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Damage Free Drying of Wood Poles

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PREFACE AND ABSTRACT

Crack growth in wood is promoted by drying. This phenomenon is unfortunate because cracks may reduce strength considerably. It is well known that fast drying is more severe in this respect than slow drying. This observation is the basis of any empirical rule which have been suggested in drying technology to optimize economy (time) and quality of wood.

The scope of this paper is to illustrate theoretically that there is a "safe" rate of drying below which the original structure of wood can be maintained. This means that the inherent defect nuclei in wood will not grow into real cracks. We consider round poles being dried from a moisture content which initially is uniformly distributed at a level lower than or equal to the one defined by the fiber saturation point (25 - 30%). The potential cracks (to avoid) are those having a leading edge parallel to the pole axis and a radial direction of propagation.

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1. INTRODUCTION

Crack growth in wood is promoted by drying. This phenomenon is unfortunate because cracks may reduce strength considerably. It is well known that fast drying is more severe in this respect than slow drying. This observation is the basis of any empirical rule which have been suggested in drying technology to optimize economy (time) and quality of wood.

The scope of this paper is to illustrate theoretically that there is a "safe" rate of drying below which the original structure of wood can be maintained. This means that the inherent defect nuclei in wood will not grow into real cracks. We consider round poles being dried from a moisture content which initially is uniformly distributed at a level lower than or equal to the one defined by the fiber saturation point (25 - 30%). The potential cracks (to avoid) are those having a leading edge parallel to the pole axis and a radial direction of propagation.

The pole material is modelled in the traditional way, meaning that assumptions are made implying cylindrical homogeneity and orthotropy as related to the pole axis. The three principal axes referred to in this respect are defined by the R(adial), T(angential) and L(ongitudinal) directions of wood.

It is furthermore assumed that the mechanical behavior of wood can be described linear-viscoelastically according to the Power Law description (e.g. 1).

2. MOISTURE CONTENT

The moisture content of the pole is assumed to be axial-symmetrically distributed as defined by the parabolic profile shown in Figure 2.1.

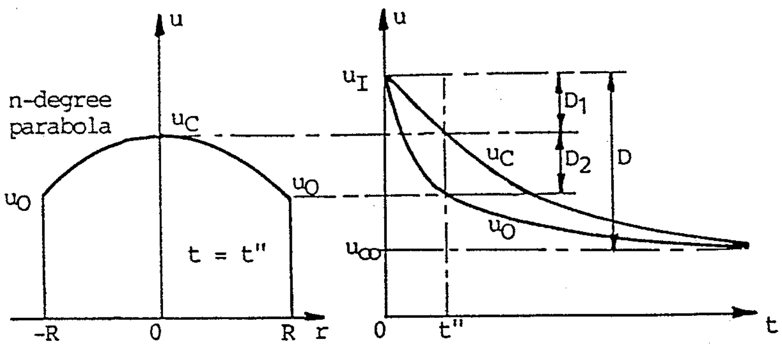

Figure 2.1. Distribution and time dependency of pole moisture content, u. Location coordinate is denoted by r. The pole radius is R.

The time-dependency of the moisture content is defined by the moisture history at the center, $u_C = u_C(t)$ and at the outside of the pole, $u_O = u_O(t)$.

For simplicity we consider the pole to have a location independent moisture content both, at $t = 0$ and at $t \to \infty$. The initial quantity, u_I, is less than or equal to the moisture content, $u_F = 25 - 30$ %, at fiber saturation. The final value, u_∞ (also $\le u_F$), is the target moisture content. Both moisture histories are assumed to decrease exponentially such that

$$u_C = u_I - D*(1 - e^{-t/\alpha_C}) \qquad (2.1)$$
$$u_O = u_I - D*(1 - e^{-t/\alpha_O})$$

where the parameters, α_C and α_O, define the drying rate at the center and at the outside respectively of the pole. The total moisture loss, D, as $t \to \infty$ is given by,

$$D = u_I - u_\infty \tag{2.2}$$

The moisture differences, D_1 and D_2, illustrated in Figure 2.1 are of special interest for the stress analysis made in the following section. We get from Equation 2.1

$$\begin{aligned} D_1 &= u_I - u_C = D*(1 - e^{-t/\alpha_C}) \\ D_2 &= u_C - u_O = D*(e^{-t/\alpha_C} - e^{-t/\alpha_O}) \end{aligned} \tag{2.3}$$

3. SHRINKAGE AND ELASTIC STRESS STATE

It is assumed that shrinkage strain, ϵ_{SH}, of wood and moisture content, u, is related by

$$d\epsilon_{T,SH}/du = s_T; \quad d\epsilon_{R,SH}/du = s_R; \quad d\epsilon_{L,SH}/du = s_L \tag{3.1}$$

where the subscripts, T, R and L, refer to directions previously defined.

The shrinkage coefficients have the following orders of magnitude when moisture content is given in %,

$$s_T \approx 4*10^{-3}/\% \quad ; \quad s_R \approx 2*10^{-3}/\% \quad ; \quad s_L \approx 10^{-4}/\% \tag{3.2}$$

Two works (2,3) have been reported recently on the stress analysis of wood exposed to drying. The following solutions, $\sigma_{T,EL}$ and $\sigma_{R,EL}$, for the tangential and radial stresses respectively in a pole subjected to a parabolically distributed moisture content are developed by the present author in (2), (subscript el indicates elastic solution),

$$\begin{aligned} \frac{\sigma_{T,EL}}{s_T E_T} &= \frac{1-S}{1-N}\,[1-\sqrt{N}(\frac{r}{R})^{\sqrt{N}-1}]*D_1 \; + \\ &+ \frac{1+n-S}{(1+n)^2-N}\,[(1+n)(\frac{r}{R})^{n} - \sqrt{N}(\frac{r}{R})^{\sqrt{N}-1}]*D_2 \end{aligned} \tag{3.3}$$

$$\begin{aligned} \frac{\sigma_{R,EL}}{s_T E_T} &= \frac{1-S}{1-N}\,[1-(\frac{r}{R})^{\sqrt{N}-1}]*D_1 \; + \\ &+ \frac{1+n-S}{(1+n)^2-N}\,[(\frac{r}{R})^{n} - (\frac{r}{R})^{\sqrt{N}-1}]*D_2 \end{aligned} \tag{3.4}$$

n is the degree of the parabola describing the moisture distribution illustrated in Figure 2.1. The stiffness ratio, N, and the shrinkage ratio, S, are given by

$$N = E_T/E_R \approx 0.5 \quad \text{and} \quad S = s_R/s_T \approx 0.5 \tag{3.5}$$

where E denotes Young's modulus in the direction given by the subscript.

The location coordinates are given by the radius vector, r, relative to the pole radius, R.

The stresses given above are plain stress solutions, meaning that the longitudinal stress, $\sigma_{L,EL} \equiv 0$. Plain strain conditions produce a finite $\sigma_{L,EL}$. The stresses, $\sigma_{T,EL}$ and $\sigma_{R,EL}$, however, are only changed insignificantly (2).

It is primarily the tangential stress which influences the propagation of the cracks considered in this paper. The influence is most significant at the outside of the pole. We will therefore limit our interest considering only $\sigma_{T,EL}$ at location coordinate, $r/R = 1$. Here we have from Equation 3.3,

$$\frac{\sigma_{T,EL}}{s_T E_T} = \frac{1-S}{1+\sqrt{N}} \ast D_1 + \frac{1+n-S}{1+n+\sqrt{N}} \ast D_2 \tag{3.6}$$

or when introducing the moisture history described by Equation 2.3,

$$\frac{\sigma_{T,EL}}{s_T E_T D} = \frac{1-S}{1+\sqrt{N}}(1 - e^{-t/\alpha_C})$$

$$+ \frac{1+n-S}{1+n+\sqrt{N}}(e^{-t/\alpha_C} - e^{-t/\alpha_D}) \tag{3.7}$$

Assuming a third degree parabolic moisture distribution ($n = 3$) and parameter ratios according to Equation 3.5 we may reduce further the $\sigma_{T,EL}$ expression. We get

$$\frac{\sigma_{T,EL}}{s_T E_T D} = 0.29 + 0.45e^{-t/\alpha_C} - 0.74e^{-t/\alpha_D} \tag{3.8}$$

The critical moisture difference, D_{CR}, is defined by Equation 3.8 introducing $\sigma_{T,EL} = \sigma_{T,CR}$ (tangential strength) and $\alpha_D = 0$ together with $t \to 0$. We get the following expression,

$$D_{CR} = \frac{\sigma_{T,CR}}{0.74 s_T E_T} \tag{3.9}$$

We may now rewrite Equation 3.8 as follows where we have introduced the load level, $SL_{T,EL} = \sigma_{T,EL}/\sigma_{T,CR}$,

$$SL_{T,EL} = \frac{D}{D_{CR}}*[0.39 + 0.61e^{-t/\alpha_C} - e^{-t/\alpha_D}] \qquad (3.10)$$

This expression is the one which will be referred to in the following when numerical evaluations are madè.

4. VISCOELASTIC STRESS STATE

As previously mentioned we consider wood to be a linear viscoelastic material behaving approximately according to the Power Law creep function,

$$c_i(t) = \frac{1}{E_i}[1 + (\frac{t}{\tau_i})^{.25}] \quad ; \quad (i = R,T,L) \qquad (4.1)$$

where the power, .25, has been suggested in (1) to be in general the best value. The "doubling time", τ, is the time, $t = \tau$, at which deformation is twice its initial value.

The doubling time is shown in (1) to be very dependent of both direction and climate. A value of $\tau_R \approx \tau_T \approx 50$ days was suggested when perpendicular to grain creep is considered at a moisture content of u = 15 % and a temperature of T = 20 °C. (This is about 100 - 1000 times less than what applies to parallel to grain creep). At constant climate, τ decreases at increasing moisture content and/or increasing temperature. However, climatic variations, up or down, will always decrease the doubling time.

The following factor, a, on τ (suggested in (1)) may be used when estimating the influence on creep of equilibrium climatic conditions different from (u,T) = (15 %,20 °C)

$$a \approx 10^{(15-u)/10 + (20-T)/15} \quad ; \quad (u(\%) \leq u_F) \qquad (4.2)$$

Another result obtained in (1) is that the following relaxation function, r(t), applies for wood,

$$r_i(t) \approx c_i(t)^{-1} = E_i[1 + (\frac{t}{\tau_i})^{.25}]^{-1} \quad ; \quad (i=R,T,L) \qquad (4.3)$$

(The simple result, $r(t) \approx 1/c(t)$, applies practically for any Power Law material as long as the power is less than 1/3).

Knowing the viscoelastic properties of wood we can now determine the actual drying stresses in a pole applying the elastic-viscoelastic analogy (e.g 4,5) to the elastic stress solutions. The actual tangential stress, σ_T, for example, is obtained from Equation 3.7 simply by replacing the elastic modulus, E_T, with the so-called relaxation-integral-operator such that

$$\sigma_T = \frac{1}{E_T}\int_{-\infty}^{t} r_T(t-\theta)\frac{d\sigma_{T,EL}}{d\theta}d\theta \tag{4.4}$$

It should be noticed that we have here utilized the suggestion made above that $\tau_R \approx \tau_T$ which implies creep to be isotropic in the RT plane ($E_T c_T(t) \equiv E_R c_R(t)$ or $r_T(t)/E_T \equiv r_R(t)/E_R$). A consequence of this concept is that the stiffness ratio, $N = E_T/E_R$, appearing in the elastic stress expressions can be considered as a real constant without any time influence on the viscoelastic solution.

Equation 4.4 may be rewritten in terms of load levels. We only have to divide on both sides with the strength, $\sigma_{T,CR}$, see text immediately before Equation 3.10. We get

$$SL_T = \frac{1}{E_T}\int_{-\infty}^{t} r_T(t-\theta)\frac{dSL_{T,EL}}{d\theta}d\theta \tag{4.5}$$

The viscoelastic load level in our example is given by Equations, 3.10, 4.3 and 4.5. We get

$$SL_T = \frac{D}{D_{CR}}\int_{0}^{t} [1+(\frac{t-\theta}{\tau})^{.25}]^{-1}[\frac{1}{\alpha_D}e^{-\theta/\alpha_D} - \frac{.61}{\alpha_C}e^{-\theta/\alpha_C}]d\theta \tag{4.6}$$

When this expression is evaluated numerically it is noticed that a sufficiently good and simple approximation of the load level considered is given by

$$SL_T \approx SL_{T,EL} * r_T(t)/E_T \approx \frac{SL_{T,EL}}{1+(t/\tau)^{.25}} \qquad (4.7)$$

where $SL_{T,EL}$ is the elastic load level as expressed by Equation 3.10. Theoretical arguments given in (6) support the validity of the approximation given by Equation 4.7 as long as the exponential functions in Equation 4.6 can be considered practically congruent with the time dependent part of the relaxation function.

5. DAMAGE FREE DRYING, ONSET OF CRACKING

The time, t_B, at which cracks start propagating in an isotropic viscoelastic material may be determined by the following expression, developed by the present author in (e.g. 7, see also 8),

$$E * \int_0^{t_B} c(t_B-\theta)\frac{dSL^2}{d\theta}d\theta = 1 \qquad (5.1)$$

As usual Young's modulus, the creep function and load level are denoted by E, c(t) and SL respectively.

Equation 5.1 also applies for the material, wood, considered in this paper: a viscoelastic material with plane-isotropic creep and crack planes perpendicular to the plane of isotropy. The normalized creep function, Ec(t), to be used is $E_i C_i(t)$ as expressed by Equation 4.1 (i = T = R). The load level is given by Equation 4.7. Then the wood specific version of Equation 5.1 becomes

$$2\left(\frac{D}{D_{CR}}\right)^2 \int_0^{t_B} [1+\left(\frac{t_B-\theta}{\tau}\right)^{.25}]Y(\theta)\frac{dY}{d\theta}d\theta] = 1 \qquad (5.2)$$

where Y, according to Equations 3.10 and 4.7, is given by

$$Y(\theta) = \frac{0.39+0.61e^{-\theta/\alpha_C}-e^{-\theta/\alpha_O}}{1+(\theta/\tau)^{.25}} \qquad (5.3)$$

We will use Equation 5.2 to determine the maximum moisture loss, D_{MAX}/D_{CR}, which just provokes crack propagation. We get

$$\frac{D_{max}}{D_{CR}} = \mathrm{MIN.}(2\int_{0}^{t_B}[1+(\frac{t_B-\theta}{\tau})^{.25}]Y(\theta)\frac{dY}{d\theta}d\theta)^{-1/2} \qquad (5.4)$$

where min. means minimum with respect to t_B.

When drying of wood poles is made at $D/D_{CR} < D_{MAX}/D_{CR}$ no defect nuclei will be transformed into cracks. In other words, such a drying procedure is damage free.

Some results of Equation 5.2 are shown in Figure 5.1. For the examples illustrated it is noticed that the influence of the doubling time, τ, on D_{MAX}/D_{CR} is surprisingly low. This means that the estimate of τ is not too critical. We will suggest a value of τ determined by Equation 4.2 with an average moisture content of $u_{AV} \approx (2u_I+u_\infty)/3$.

An example: The central parts of a pole is drying according to Equations 2.1 and 2.2 with u_I = 25 %, α_C = 50 days and u_∞ = 15 % (D = 10 %). The temperature is T = 20 °C. Strength, shrinkage and stiffness are given by $(\sigma_{T,CR}, s_T, E_T)$ = (6 MPa, .004/%, 600 MPa). How should we dry the outside of the pole in order not to damage the structure ?

A critical moisture loss of D_{CR} = 3.4 % is derived from Equation 3.9. Thus D/D_{CR} = 2.7. A doubling time of τ = 20 days has been estimated from Equation 4.2. Then Figure 5.1 tells us that a drying process with α_O > 3 weeks will maintain the original wood structure. If a more severe drying process is chosen (α_O < 3 weeks) a final moisture content of u = 15 % can not be obtained without wood damage.

It should be noticed that drying time can be reduced increasing the temperature. This will increase creep (reduce τ, see Equation 4.2) which again, according to Figure 5.1, will reduce α_O.

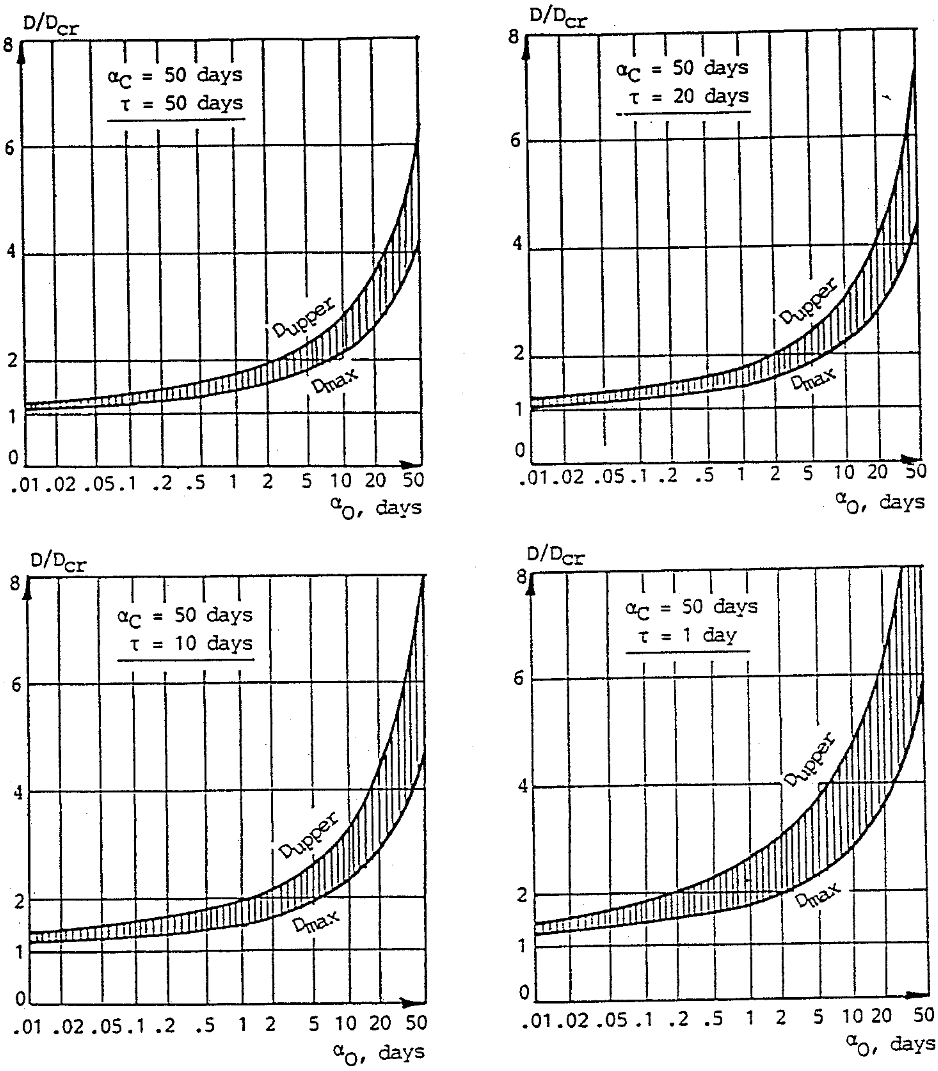

Figure 5.1. State of surface damage as related to total moisture loss, D, during drying of a pole. 1) Below shaded area: No damage. 2) Shaded area: Moderate damage. 3) Above shaded area: Total damage. (Symbols used are explained in the text).

5.1. DRYING WITH STRUCTURAL DAMAGE

Drying at $D/D_{CR} < D_{MAX}/D_{CR}$ has been shown in the preceding section to ensure a damage free wood product. This does not necessarily mean that a more severe drying will completely destroy the material. Defect nuclei, however, will expand into cracks which produce a lower strength end product.

Equation 4.7 (or more exactly Equation 4.6) may be used to determine an upper bound, D_{UPPER}/D_{CR}, which cannot be exceeded without materials destruction. We only introduce $SL_T = 1$, meaning that the tangential stress, σ_T, equals the tangential strength, $\sigma_{T,CR}$. When the approximate Expression 4.7 is used we get

$$\frac{D_{UPPER}}{D_{CR}} = MIN.(Y(t))^{-1} \tag{5.5}$$

where min. means minimum with respect to time. The abbreviation, Y, is given by Equation 5.3. Some results of Equation 5.5 are shown in Figure 5.1. It is noticed that D_{UPPER} is relatively more creep influenced than D_{MAX}.

Let us consider the same numerical example as presented in Section 5 with $D/D_{CR} = 2.7$ and $\tau = 20$ days giving safe (damage free) drying rates corresponding to $\alpha_D > 3$ weeks. Figure 5.1 tells us that we can dry faster if strength loss is accepted. A total loss, however, is the consequence of drying faster than defined by $\alpha_D \leq 1$ week.

A temperature increase while drying will have a similar effect on drying time (reducing α_D) as explained in the numerical example on damage free drying in Section 5.

It should be emphasized that the upper bound for D as determined by Equation 5.5 is not the best bound. A true bound must consider that cracks propagate because of creep during drying when $D > D_{MAX}$. This phenomenon means that $\sigma_{T,CR}$ decreases implying a more restrictive upper bound than the one shown in Figure 5.1. However, to day we cannot give a better bound. We first have to overcome the mathematical complexity of predicting relaxation stresses in a cracked viscoelastic material the stiffness of which also changes because of crack propagation.

6. FINAL REMARKS

Assuming we have a true upper bound of D. Then three areas define the effect of drying: 1) $D < D_{MAX}$: Original wood structure is maintained. 2) $D_{MAX} \leq D < D_{UPPER}$:

Wood structure is increasingly damaged resulting in strength reduction. 3) $D_{UPPER} \leq D$: Wood structure is badly damaged causing total loss of strength. Area 2) is represented by the shaded sections of Figure 5.1.

We recall that we have considered especially the areas at the surface of a pole. This should be kept in mind when evaluating the statements made on drying with damage. For example, the pole considered does not necessarily lose its strength totally when deep cracks appear at the surface. The first cracks developed may very well produce a stress relaxation inside the pole which reduces the chances that damage will occur in this area. Mathematically the drying problem of wood components with propagating cracks is extremely difficult to solve. This has already been indicated in the preceding section.

It is, however, very satisfactory that the drying process which leaves wood with its best end-quality is accessible for analysis. This paper has given an example of that: Poles drying as shown in Figure 2.1. Other examples, involving other cross-sections and moisture histories may be analyzed in exactly the same way.

LITERATURE

1) Nielsen, L. Fuglsang: "Power Law Creep as Related to Relaxation, Elasticity, Damping, Rheological Spectra and Creep Recovery - With Special Reference to Wood". IUFRO Wood Engineering Group Meeting (Int. Union of Forestry Res. Org.), Xalapa, Mexico, December 1984. Proc. Building Materials Lab., Techn. Univ. of Denmark, Copenhagen 1985, 181-204.

2) Nielsen, L. Fuglsang: "Stresses in Wood caused by Drying". Build. Mat. Lab., Techn. Univ. of Denmark, Copenhagen. Techn. Report 165(1986). (Progress report on research project, StvF-16-3785.B).

3) Ranta-Magnus, A.: "Pyöreän puum kuivumisjännitysten lineaarinen analyysi". ("A linear Analysis of Drying Stresses in round Timber", in Finish). Rakenteiden Mekaniikka, 19(1986), 43-55.

4) Alfrey, T.: "Non-Homogeneous Stresses in Viscoelastic Media". Qu. Appl. Math., 2(1944), 113.

5) Flügge, W.: "Viscoelasticity". Blaisdell Publ. Comp., London 1967.

6) Nielsen, L. Fuglsang: "Constitutive Equations for Concrete". Bygningsstatiske Meddelelser (Copenhagen), 45(1974), 65.

7) Nielsen, L. Fuglsang: "Crack Failure of Dead, Ramp, and Combined Loaded Viscoelastic Materials". First Int. Conf. on Wood Fracture, Banff, Alberta, Canada, August 1978. Proc., 1979, Western Forest products Lab., Univ. Brit. Columbia, Vancouver, B. C., Canada, 187-200.

8) Johns, K. and Madsen B.: "Duration of Load Effects in Lumber. Part I: A Fracture Mechanics Approach". Can. J. Civ. Eng., 9(1982), 502-514.