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Mechano-sorptive effects in wooden material

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Summary The effects on wood of simultaneous mechanical and moisture loading are studied. In order to clarify the mechano-sorptive behaviour of wood, a review of different phenomena presented in the literature is included. Based on this review a constitutive model is proposed for the case of uniaxial stress in the longitudinal direction. The validity of the model is checked independently against test results. The calculations show that the model is capable of describing the response of wood with reasonable accuracy. Simulations indicate that the response of small test specimens is more difficult to describe than that of larger beams. Some differences in behaviour are found to depend on loading mode and nature of moisture cycling. Very large and fast moisture cycles seem to give larger mechano-sorption than smaller variations. The results of the simulations show that there is a significant influence of strain on the shrinkage and swelling response.

Introduction

Wood used for engineering purposes is usually subjected to variations in the surrounding climate. Due to these variations the properties of wood vary with time. The humidity variations often also lead to unpredicted and undesired deformations due to differential shrinkage. Much effort has been put into research concerning phenomena related to mechano-sorption. A great number of experimental investigations of the response of wood to moisture variations have been performed since the late fifties. If the results trom these investigations are gathered and an attempt is made to use these as a base for an explanation and description of the phenomena of mechano-sorption it can be more confusing than clarifying. In the following sections some of the more important observations, in the author's opinion, will be described. Based on these a constitutive model has been developed. The development of such a model has to be restricted with regard to the type of phenomenon that is to be described by it. A very general threedimensional model that takes both time and moisture dependence into account may be developed, see Mårtensson (1992), but unfortunately it is nearly impossible to adopt such a model in practice. The model described in the following is therefore restricted to uniaxial stress in the longitudinal direction. This model is well suited to describe the behaviour of ordinary timber and glulam beams.

The phenomenon of mechano-sorption

Wood under load, when subjected to moisture content changes, exhibits much greater deformations than under constant humidity conditions. This mechano-sorptive phenomenon has been

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known since the late fifties and early sixties (Perkitny 1960; Armstrong, Christensen 1961). The results from the extensive experimental investigations performed since then are sometimes contradictory, and new effects seem to be found all the time. A number of factors influence the mechano-sorptive behaviour. Primarily the nature of the wood itself affects the behaviour. Different species behave differently, within the tree trunk different parts can behave differently, the orthotropy of wood and the heterogeneous structure with defects and anomalies makes it difficult to predict and model the mechano-sorptive response. The apparent differences between different loading modes, including recovery effects, also complicate the description.

Lists of requirements of models of mechano-sorption have been given by Grossman (1976), Hoffmeyer (1990), and Hunt (1991). The contents of the lists differ somewhat between different authors, often due to differences in interpretation of results. The version given here is based on test results and discussions published in the literature as well as the author's own test results. Except where stated otherwise, the list below refers to longitudinal effects only. Mainly the stress levels are low or medium, since the behaviour at high stress levels becomes nonlinear with stress, which makes the evaluation more difficult. The stress level where mechano-sorptive behaviour becomes non-linear is hard to define with certainty, but in compression the non-linearity starts at about 10–20% of ultimate stress, Hunt (1989), and in tension and bending at about 20–30% of ultimate stress. The working stresses in normal structures are in most cases lower than these values. Since the main aim here is to deal with serviceability problems it is considered to be correct to assume a linear behaviour.

Some of the terms used in the following discussion will be defined. A uniaxial loading case is considered with strain used as the measure of deformation, defined as the change in length in relation to the initial length of the tested specimen. In Fig. 1 a principal sketch of the strain development in a test piece is given, and the response in both compression and tension is shown. Initially there is an elastic strain, ε_i, in response to the load applied to the specimen. If the test piece is thereafter kept under constant load and constant climate conditions the strain increases with time, i.e. pure creep occurs, ε_c. If the test piece is instead subjected to humidity changes, the total strain oscillates due to the moisture changes, and the total increase in strain after a full moisture cycle is larger than the pure creep. The total change from dry to wet conditions – or vice versa – does not have the same magnitude in all cycles. The amplitude of the strain curve is defined as half the value of the strain difference between one maximum strain and the following minimum strain, see also Fig. 1. Further, if the test piece is unloaded after a number of cycles, recovery takes place. Fig. 1 also shows the response of a non-loaded test piece. The strain ε_{so} of this is referred to as free dimensional change.

The total strain at any time is denoted ε_t. Another measure used in the following is zero-load compensated strain or reduced strain, ε_r, which is the strain obtained if the free dimensional change is subtracted from the total scrain, $\varepsilon_r = \varepsilon_t - \varepsilon_{so}$. ε_r is then the sum of ε_c, the mechano-sorptive strain ε_{ms} and the initial elastic strain ε_i, which means that mechano-sorptive strain is defined as $\varepsilon_{ms} = \varepsilon_t - (\varepsilon_c + \varepsilon_{so}) - \varepsilon_i$. As will be shown in the following the shrinkage and swelling is influenced by stress and since this is not considered in the definition of ε_{so} it follows that one part of the mechano-sorptive strain consists of this dimensional change due to stress influence on dimensional changes.

In bending the deformation measure used is deflection, δ. The main difference between tension and bending is that in the latter the deflection is not directly affected by free shrinkage-swelling. This means that the mechano-sorptive deflection is defined as $\delta_{ms} = \delta_t - \delta_c - \delta_i$, where δ_t is total deflection, δ_c is pure creep and δ_i is the initial deflection. Both in the case with uniaxial loading and bending there is also an indirect effect of the shrinkage-swelling, namely the change in geometry which affects the elastic deformation. This effect is, however, counteracted by the changes in elastic modulus, i.e. the latter decreases when the cross section increases and vice versa.

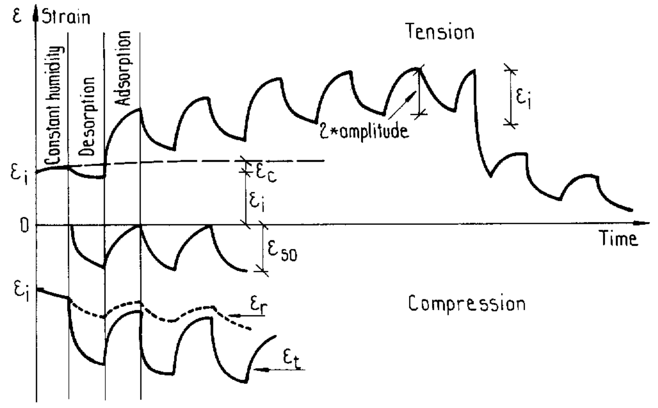

Fig. 1. Principal sketch of strains in wooden specimens subjected to compressive, tensile and zero load. The notations used in the figure are explained in the text

The following phenomena have been found concerning the mechano-sorptive phenomena:

1. Moisture desorptions, both in tension and compression, lead to an increase in the absolute value of zero-load compensated strains (Eriksson, Norén 1965; Mårtensson 1992). This means for instance that a tensile stress, see Fig. 2, reduces shrinkage, especially during the first desorption.

2. For adsorption during tension some tests have shown that the zero-load compensated strain decreases (Eriksson, Norén 1965), see also Fig. 2. In other tests, however, the opposite has been found (Mohager 1987; Hunt 1979). When the very first sorption is an adsorption period the zero-load compensated strain always increases.

3. For adsorption during compression the data are also somewhat confusing. Test results from Toratti (1992), and Mårtensson (1992), show that the absolute value of compressive zero-load compensated strain decreases. Results from Hunt (personal communication 1990), and Cheng and Schniewind (1985) show, however, the reversed relation.

4. In bending the first adsorption and all desorption periods cause increases in deflection, while later adsorptions tend to decrease the deflection, Fig. 3, (Hearmon, Paton 1964; Mohager 1987; Hunt, Shelton 1988). This is applicable in cases where the moisture content changes take place within previously attained moisture content limits. Fig. 3 also shows the effect of non-linearity with stress discussed earlier.

Bending is an effect of the behaviour in the tensile and compressive zones. During desorption the absolute value of the zero-load compensated strain increases in both zones which leads to the expected increase in deflection. An initial adsorption leads to an increase in zero-load compensated strain in the tensile zone, if the same holds for the absolute strain value in the compressive zone which would lead to the desired increase in deflection. Later adsorption periods may lead to both increases and decreases in zero-load compensated strain according to paragraphs 2 and 3. If it on both sides leads to decreases in zero-load compensated absolute strain values this would lead to the expected rise of a beam in bending. It could, however, be sufficient if the decrease occurs only in one zone, if it is large enough in comparison to the effect in the opposite zone.

5. The effect of moisture content changes in both tension and compression seems to be more pronounced for changes outside earlier attained moisture content limits in comparison with the behaviour when the changes take place within the moisture limits earlier attained.

6. An effect of stress on the shrinkage-swelling behaviour exists, which leads to decreased shrinkage-swelling for wood loaded in tension parallel to the grain and to increased shrinkage-swelling for wood loaded in compression parallel to the grain (Hunt, Shelton 1988). It might be

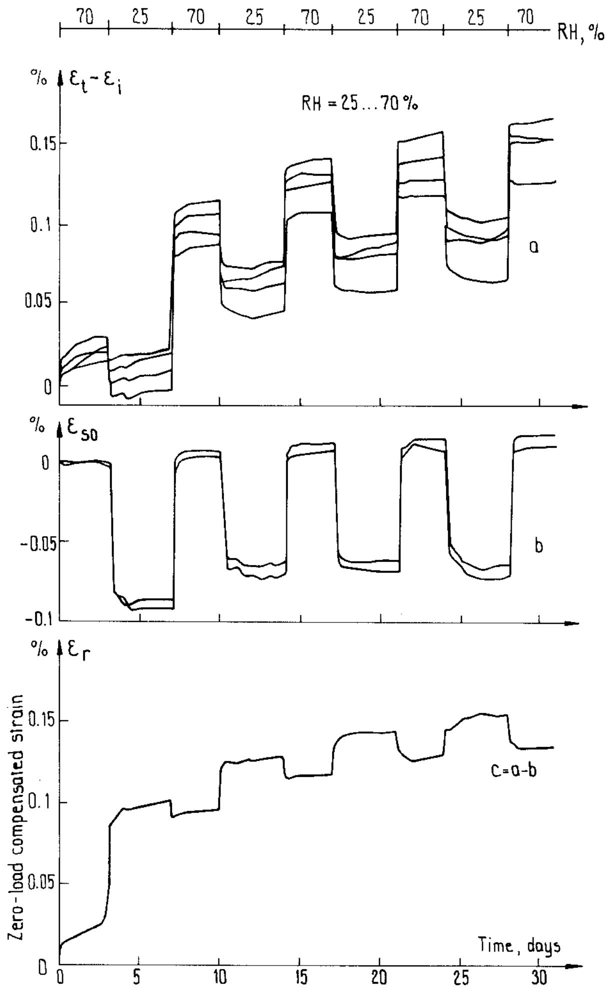

Fig. 2. Results from tensile tests made on pine (0.4 × 5 × 150 mm), loaded parallel to grain (Eriksson, Norén 1965). The upper figure shows the strain (the initial elastic strain is subtracted), measured on four samples, and the middle figure shows the free shrinkage-swelling, measured on two samples. The lower figure shows the zero-load compensated strain, i.e. the difference between the upper and the middle figure, here the medium values of the four respectively the two samples have been used

argued that it is more correct to see this effect as an effect of accumulated strain, since after unloading there seems to remain an effect on the shrinkage-swelling.

7. The effect of moisture content change on the deformation is in general much greater than the effect of time.

8. When moisture cycling takes place between two fixed limit values, the deflection goes towards a limiting value (Hearmon, Paton 1964; Mohager 1987; Hunt, Shelton 1988). Hunt has introduced the term 'creep limit' to describe this behaviour. The same behaviour has been found in uniaxial tests, i.e. the strain approaches a limiting value.

9. In addition to the observation in 8 it has been noted that in the beginning of a test under low stress, the oscillation amplitudes of the deflection curve in bending tend to increase with total deflection (Hearmon, Paton 1964; Mohager 1987). After a number of cycles the behaviour observed in 8 leads to a constant amplitude. At higher stresses the increase in amplitude never

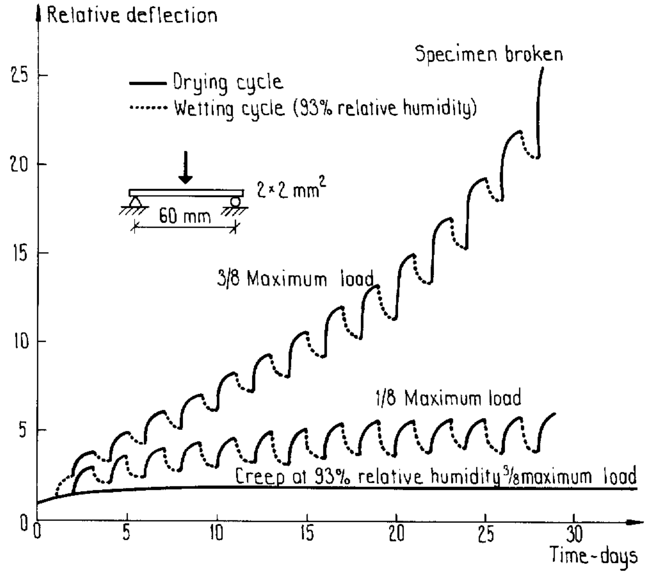

Fig. 3. Wooden beam (beech) subjected to moisture cycling while under load (Hearmon, Paton 1964). The relative humidity during the drying cycle is not given in the reference, which means that the figure only can be said to present the principal behaviour

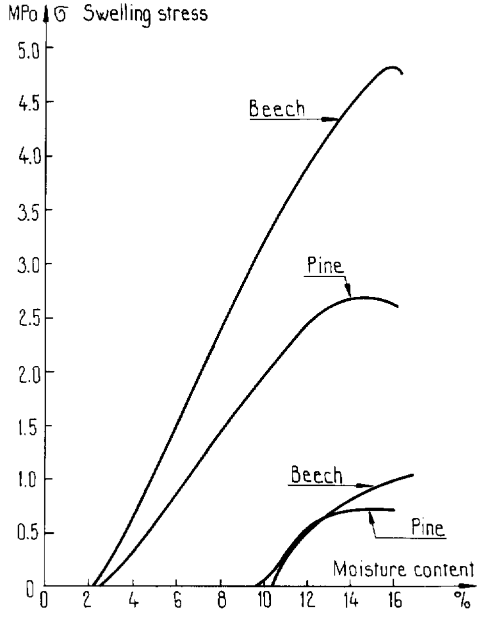

Fig. 4. Stress required to keep a wooden specimen restrained from swelling; tests made on pine and beech parallel to grain (Keylwerth 1964)

ceases, which may lead to failure. In tension the oscillation amplitude decreases, at least at low stress levels (Mohager 1987; Hunt, Shelton 1988). It can be deduced from this that the effect in compression would be the same as in bending, since the bending deflection oscillations are related to the behaviour on the tension and compression sides. This is in accordance with test results from Hunt and Shelton (1988).

10. Mechano-sorption also gives rise to increased deflection for structural timber (Bethe 1969; Meierhofer, Sell 1979; Hoyle et al. 1986; Mohager 1987; Leivo 1988). Mohager (1987), for in-

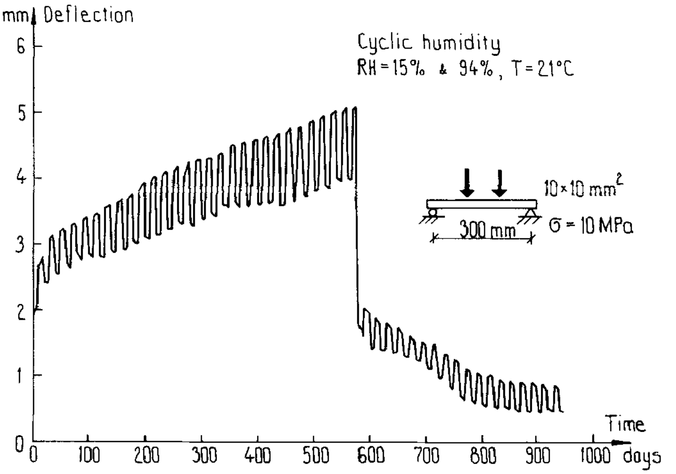

Fig. 5. Beam, made of pine, subjected to moisture cycling under load. After a number of moisture cycles the load is removed and recovery takes place. The recovery is increased by further moisture cycling (Mohager 1987)

stance, has shown that the relative deflection of full size beams (44 × 94 mm, length 4 m) is nearly as large as the relative deflection of small beams (10 × 10 mm, length 300 mm). Relative deflection is deflection at time t divided by initial deflection.

11. In cases where wood is restrained from swelling by an external force, the magnitude on the restraint force is much less than the force would be it the piece was first allowed to swell and then forced back to its original length. This has been shown to apply both perpendicularly as well as parallel to grain (Keylwerth 1964; Perkitny, Kingston 1972; Krauss 1988), see Fig. 4.

12. After unloading, an instantaneous elastic recovery takes place. The magnitude of this recovery is equal to or greater than the initial elastic response (Gibson 1965; Mohager 1987), see Fig. 5.

13. The recovery of wood after unloading is similar to that for normal creep. The recovery is, however, accelerated by moisture cycling (Christensen 1962; Arima, Grossman 1978) and is larger during adsorption than during desorption (Armstrong, Christensen 1961; Ranta-Maunus 1975; Mohager 1987). If the recovery is total, i.e. the accumulated mechano-sorptive strain has vanished totally, a new loading period with moisture content changes shows the same behaviour as the previous one (Christensen 1962).

14. The mechano-sorptive effect has been found in all species studied. Differences in behaviour between different species have been found, but it is hard to say if they are only of quantitative nature, or if they are also, of qualitative nature (Ranta-Maunus 1975; Hunt 1986).

15. Investigations have shown that the mechano-sorptive effect also exists in loading perpendicular to the grain. Tests in this loading direction have mainly concerned drying processes (Hisada 1986; Kolb et al. 1985) and swelling pressures, see also paragraph 11.

16. The mechano-sorptive effect has also been found in wood-based materials such as particleboards (Armstrong, Grossman 1972; Gressel 1984; Dinwoodie et al. 1990) and fibreboards (Sauer, Haygreen 1968; Mårtensson 1988 a, 1988 b; Mårtensson, Thelandersson 1990). The behaviour differs, however, in a fundamental way between wood and wood-based materials. The typical fluctuations in deflection that occur in bending under moisture variations for wood is not as pronounced during the same loading for board materials (Dinwoodie et al. 1990). The increase in total deflection is, however, more significant for board materials than for the wood. Large differences in behaviour also exist between different types of wood-based materials, depending on the size of the chips or fibres in the material and on the type of components added to the boards.

17. Chemical treatments such as acetylation and formaldehyde cross-linking (Norimoto et al. 1987) have been shown to have a reducing effect on the mechano-sorptive effect. Acetylation means that the hydroxyl groups in the wood react with acetic anhydride, with the result that the moisture uptake is reduced (Feist et al. 1991).

18. Fridley et al. (1990) have tested lumber in bending both at different constant temperature levels and in cyclic temperature conditions, where in all tests the humidity was kept constant. The results show that the higher the temperature is, the shorter is the time to failure. It was also shown that if the temperature is cycled between 20 °C and 55 °C, the time to failure is shorter than it is for beams subjected to a constant temperature of 20 °C. Beams subjected to a constant high temperature, 55 °C, failed, however, earlier than beams subjected to cyclic temperature. This indicates that a phenomenon similar to the mechano-sorptive behaviour does not exist for temperature variations, or at least that it is small.

Constitutive model

The orthotropic nature of wood leads to complex relations between stresses and strains, especially when time dependence and moisture dependence are to be considered. A number of material models have been developed (Leicester 1971; Ranta-Maunus 1975; Mukudai and Yata 1986; van der Put 1989; Toratti 1992) with more or less success. It would be desirable to use a three-dimensional formulation in order to enable an adequate description of the behaviour of wood. In Mårtensson (1992) a general three-dimensional form of a constitutive model that describes simultaneous moisture and mechanical loading has been developed, but the description here will be restricted to the case with a uniaxial stress applied in the longitudinal direction of wood. This restriction was mainly done in order to simplify the evaluation of the parameters and the validation of the model. In normal bending of timber beams this loading mode has the major influence which shows that it is reasonable to introduce this restriction. Due to the restricted space given in this paper no values will be given on the parameters used in the equations nor will the evaluation of the mathematical model be gone through, for those interested see Mårtensson (1992).

The constitutive relation is given in rate form, i.e. the time derivatives of the strain are functions of, for instance, stresses and moisture conditions. In this study it has been assumed that the material parameters were the same in both tension and compression.

The total strain rate $\dot{\varepsilon}$ is assumed to consist of four main parts, one elastic part, one part describing creep under constant humidity conditions, one part describing the shrinkage-swelling behaviour and finally one mechano-sorptive part. The constitutive relation will then be

$$\dot{\varepsilon} = \dot{\varepsilon}_e + \dot{\varepsilon}_c + \dot{\varepsilon}_{st} + \dot{\varepsilon}_{ms} \tag{1}$$

where

$$\dot{\varepsilon}_e = \frac{\dot{\sigma}}{E} \quad \text{is the elastic strain rate}$$

$$\dot{\varepsilon}_c = \frac{d}{dt}\left[\sum_{n=1}^{N} \int_0^t J_n \left[1 - \exp\left(-\frac{\xi(t) - \xi(t')}{\tau_n}\right)\right] d\sigma(t')\right] \quad \text{is the pure creep strain rate}$$

$$\dot{\varepsilon}_{st} = (\alpha - \Delta\alpha)\dot{u} \quad \text{is the shrinkage-swelling strain rate}$$

$$\dot{\varepsilon}_{ms} = m\sigma|\dot{u}| \quad \text{is the mechano-sorptive strain rate}$$

Here u is the moisture content, σ is the current stress, α is the shrinkage-swelling coefficient. E is the elastic modulus and m is the mechano-sorptive parameter. The formulation of the creep rate is a conventional viscoelastic formulation with material parameters J_n and τ_n and the material time ξ. All material parameters can be functions of the moisture content.

In the formulation of shrinkage-swelling the part $\Delta\alpha$ is introduced in order to describe the effect of strain and stress on shrinkage-swelling that has been found in experiments. The formulation of this term is as follows

$$\Delta\alpha = kp\varepsilon_e + k(\varepsilon_c + \varepsilon_{ms}) \tag{2}$$

i.e. it is a function of the elastic strain, the creep strain and the mechano-sorptive strain. The parameter k is a material parameter and the factor p is used to describe the influence of the elastic strain ($0 \leq p \leq 1$). Since $\Delta\alpha$ is positive for tensile strains and negative for compressive strains, the shrinkage-swelling will be larger during compression than during tension which corresponds to what has been found in tests (Hunt, Shelton 1988; Leivo 1991).

The mechano-sorptive parameter m in the mechano-sorptive strain rate $\dot{\varepsilon}_{ms}$ is given by

$$m = \begin{cases} m_0 & \text{if } u < u_{min} \text{ or } u > u_{max} \\ m_0 \exp\left(-\dfrac{\varepsilon_{mst}}{\varepsilon_{ms\infty} - \varepsilon_{mst}}\right) & \text{if } u_{min} \leq u \leq u_{max} \end{cases} \tag{3}$$

where

$\varepsilon_{mst} = \int_0^t \dot{\varepsilon}_{ms} dt$ is the total mechano-sorptive strain

and m_0 is a constant. This means that if the moisture content reaches values not previously attained the increase in mechano-sorptive strain is larger than if the moisture content is within the moisture limit values. If the moisture content is varied within the limits there is a limit value of the total mechano-sorption, $\varepsilon_{ms\infty}$. A number of experimental results have indicated that such a mechano-sorptive creep limit exists (Hearmon, Paton 1964; Mohager 1987; Hunt, Shelton 1988), but the definition has not been totally clarified. The present work has indicated that the creep limit can not be defined as a pure material parameter but is also a function of the loading condition, both mechanical and moisture loading.

Validation of the constitutive model

The model contains a number of material parameters. The applicability of the model depends on whether material parameters calibrated against one test series can be used in the simulations of other tests and thereby also in simulations of practical examples. Both the influence of the different parameters and the possibility to use the same values of the parameters in simulations of a number of tests of different type and on different materials have been investigated. In order to perform the simulations the constitutive model has been implemented in a finite element program.

In Figs. 6, 7 and 8 results from calculations and tests on full size timber beams are presented. The results are presented as relative deflection, i.e. the deflection at time t divided by the initial deflection. In all the calculations the moisture distribution within the beams has been calculated with the finite difference program JAM developed by Arfvidsson (1989). In Fig. 6 the test results are from Mohager (1987). The material parameters used for the simulations presented in Figs. 6 to 8 have been calibrated from bending tests performed by Mohager on small specimens ($10 \times 10 \times 300$ mm), see also Fig. 5. As can be seen from Fig. 6 the model describes very well the behaviour of the tested material. In the model given by Eq. (1) no special term describing the recovery has been included. It is, however, included to some extent in the other terms. Attempts that have been made (Mårtensson, 1992) with a recovery term included showed a somewhat better agreement than the present one, i.e. the calculated recovery became larger than the one presented in Fig. 6. The behaviour given by Eq. (1) describes, however, the recovery behaviour with sufficient accuracy.

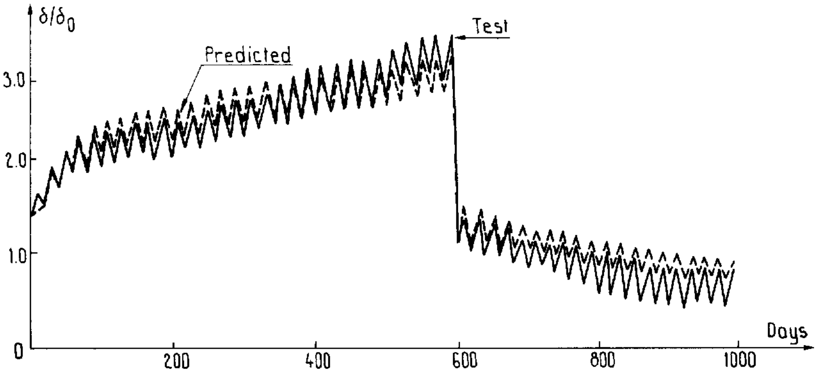

Fig. 6. Results from a test, performed on beams made of pine, by Mohager, surface stress = 10 MPa. Cyclic humidity variations, 15% RH to 94% RH, 10 days at each level. The load was removed after 600 days and thereafter the recovery due to moisture cycling was recorded for another 400 days. Simulation results are shown for comparison. Cross section 45 × 94 mm, length 3.9 m

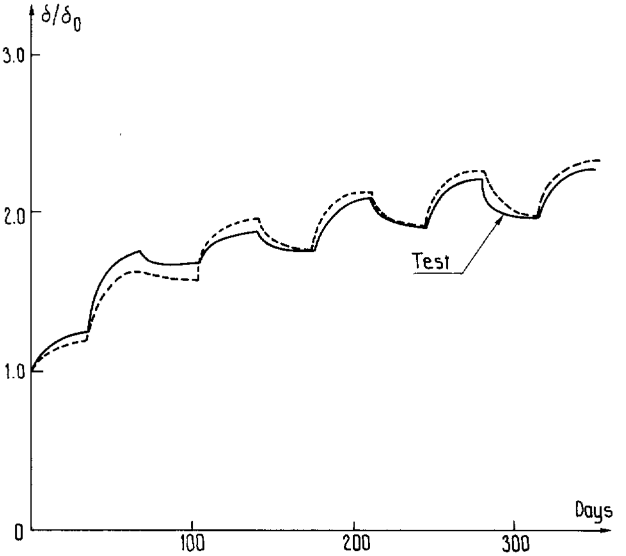

Fig. 7. Results from bending tests performed by Leivo on beams of spruce, surface stress 5.0 MPa. Simulation results are shown for comparison. Relative humidity varied between 35% and 90%, 35 days in each humidity. Initial relative humidity was 90%, which was also kept constant during the first 35 days. Cross section 45 × 95 mm, length 2.0 m

In Mårtensson (1992) results from calibrations made on small specimens subjected to tension and compression are reported. These calibration attempts have shown that it seems to be more difficult to simulate the response of small test specimens than to simulate the response of beams of structural size. The accuracy of the material parameters was shown to be more important for the small test specimens especially in the uniaxial cases. For such specimens it was not always possible to use the material parameters evaluated from one test series in simulations of other test series although the same material was used in the different tests.

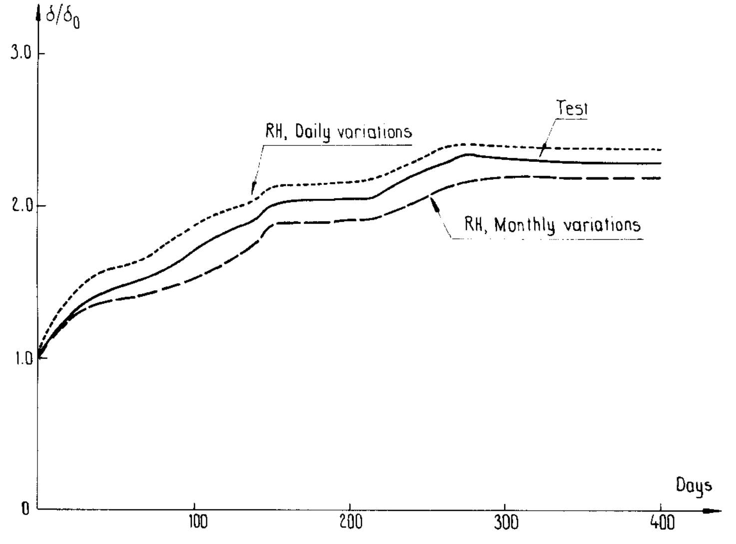

Fig. 8. Results from tests made by Taylor et al. on European whitewood compared to simulation results. Cross section 45 × 150 mm, length 1.72 m

In Fig. 7 the test results are from Leivo (1988). The calculation presented in the figure has been carried out with the same material parameters as in Fig. 6, with one exception, the mechano-sorptive creep limit $\varepsilon_{ms\infty}$, which had a lower value in the simulations of the tests performed by Leivo. The main influence of the value of the mechano-sorptive creep limit is that if the value of this parameter is too large the calculated deflection becomes too large after a number of cycles. The tests performed by Mohager were done with large amplitudes on the humidity cycles and with short intervals between humidity changes and under a relatively high load. The tests performed by Leivo were performed with smaller amplitudes and with longer intervals between the humidity changes. The results indicate that the creep limit becomes larger for greater humidity changes.

In Fig. 8 test results from Taylor et al. (1991) are presented together with simulation results. The experiments carried out by Taylor et al. are long term tests on beams subjected to naturally varying climate, which of course is of great value. Two different simulations were performed, one where only the monthly variations in the humidity were considered and one where the daily humidity variations were considered. As can be seen from Fig. 8 the calculated relative creep was somewhat larger when the daily fluctuations were taken into consideration. The major part of the difference between the two simulations develops during the initial period. After that the description is relatively similar in both cases. Both simulations showed good agreement with the test results which shows that the description provided by the simulation is satisfactory.

The results of the calibrations show that it is possible to use material parameters evaluated from one test series in simulations of other tests and get a good estimation of the behaviour in these tests. This shows that it is possible to use the developed model with material parameters evaluated from tests in simulations of the behaviour of structural timber structures subjected to simultaneous mechanical and moisture loading.

Concluding remarks

In this paper the effect of interaction between moisture variations and mechanical loading on wood has been studied. A review of the phenomenon reported in the literature is made in order to identify important factors that may have an influence on the behaviour of wood. A theoretical model is developed and based on this, calculations are performed. These calculations show that the model is capable of describing the response of wood with reasonable accuracy. In this study it was assumed that the material parameters were the same in both tension and compression. The differences between tension and compression discussed previously in the review are thereby totally explained by the difference in free shrinkage-swelling in the model. Further refinement of the model could include a further differentiation between tensile and compressive behaviour. When the model was calibrated against bending tests for small clear specimens, very good agreement was achieved in simulations of creep tests for timber in structural sizes. The results of parameter studies and simulations show the importance for the researcher to decide on what level the studies are to be performed, for small test specimens in order to clarify the response for different loading conditions, or for structural beams.

Tests have shown that pure mechano-sorption is of major importance during the first sorption period. Thereafter the magnitude of the mechano-sorptive strain rate decreases. This effect has been introduced in the model as a mechano-sorptive limit. The value of this limit seems to depend on load level and nature of moisture cycling. It seems that for very large and fast moisture changes, the mechano-sorption becomes larger than for smaller variations. The introduction of a strain dependence in the shrinkage-swelling improves the capability of the model to describe deflection fluctuations during moisture cycling.

Previously, nearly all studies have been carried out for constant load cases and with a controlled humidity. In reality neither of these circumstances are valid. In order to study the effect of a naturally varying climate, calculations have been carried out for a beam in outdoor climate. These calculations show good agreement with test results, and it is also shown that the short term humidity fluctuations that occur each day have a rather small influence on the long term deflection of timber in structural sizes.

The results of this work show that the constitutive model can be successfully used in studies of the response of wood to moisture variations and simultaneous load. It has also been shown that some effects found in tests on small specimens are less important for larger structures, which simplifies the description in those cases. The possibility to find a model that can be used for reliable simulations of a limited range of situations is demonstrated, as well as the impossibility to develop *the model* that could be used to describe all conceivable effects of moisture variations on wood behaviour.

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