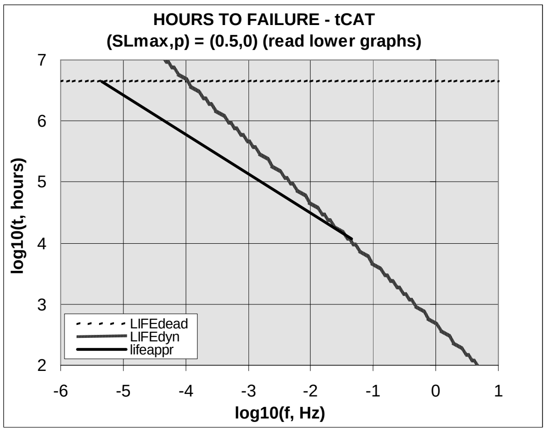

***Figure 18.** Predicted time to fatigue failure. FL=0.25, u ≡11%.*

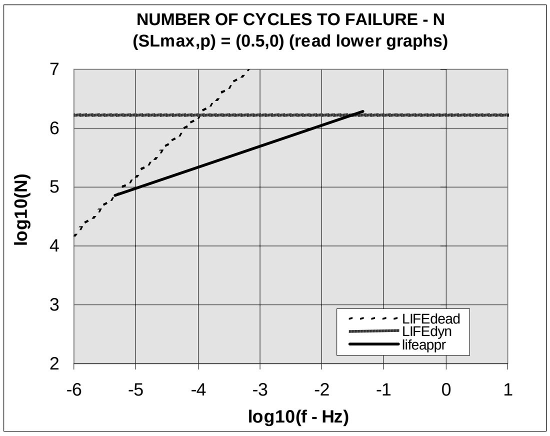

***Figure 19.** Predicted number of load-cycles to fatigue failure. FL=0.25, u ≡11%.*

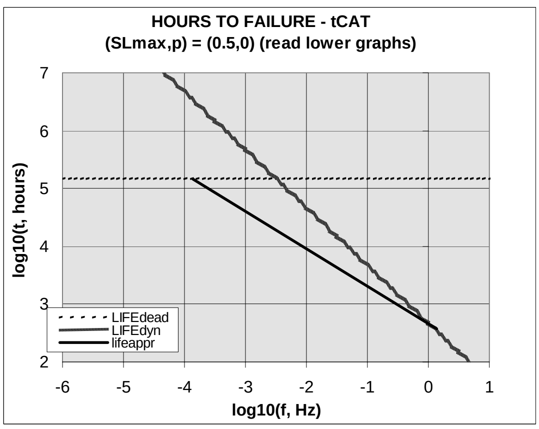

***Figure 20.** Predicted time to fatigue failure. FL=0.25, variable u = 11-20%*

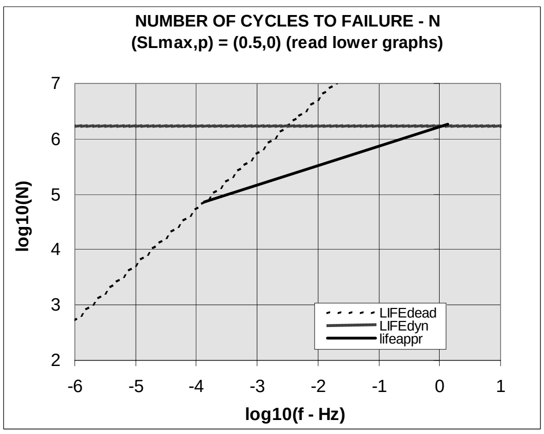

***Figure 21.** Predicted number of load cycles to fatigue failure. FL=0.25, variable u = 11-20%*

4. FINAL REMARKS

It seems logical to the author that the failure mechanism (damages) in wood stays practically independent of moisture content – leaving differences in strength behavior to be the results of moisture induced changes in viscoelastic behavior. The results presented in this paper justify this concept – and support the idea, outlined in the introductory section, of establishing a simple design procedure based on a simple basic model with the fewest possible parameters. These remarks are consistent with the observations made in Section 3.3.

Furthermore, it seems logical to generalize damage-based solutions to apply also when different loading modes are considered, such as in: Torsion, various slopes of lamellae in Glu-lam, and various joint systems.

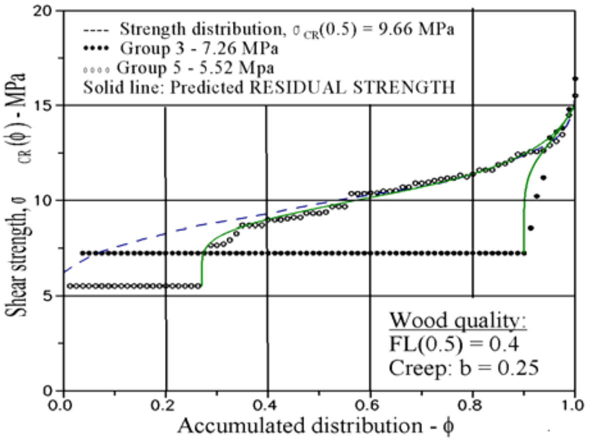

Figure 22. Residual strength distribution in duration of torsional shear load experiments on small clear wood specimens. Experimental data [15]. Horizontal string represents no residual strength.

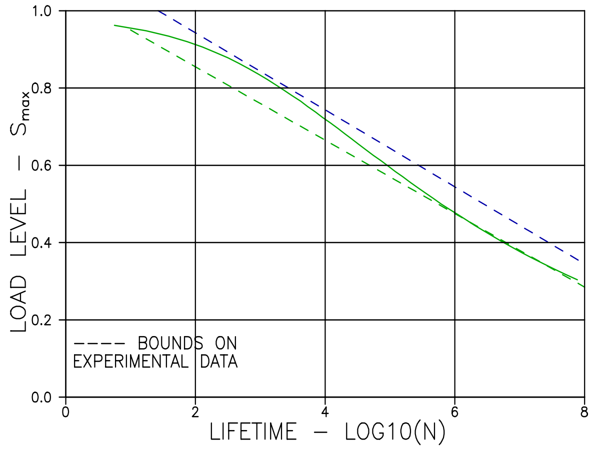

Figure 23. Lifetime of Doug-Fir finger joints loaded in tension ≠ grain with (p,f) = (0.1,15 Hz). Experimental data from [16,17].

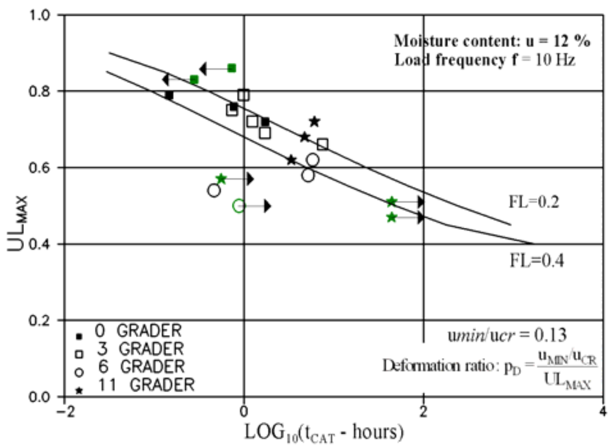

Figure 24. Glu-Lam beam. Deformation control. Single sided bending. (b,tau) = (0.25 5 days). 'Grader' is angle between beam direction and lamella. Experimental data reported in [18].

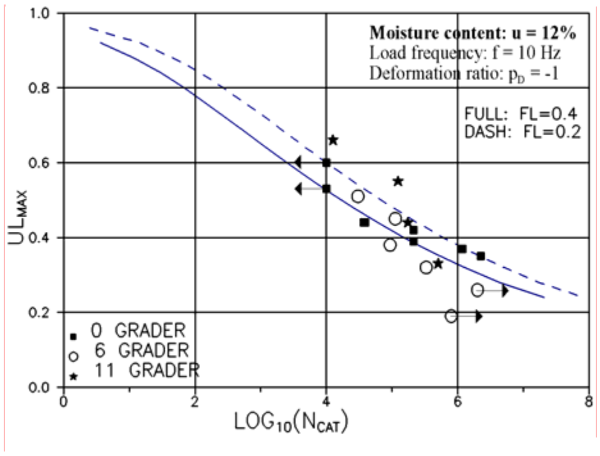

Figure 25. Glu-Lam beam. Deformation control. Double sided bending. (b,tau) = (0.25 5 days). 'Grader' is angle between beam direction and lamella. Experimental data reported in [18].

Support to this idea can be found in the DVM-theory: We reproduce from [2]: The advantage of the DVM-theory to operate in general with non-dimensional load ($SL = \sigma/\sigma_{CR}$) and non-dimensional materials quality ($FL = \sigma_{CR}/\sigma_L$) means that these terms can often be evaluated in a generalized way involving forces and structural dimensions. For example, when load is a normal tensile force N on a cross-section we may consider N as a generalized load. Load level is $SL = N/N_{CR}$ and materials quality is $FL = N_{CR}/N_L$ where N_{CR} and N_L are forces which produce short-time failure and theoretical failure (no cracks), respectively. It is shown in [2] that this deduction applies for the damage model applied (Dugdale crack) for practically any loading mode.

The generalizing suggestions made are supported by comparing theoretical DVM-results with test results reported by Spencer/Madsen [15], Bohannan/Kanvik [16], MacNatt [17], and Nielsen [18] - see Figures 22 – 25.

It has been demonstrated in this paper that the simplifications made of design for lifetime and recycle strength of wood is a logical consequence of *not changing wood structural models* every time new problems are met. Other analytical procedures might also benefit from such a simplification concept: Reliability studies may become more 'reliable' by knowing that property distributions can be related. This feature is illustrated in Figures 26 and 27 reproduced from [19].

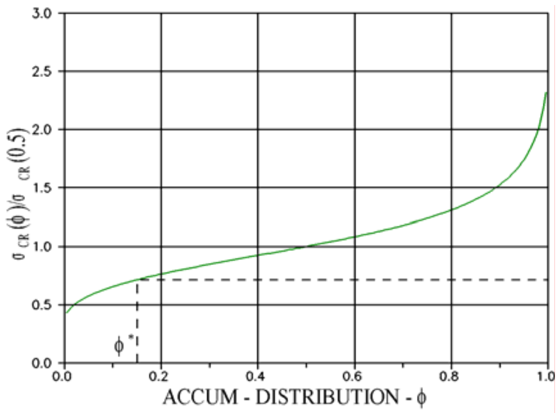

Figure 26. *Strength distribution. Reproduced from [19].*

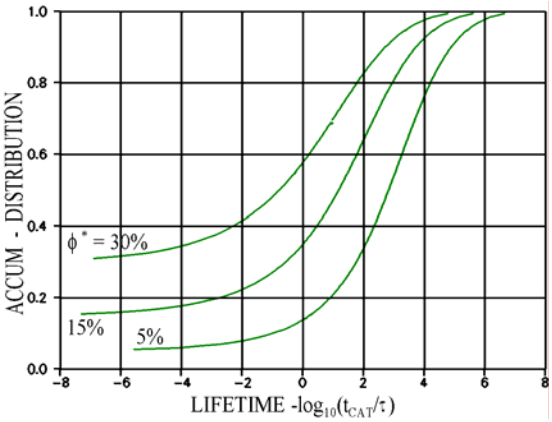

Figure 27. *Lifetime distribution associated with the strength distribution in Figure 26. Load is $\sigma = \sigma_{CR}(\varphi^*)$. $FL = FL(\varphi^* = 0.5) = 0.2$. Reproduced from [19].*

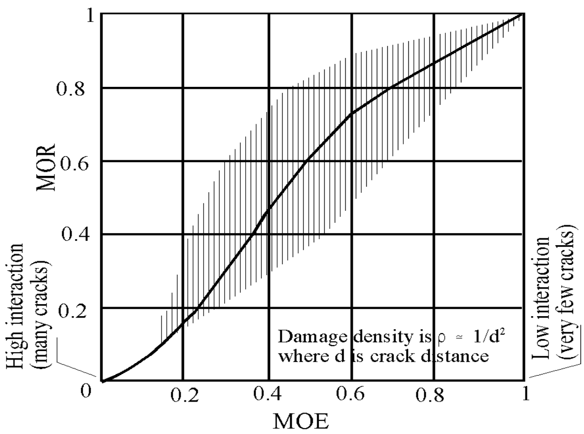

Figure 28. *MOE-MOR relation for wood. Shaded area covers roughly the data for 1200 oak and cottonwood beams presented in [22]. Roughly reproduced from, [21,Figure 9].*

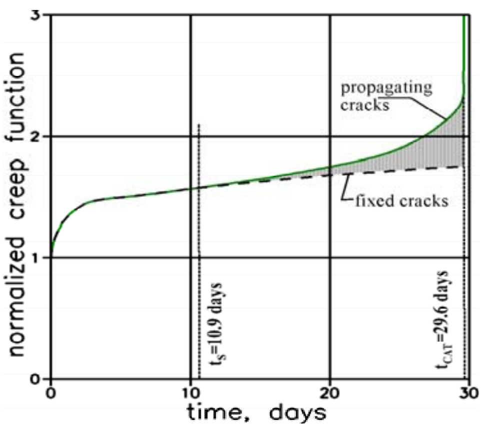

Figure 29. *Creep function for clear wood. Multi-crack model. The shaded area represents the effect of running cracks. Roughly reproduced from, [20,Figure 7].*

Finally, the author is presently investigating the deformational behavior of wood caused by damage mechanisms - also from the viewpoint of applying existing material/structural models. For deformations the simplification concept mentioned above is slightly more complicated. Deformation is a consequence of the joint behavior of many damages – while failure primarily is a consequence of one major defect. The results of the investigation are not yet fully presentable – except for the examples, Figures 28 and 29, already presented in [20,21] with experimental MOE-MOR data from [22] (Modulus Of Elasticity - Modulus Of Rupture).

LIST OF SYMBOLS

The symbols most frequently used in this paper are listed below. The list does not include local symbols used only in intermediate results. The extensive use of normalized quantities such as load level and strength level should be noticed.

Load and strength	
Load in general	σ
Strength (reference)	σ_{CR}
Theoretical strength	σ_l
Strength level	$FL = \sigma_{CR}/\sigma_l$
Load level	$SL = \sigma/\sigma_{CR}$
Minimum load	σ_{MIN}
Minimum load level	$SL_{MIN} = \sigma_{MIN}/\sigma_{CR}$
Maximum load	σ_{MAX}
Maximum load level	$SL_{MAX} = \sigma_{MAX}/\sigma_{CR}$
Load ratio	$p = \sigma_{MIN}/\sigma_{MAX} = SL_{MIN}/SL_{MAX}$
Residual strength (re-cycle strength)	$S_R = \sigma_{CR}(t)/\sigma_{CR}$
Deformational load	
Deformation	u
Deformation at fracture	u_{CR}
Deformation level	$UL = u/u_{CR}$
Minimum deformation	u_{MIN}
Maximum deformation	u_{MAX}
Minimum deformation level	$UL_{MIN} = u_{MIN}/u_{CR}$
Maximum deformation level	$UL_{MAX} = u_{MAX}/u_{CR}$
Deformation ratio	$p_D = u_{MIN}/u_{MAX} = UL_{MIN}/UL_{MAX}$
Deformation	
Crack length	l
Initial crack length (reference)	l_o
Damage ratio (or just damage)	$\kappa = l/l_o$
Damage density	ρ, number of damages per volume or area unit
Fatigue parameters	
Damage rate constant	$C \approx 3$
Damage rate power	$M \approx 9$
Time and creep	
Time in general	t
Relaxation time (or doubling time)	τ
Creep power	b
Young's modulus	E
Creep function	$c = (1 + (t/\tau)^b)/E$
Normalized creep function	$C = 1 + (t/\tau)^b$
Time shift parameter	$q = (0.5(1 + b)(2 + b))^{1/b}$
Lifetime and load cycles	
Cycling time	T
Frequency (cyclic)	$f = 1/T$
Frequency (angular)	$\omega = 2\pi/T$

Lifetime	t_{CAT}
Number of load cycles to failure	$N_{CAT} = t_{CAT}/T = f^*t_{CAT}$
Moisture	
Surface moisture content	u_S
Moisture content in middle parts	u_C
Moisture flow relaxation time	α
Moisture modification factor	K

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