MODELLING THE CREEP OF WOODEN STRUCTURES

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ABSTRACT

The purpose of this study is to model and experimentally verify factors influencing changes in the instantaneous, medium-term and long-term stiffness of nail plate joints, sawn timber and nail plate trusses.

The experimental testing of the stiffness models was achieved with the aid of an extensive test series. In the instantaneous stiffness tests, 4 series of nail plate joints were loaded in 20 different service conditions and 14 test trusses were loaded in 10 different service conditions. Long-term tests were performed on sawn timber and nail plate joints in constant condition of 35 % RH and 90 % RH as well as in cyclically varying moisture conditions of 35 - 90 % RH. There were 2 sawn timber test series in each of the test conditions and 4 - 6 joint test series. 11 trusses were subjected to full-scale loading in a test house. The duration of creep tests performed on the joints, sawn timber and nail plate trusses was about 1 year.

INSTANTANEOUS STIFFNESS OF NAIL PLATE JOINTS

The following observations were made in the nail plate joint tests:

- The stiffness of the nail plate joints was linear in regard to the loading cycles, and changes in moisture content and temperature.
- Each moisture deformation occurring in the wood stabilization conditions increased the instantaneous slip of the joints. The effects of the moisture deformations on the stiffness of the joints during adsorption and desorption were approximately equal.
- The slips of cold specimens were smaller than those of the warm specimen with the same moisture content. Temperature changes alter the elastic properties of sawn timber and affect the slip coefficient between the nail plate tooth and the wood.
- Each loading increased the joint slip, and stabilization of the instantaneous joint slips did not stabilize during the course of 20 loadings. Stabilization of the total slips occurred only in the contact joint test series after the 10th loading.
- The loading, moisture and temperature cycles affected the ultimate loads of the contact joints so that the average ultimate load of the unloaded specimens was 16 % higher than that of the cyclically loaded specimens.

The instantaneous stiffness of nail plate joints was described with a new model formulated during the course of this study. Formula (1) described well the change in the joint stiffness as a function of moisture content, temperature and the loading cycles. The moisture content and temperature changes have been taken into account in the model by introducing separate terms for them both.

$$\phi(n,u,du,T,dT,P) = \phi_0(u,T,P)\left(1 + A_1\,|du_1| + A\sum_{i=2}^{n}|du_i| + B_1\,dT_1 + B\sum_{j=2}^{n}dT_j + C_1 + \sum_{k=2}^{n}C_k\right) \qquad (1)$$

where $du_i = u_i - u_{i-1}$ (%) and $dT_j = T_j - T_{j-1}$ (°C).

Figures 1 - 2 show the average changes of the total rotation and instantenous rotation in one out of four test series and the values of model (1).

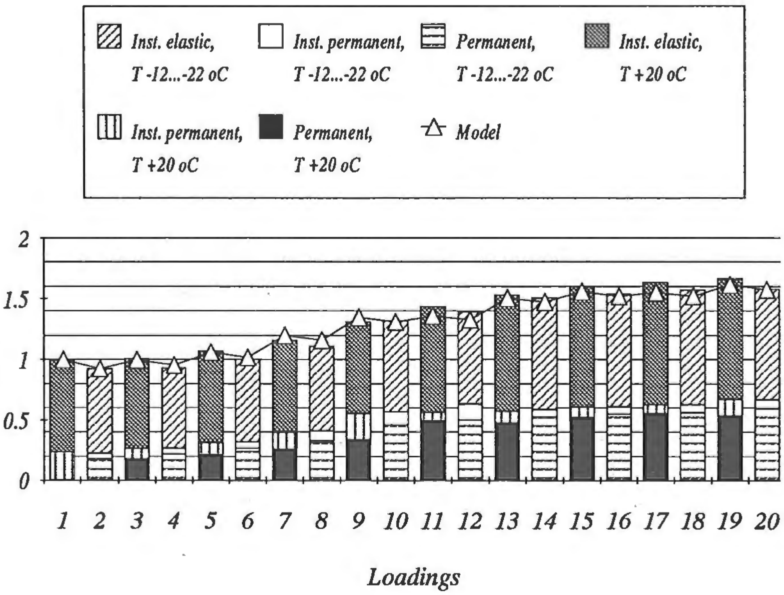

Figure 1. Average changes of the total rotations in test series (the size of nail plate 75 x 196 mm2, the size of timber 45 x 95 mm2, 3 mm gap and 100 % of allowable bending load) and the values of the stiffness model (1).

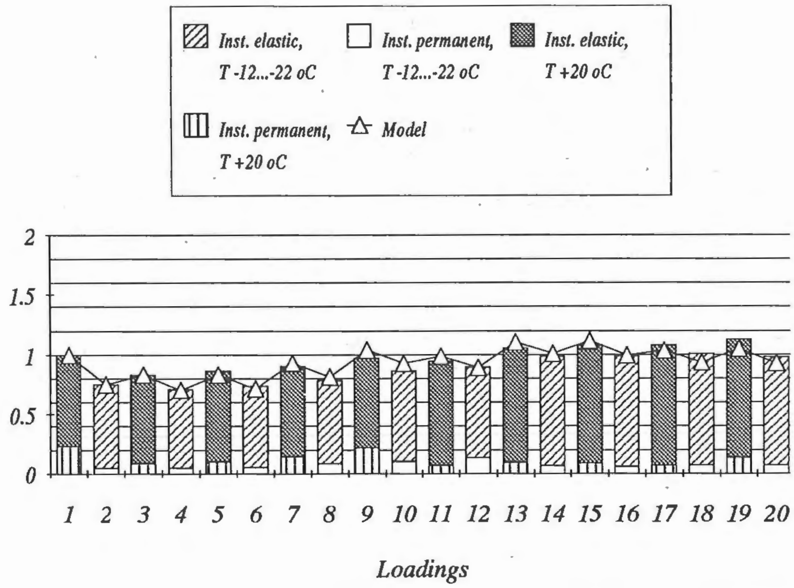

Figure 2. Average changes of the instantaneous rotations in the test series (the size of nail plate 75 x 196 mm2, the size of timber 45 x 95 mm2, 3mm gap, 100% of allowable bending load) and the values of the stiffness model (1).

INSTANTANEOUS STIFFNESS OF SAWN TIMBER

The moisture content of sawn timber affects both the elastic properties and the shape of the cross-section. The MOE of sawn timber with a high moisture content is lower than that of dry timber. On the other hand, the cross-section and the moment of inertia I computed from it are greater in wet timber. A model was developed for the instantaneous stiffness of sawn timber, with expressions (2) and (3) describing the change in instantaneous axial and bending stiffness as a function of moisture content of wood and temperature.

$$EI(u_i,T_i)/EI(28\%,20^{\circ}C) \cong 1 + 0.0080\ du_i - 0.000104\ (du_i)^2 + 0.0020\ dT_i + 0.000016\ du_i\ dT_i \quad (2)$$

$$EA(u_i,T_i)/EA(28\%,20^{\circ}C) \cong 1 + 0.0120\ du_i - 0.000061\ (du_i)^2 + 0.0020\ dT_i + 0.000024\ du_i\ dT_i \quad (3)$$

where $du_i=(28\ \% - u_i)$ and $dT_i=(20\ ^{\circ}C - T_i)$.

Figure 3 shows the effect of the wood's moisture content on the MOE, estimated change in stiffness according to expressions (2) and (3), or models 1, as well as the estimates corresponding to the expressions, or models 2, where the shape of the cross-section is defined by means of polar coordinates and the moments of inertia and area computed using numeric integration. As a reference value, we selected the standard moisture content of sawn timber when cut to size or planed, namely 18 %.

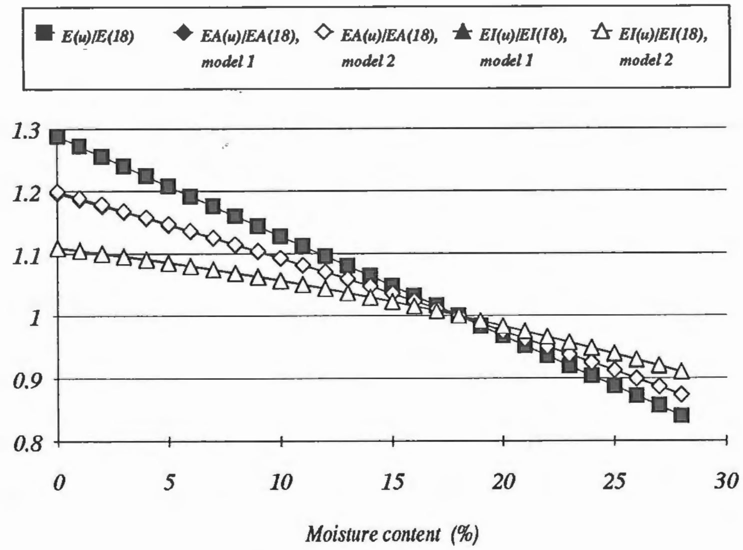

Figure 3. Changes in stiffness EA and EI of cut-to-size and planed timber as function of moisture content.

The change in instantaneous stiffness of sawn timber resulting from a change in moisture content is considerably smaller than the change in the MOE. At low and high moisture content levels or moisture classes 1 and 4, the change in stiffness is only about 38 - 55 % of the change in the MOE.

INSTANTANEOUS STIFFNESS OF NAIL PLATE TRUSSES

The following observations were made in the tests on the trusses:

- Humidity and loading cycles reduced the stiffness of the truss.
- A low temperature increased the stiffness of the structure as in the case of nail plate joints.

A model was developed in the study for the instantaneous stiffness of the nail plate truss using the stiffness models for nail plate joints and sawn timber. It was established that 35 % of the deflection of the structure consisted of joint slip while 60 % was caused by deflection due to normal force and 5 % due to the bending moment. In the stiffness models for nail plate trusses, the stiffness models for the structural components were weighted by the these percentages.

Figures 4 and 5 show the estimated estimated stiffness changes suggested by the models as well as the average values for the first and second lift.

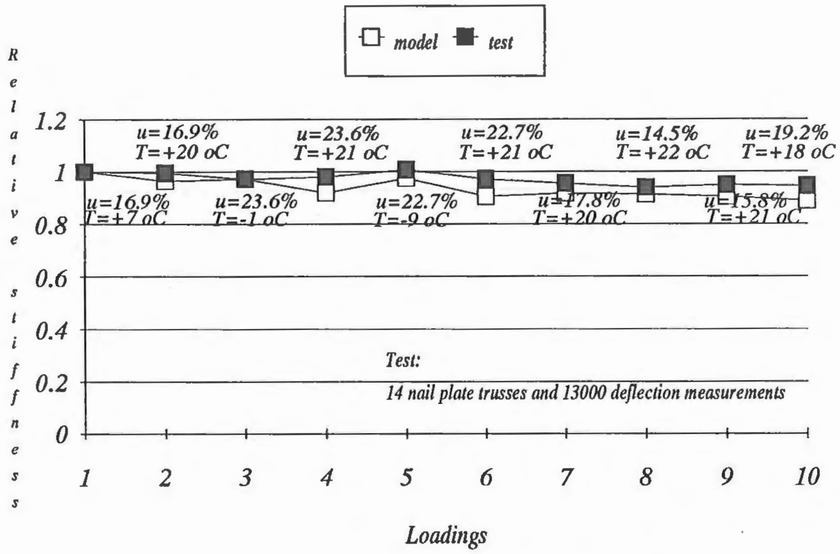

Figure 4. Average values for the change in stiffness in four different truss series and the estimates suggested by the model for the first lift.

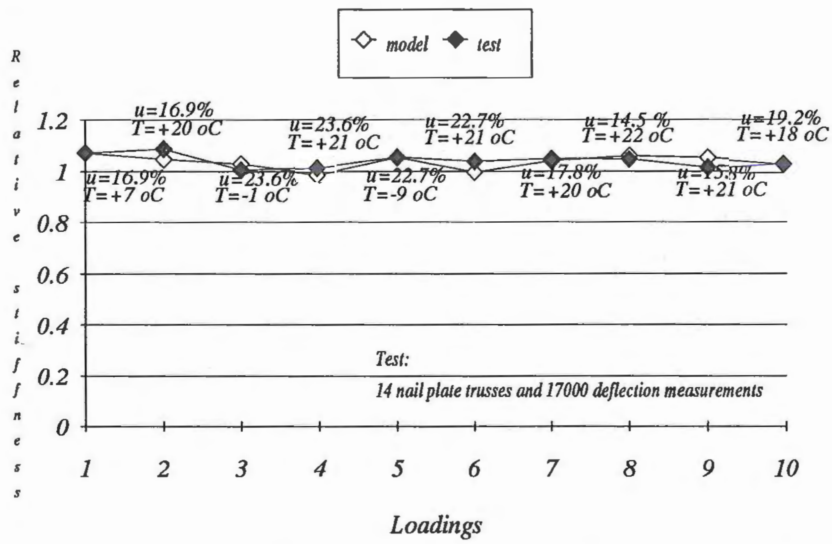

Figure 5. Average values for the change in stiffness in four different truss series and the estimates suggested by the model for the second lift.

LONG-TERM STIFFNESS OF WOODEN STRUCTURES

There are conceptual inconsistencies in the definitions of creep, as relative creep is treated either as a ratio of the deformation increase to the instantaneous deformation or as a ratio of the total to instantaneous deformation. The creep values presented hereinafter have been selected in accordance with design instructions of the Building Code of Finland and the relative creeps or creep factors are the ratio of deformation at time t_n to the instantaneous deformation at the beginning of the loading, i.e. $v(t_n)/v(t_0)$.

LONG-TERM STIFFNESS OF NAIL PLATE JOINTS

The following observations were made in the tests on the joints:

- The creep of rotation in joints subjected to constant loading were much lower in constant humidity conditions than in variable humidity. Changes in moisture content have a greater effect on the long-term stiffness of the nail plate than load duration in constant conditions. The average creep in test series A41 - A78 was **6.05** after the 9th 35 - 90 % RH moisture cycle and a loading period of 7 342 hours, **1.97** for test series B41 - B74 in a constant 35 % RH and after a loading period of 9 572 hours, and **2.42** for test series C41 - C74 in a constant 90 % RH and after a loading period of 9 267 hours.
- About 32 % of the relative creep developed during the first week and 58 % during the first 1.5 months.
- The relative creep of the joints increased during both adsorption and desorption.
- The 90 % RH constant humidity tests on joints did not stabilize as did the 35 % RH tests, since minor fluctuations in humidity occurred continuously in the 90 % RH test condition.
- The average ratio of the ultimate moment of unloaded test specimens to that of the loaded specimens in test series C4 - C7 was 0.96. Small creeps developing in constant humidity conditions do not affect the ultimate capacity, whereas the large creeps which developed in the variable humidity test series reduced the ultimate capacity of contact test specimens. In test series A5 - A6 carried out in variable humidity conditions, the average ratio of the ultimate moment of unloaded test specimens to that of loaded specimens was 1.16.

Table 1 shows a summary of the relative creep of rotation in variable humidity 90 - 35 % RH test series A2 - A3, variable humidity 35 - 90 % RH test series A4 - A7, constant humidity 35 % RH test series B4 - B7 and constant humidity 90 % RH test series C4 - C7.

Table 1. Creep of series A2 - A7, B4 - B7 and C4 - C7. The size of nail plate was in series A2 - A3 75 x 196 mm2 and series A4 - C7 60 x 150 mm2; the loading was either 50 % allowable bending load or 100 %; the size of timber was 45 x 95 mm2.

Series	Long-term (1-year)		Medium-term (1.5 months)		Short-term (1 week)		Test
	Creep	Time	Creep	Time	Creep	Time	
A2	7.21	8042 h					cyclic humidity 90-35% RH
A3	5.53						
A4	7.43	7342 h					cyclic humidity 35-90% RH
A5	7.04						
A6	5.56						
A7	4.16						
B4	2.16	9572 h	1.68	1080 h	1.36	168 h	constant humidity 35% RH
B5	1.95		1.59		1.31		
B6	1.81		1.51		1.27		
B7	1.94		1.57		1.33		
C4	2.9	9267 h	1.97	1080 h	1.53	168 h	constant humidity 90% RH
C5	2.00		1.58		1.35		
C6	2.33		1.73		1.44		
C7	2.45		1.79		1.46		

Three models were used in this study for the relative creep of joints: model 1 is an experimental viscoelastic model frequently used in creep research, while models 2 and 3 are derived from joint models which incorporate a mechanosorptive term.

Model 1 is of the form

$$\phi(t_n)/\phi_0 = 1 + V\, t_n^{\,d} \tag{4}$$

Use of joint model 1 is restricted to the specific loading test, as the moisture content fluctuations are included in the time-dependent term. The power index values for model 1 were selected to ensure that they would be suitable for design instructions, which also means that they must be presentable in the form of simple fractions.

As it was found that a change in moisture content increased joint slips during both adsorption and desorption, a mechanosorptive term for the effects of moisture content fluctuations was added to the model for the applications explained below. An additional feature of the mechanosorptive term is that the timber behaved exceptionally during the first adsorption period; this was taken into account by introducing a separate mechanosorptive term to describe the first adsorption cycle.

Model 2 is of the form

$$\phi(t_n)/\phi_0 = 1 + V\, t_n^{\,d} + M_1 \mid du_{max} \mid + \sum_{i=2}^{n} M\, |du(t_i - t_{i-1})| \qquad (5)$$

The viscoelastic term is the same as in model 1. Term $\mid du_{max} \mid$ describes the range of extreme values recorded during the test.

The terms in model 2 are natural since the relative creep due to medium-term loading is modelled using the viscoelastic and mechanosorptive term and creep due to long-term loading using mainly the mechanosorptive term. Humidity fluctuations in service conditions are a significant factor in the creep of joints, and the role of these fluctuations is underlined in long-term loading.

The effect of the viscoelastic term on the creep of a joint is small at long-term loading values. The creep of joints clearly exhibits a two-stage development, emphasizing the role of the creep of deformations due to large local stresses. Similarly, the mechanosorptive creep due to moisture content differences becomes more pronounced over a longer period.

Model 3 is derived from model 2, with the viscoelastic term explained by moisture content fluctuations. This model also places greater emphasis on the role of first moisture content change than does model 2, because the effect of the viscoelastic term in model 2 is explained by moisture content variation taking place at the beginning of the loading.

Model 3 is of the form

$$\phi(t_n)/\phi_0 = 1 + MN_1 \mid du_{max} \mid + \sum_{i=2}^{n} MN\, |du(t_i - t_{i-1})| \qquad (6)$$

Model 3 only incorporates terms dependent on change in moisture content, and emphasizes the importance of service conditions with respect to the creep of joints. The method of measuring the moisture content of timber, the time step and the magnitude of the mechanosorptive term are interrelated, meaning that a wider use of the mechanosorptive joint model, e.g. in design instructions, would require standardization of moisture content measurements.

The new type of mechanosorptive creep models 2 and 3 developed for nail plate joints describe well the creep behaviour of the joints tested in variable humidity conditions. Model 2 included both a viscoelastic and a mechanosorptive term that takes account of the minor humidity fluctuations that occur in "constant" humidity conditions. The mechanosorptive term for constant humidity tests explained most of the increase in relative creep at time values beyond the medium-term loading period.

Figures 6 to 9 provide a summary of the average measured creep values and model 2 estimates for nail plate joints in constant and variable humidity conditions.

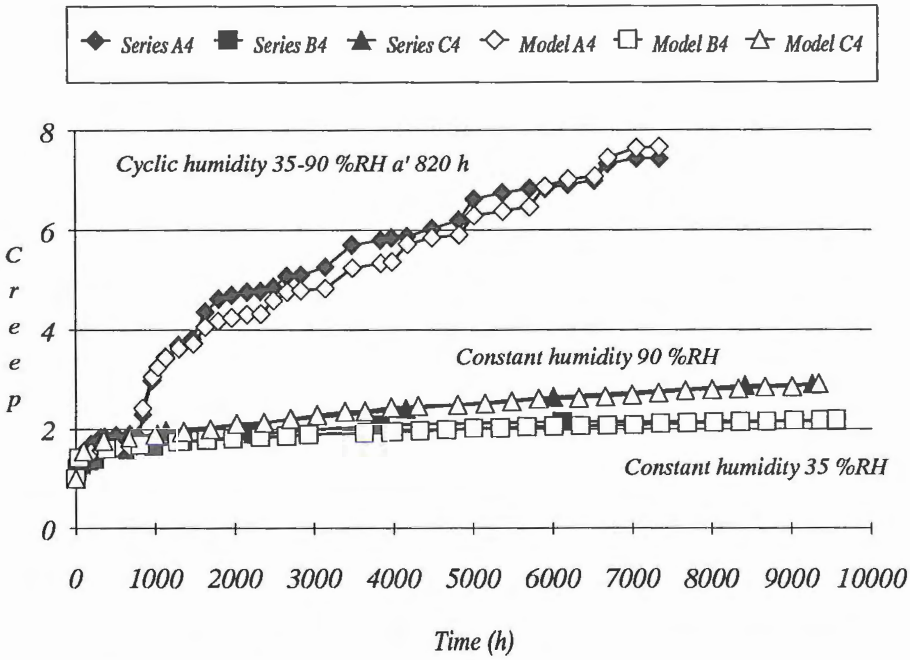

Figure 6. Average measured creep values in test series A4, B4 and C4 (3 mm gap and 50 % loading) and model 2 estimates.

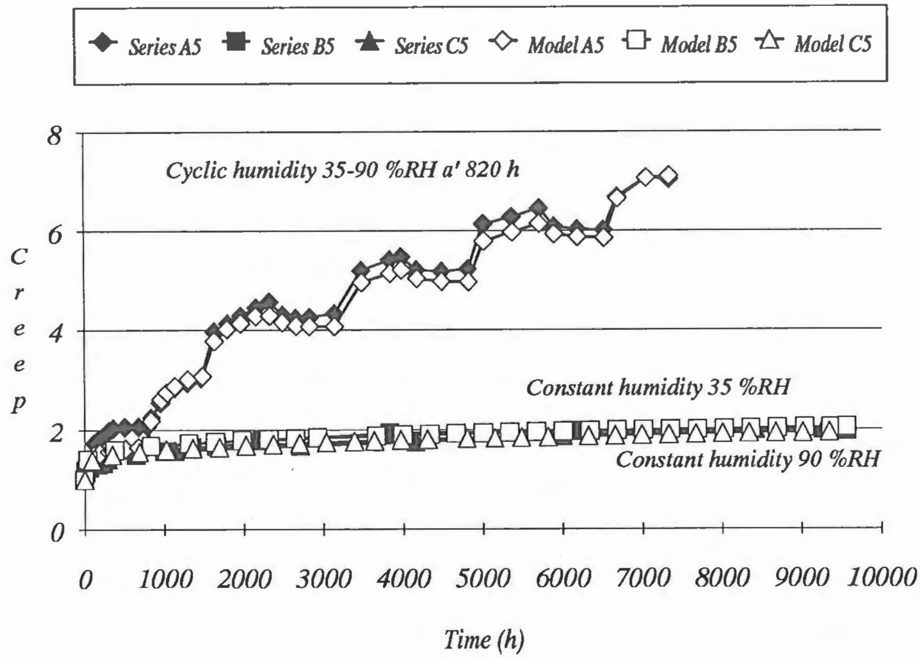

Figure 7. Average measured creep values in test series A5, B5 and C5 (0 mm gap and 50 % loading) and model 2 estimates.

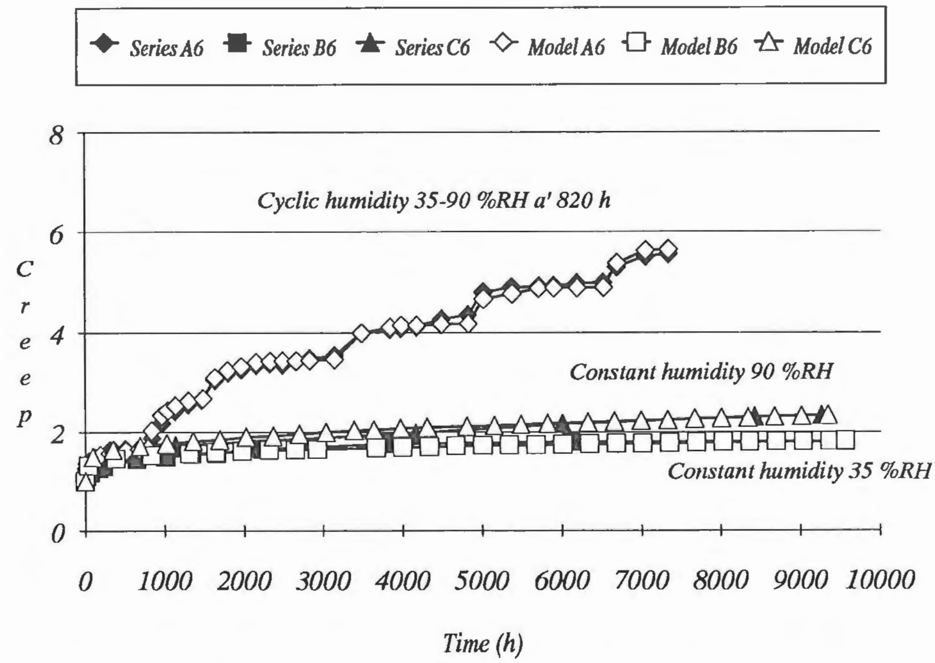

Figure 8. Average measured creep values in test series A6, B6 and C6 (0 mm gap and 100 % loading) and model 2 estimates.

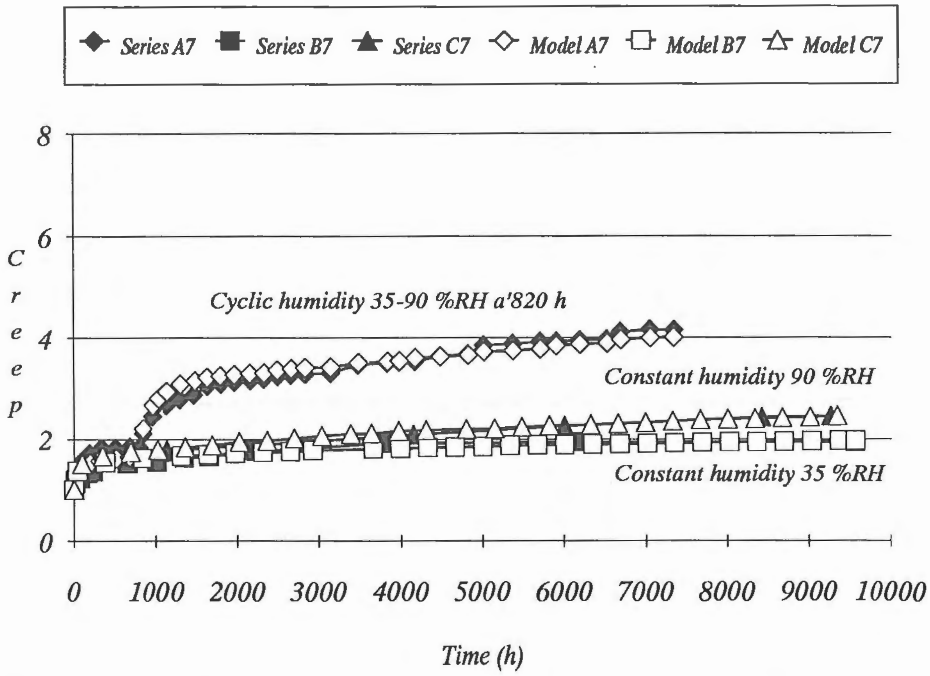

Figure 9. Average measured creep values in test series A7, B7 and C7 (3 mm gap and 100 % loading) and model 2 estimates.

LONG-TERM STIFFNESS OF SAWN TIMBER

The following observations were made in the tests on sawn timber:

- The average relative creep for sawn timber specimens A1 - A18 after 10 moisture cycles of 90 to 35 % RH and a loading period of 8 038 hours was **2.20**. For test specimens B1 - B14 at a constant humidity of 35 % RH and after a loading period of 9 576 h it was **1.44**, and for test specimens C1 - C14 at a constant humidity of 90 % RH and after a loading period of 9 263 hours **1.33**.
- The relative creeps in the test series at different loading levels were equal. Creep was linear with respect to the load acting on the structures, in other words, the greater the elastic slip, the greater the increase in slip due to creep.
- Humidity fluctuations had a clear effect on the relative creep of sawn timber, although such an effect was greater in nail plate joints. The creep of specimens tested at a constant humidity of 90 % RH was lower than at a constant humidity of 35 % RH, because the specimens tested in the more humid environment were treated with a moisture inhibitor, which retarded the effect of the change in relative humidity on the moisture content of the sawn timber.

- The moisture deformations of sawn timber on the compression and tension sides were different and this observation supports the model suggested by other researchers, i.e. that moisture deformation is a function of both moisture content difference and stress.
- Relative creep took place in tension side during the cycles because the strain developing during desorption was smaller than the strain developed during adsorption. On the compression side, the strain was more or less equal during adsorption and desorption.

Table 2 provides a summary of the relative creeps of rotation calculated from the strain in cyclic 90 - 35 % RH test series A0 - A1, constant 35 % RH series B0 and B1, and constant 90 % RH series C0 - C1.

Table 2. The relative creeps of series A0 - A1, B0 - B1 and C0 - C1. The size of timber 45 x 95 mm2 and the loading either 50 % or 100 % of allowable bending load.

Series	Long-term (1 year)		Medium-term (1.5 months)		Short-term (1 week)		Test
	Creep	Time	Creep	Time	Creep	Time	
A0	2.19	8038 h					cyclic humidity 90-35% RH
A1	2.20						
B0	1.45	9576 h	1.30	1080 h	1.13	168 h	constant humidity 35% RH
B1	1.43		1.3		1.13		
C0	1.35	9263 h	1.14	1080 h	1.06	168 h	constant humidity 90% RH
C1	1.31		1.1		1.05		

Three models were used during the course this study to describe the relative creep of sawn timber: model 1 is an experimental viscoelastic model, while models 2 and 3 are based on mechanosorptive creep models presented in the literature.

Model 1 is of the form

$$v(t_n)/v_0 = 1 + V\, t_n^{\,d} \tag{7}$$

Creep models 2 and 3 were fitted to the strains in the upper and lower surfaces of a deflected beam in variable humidity and at constant temperature. Changes in bending stiffness are taken into account using formula (2) and differences in the moisture behaviour of the compression and tension sides with the aid of the strain-induced moisture deformation coefficient. Moreover, the following model takes account of the exceptional behaviour of the mechanosorptive term during the first change in moisture content.

Model 2 is of the form

$$\varepsilon(t_n) = \varepsilon_0 \, ((EI)_{u0} \, h_{un})/((EI)_{un} \, h_{u0}) \, (1 + V \, t_n^{\,d}) \qquad (8)$$

$$+ (\alpha(\varepsilon) + m_1 \, \sigma) \, du(t_1 - t_0) + \sum_{i=2}^{n} (\alpha(\varepsilon) + m^{-+} \, \sigma) \, du(t_i - t_{i-1})$$

The unit of time t is (h) and that of moisture content u (%). Model 2 was fitted to the creep of the strains in the variable humidity test series. Model 3 is derived from model 2, with the viscoelastic term explained by moisture content fluctuations. This model also places greater emphasis on the role of first moisture content change than does model 2, because the effect of the viscoelastic term in model 2 is explained by moisture content variation taking place at the beginning of the loading.

Model 3 is of the form

$$\varepsilon(t_n) = \varepsilon_0 \, ((EI)_{u0} \, h_{un})/((EI)_{un} \, h_{u0}) \qquad (9)$$

$$+ (\alpha(\varepsilon) + m_1 \, \sigma) \, du(t_1 - t_0) + \sum_{i=2}^{n} (\alpha(\varepsilon) + m^{-+} \, \sigma) \, du(t_i - t_{i-1})$$

The unit of moisture u is (%). Model 3 was fitted to the relative creeps of strains in the variable humidity test series.

Figures 10 and 11 provide a summary of the average measurements for loaded sawn timber test specimens in variable and constant humidity, as well as the creep estimates calculated using models 1 and 2. Model 1 provides the estimated values for the constant humidity test series and model 2 for the variable humidity tests.

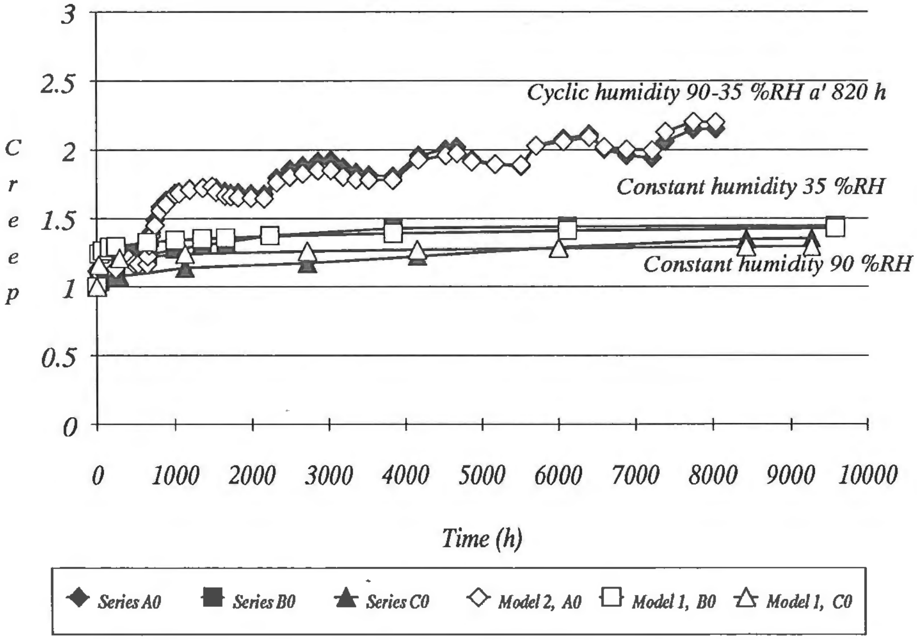

Figure 10. Average relative creeps in test series A0, B0 and C0 (the size of timber 45 x 95 mm2 nad 100 % of allowable bending load) as well as values estimated using models 1 and 2.

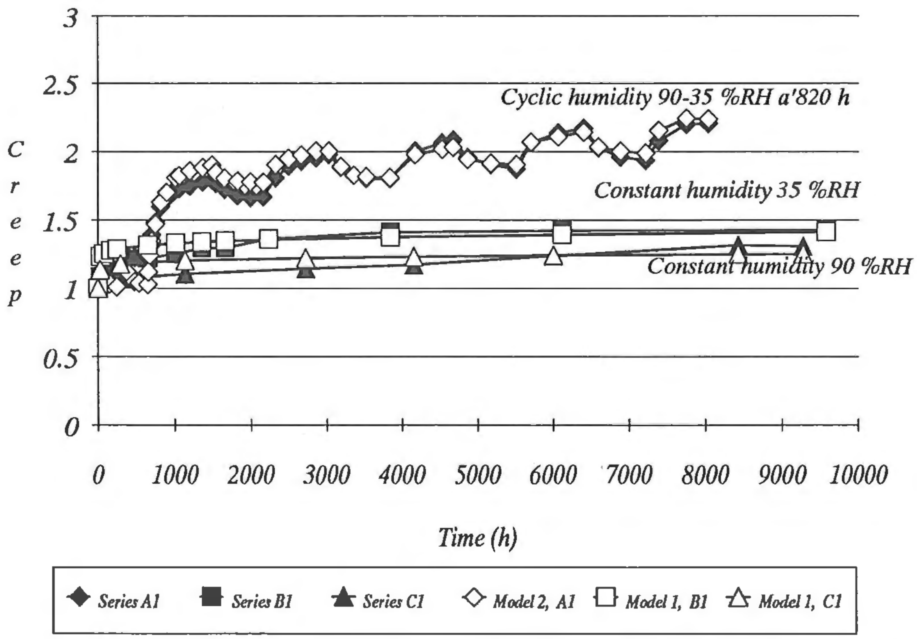

Figure 11. Average relative creeps in test series A1, B1 and C1 (the size of timber 45 x 95 mm2 and 50 % loading of allowable bending load) as well as values estimated by models 1 and 2.

LONG-TERM STIFFNESS OF NAIL PLATE TRUSSES

The following observations were made in the truss tests:

- The creep of the trusses developed in two stages during a period of one year. In the first stage, the relative creep increased logarithmically and then stabilized at the end of the medium-term loading period (about 1.5 months). In the second stage, a new logarithmically increasing creep occurred after a period of relative stability, stabilizing once again before the one-year loading period was over.
- At the end of the first stage, i.e. the medium-term loading period, the average relative creep of the trusses was 1.22. In the second stage, the moisture content of the timber used in the trusses fell. The creep in the second stage was mainly due to the changed service conditions. The relative creep stabilized towards the end of the long-term loading period, the final average value being 1.55.
- The relative creeps in the truss test series are equally large. Neither the arrangement of the timbers in the truss nor the surface areas of the joints had any significant effect on the creep.

Creep tests performed on the joints and sawn timber made it possible to explain the mechanosorptive behaviour of the nail plate trusses in VTT's test house which were subjected to loading for a period of one year. In constant humidity conditions, the relative creep of trusses stabilized at a value of 1.22 during medium-term loading. The creep consisted mainly of the viscoelastic, time-dependent creep of the nail plate joints and sawn timber.

A clear jump in the creep to 1.55 took place when the sawn timber was drying, the creep of both joints and sawn timber increased during desorption. Most of the change in creep can be explained by the creep of joints. The creep of the nail plate trusses stabilized during adsorption. The creep consisted of an increase in the creep of nail plate joints with gaps and a reduction in the creep of contact joints and sawn timber. According to the mechanosorptive model, moisture deformation of a member under compression is greater than that of a member under tension. Truss deflection increases as the axial deformation of the upper chord increases more than that of the lower chord during desorption. Conversely, the deflection is reduced during adsorption.

Two models were used in the study to describe the relative creep of nail plate trusses: model 1 is a frequently used viscoelastic creep model employing a power function, while model 2 is a newly derived mechanosorptive creep model for nail plate trusses.

Any computational model intended for use in the design of nail plate trusses should be clear-cut and easy to use. The viscoelastic creep model is easy to use and its application to the evaluation of the creep due to snow loading is justified because the service conditions during the medium-term snow loading are relatively constant. The following model is highly suitable for evaluating the medium-term creep of nail plate trusses.

Model 1 is of the form

$$v(t_n)/v(0) = 1 + 0.065\, t^{1/6} \tag{10}$$

The unit of time t is (h).

Any estimate of the creep of nail plate trusses subjected to long-term loading should take account of the effects of humidity fluctuations. Mechanosorptive model 2 for joints and sawn timber can be used to model the creep of nail plate trusses when the contributions of both components are weighted by their effect on the stiffness of the entire structure. The only model incorporated into creep model 2 for nail plate trusses was creep model 2 for joints.

Prior to the installation of the snow load, the nail plate trusses in the test house were subjected to dead-weight loading for a period of two years. This type of load can be considered as equivalent to actual service conditions because the design snow load does not occur every year. Joint slip accounted for 30 % of total deflection, while the remainder was due to the deformation of the sawn timber. Because of the loading history of the nail plate trusses, the coefficients of the mechanosorptive term obtained in the joint tests were simplified.

Model 2 is then of the form

$$v(t_n)/v_0 = 1 + 0.050\, t_n^{1/6} + 2.4\mathrm{x}10^{-2}/\%\, |du_{max}| + \sum_{i=2}^{n} 1.7\mathrm{x}10^{-2}/\%\, |du(t_i - t_{i-1})| \tag{11}$$

The unit of time t is (h), and that of moisture u (%). In addition to the first change in humidity, term $|du_{max}|$ describes the maximum moisture content difference during loading.

Figure 12 shows creep models 1 and 2 as well as the average creep curve. The purpose of creep model 1 is to describe creep in medium-term loading, or during the first 50 days. The curve of model 1 in Figure 12 has been extended to encompass the entire one-year loading period to illustrate its unsuitability for long-term loading.

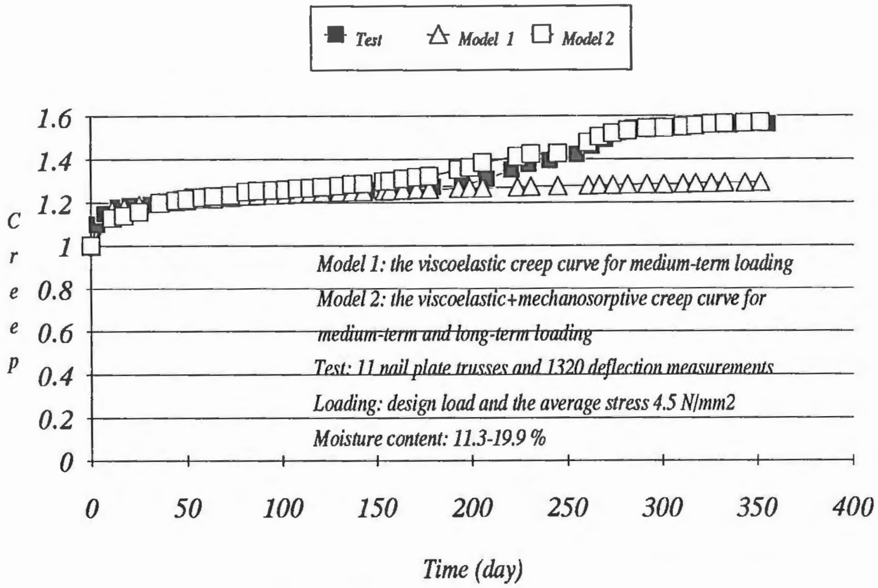

Figure 12. Creep models 1 and 2 as well as the average creep curve for the tested nail plate trusses.

CONCLUSIONS

Change in the instantaneous stiffness of nail plate joints can be modelled according to number of loading cycles, moisture content differences and temperature differences..

The change in the instantaneous stiffness of sawn timber is smaller than the change in the modulus of elasticity used for design purposes. The elastic properties of the cross-section diminish and the area and moment of inertia increase during desorption, in which case the change in the axial and bending stiffness is not as great as the change in the modulus of elasticity. The stiffness of the cross-section can be modelled by taking account of cross-sectional moisture deformations.

The instantaneous stiffness of nail plate trusses can be modelled with the aid of the truss components: the nail plate joint and sawn timber. The contribution of these components to the overall truss deformation is weighted by the magnitude of their effects.

The performed creep tests underline the importance of the stability of the constant humidity test condition, because even small fluctuations in the constant conditions lead to the occurrence of mechanosorptive creep. This observation complicates the analysis of tests carried out by other researchers in those cases where accurate measurements of the test conditions are not available.

Variations in humidity have a greater effect than time does on the creep of the nail plate joint. Joint creep in both constant and variable humidity can be described by means of mechanosorptive models.

The different creep behaviours on the compression and tension side of a sawn timber beam result in mechanosorptive creep of the structure. The different mechanosorptive features of the compression and tension side can be modelled naturally with the aid of a moisture deformation coefficient that is a function of the strain. The creeps of sawn timber in constant conditions are considerably smaller than in variable humidity, and constant humidity creeps can be estimated using experimentally determined creep models based on a power function.

The long-term behaviour of nail plate trusses in variable humidity was similar to that of the nail plate joints, and the mechanosorptive creep of such trusses can be modelled solely by means of the joint model. An easy-to-use power function is suitable for estimating the creep due to medium-term loading.

REFERENCES

Anon. 1983. The Building Code of Finland. B10: Wooden structures, Instructions. Helsinki, Ministry of the Interior, 3 p. (In Finnish).

Anon. 1987. Wood Handbook: Wood as an engineering material. Agric. Handb. 72. Washington DC, U.S.D.o.A, Forest Products Laboratory. 466 p.

Bazant, Z. P. 1985. Constitutive equation of wood at variable humidity and temperature. Wood Science and Technology 19, pp. 159 - 177.

Bodig, J. & Jayne, B. A. 1982. Mechanics of wood and wood composites. New York, Van Nostrand Reinhold Company Inc. 699 p.

Feldborg, T. & Johansen, M. 1987. Slip in joints under long-term loading. Dublin, Structural Division CIB-W18/20-7-2. 10 p.

Feldborg, T. 1989. Timber joints in tension and nails in withdrawal under long-term loading and alternating humidity. Forest Products Journal, December. Pp. 8 - 12.

Hearmon, R. & Paton, J. 1964. Moisture content changes and creep of wood. Forest Products Journal, August, pp. 357 - 359.

Hunt, D. G. & Shelton, C. F. 1988. Longitudinal moisture-shrinkage coefficients of softwood at the mechano-sorptive creep limit. Wood Science and Technology 22, pp. 199 - 210.

Illston, J. et al. 1979. Concrete, timber and metals. New York, Van Nostrand Reinhold Company Inc. 663 p.

Kollman, F. & Cote, W. 1968. Principles of wood science and technology I, Solid wood. Heidelberg, Springer-Verlag Berlin. 592 p.

Mohager, S. 1987. Studies on the creep of wood. Stockholm, The Royal Technical University of Stockholm. 139 p. (In Swedish).

Mårtensson, A. 1988. Interaction between moisture and stress in wooden materials. Lund, Lund Institute of Technology, Report TVSM - 3011. 97 p.

Norén, B. 1968. Nailed joints - their strength and rigidity under short-term and long-term loading. Stockholm, The National Swedish Institute for Building Research, Report 22. 77 p.

Ranta-Maunus, A. 1975. The viscoelasticity of wood at varying moisture content. Wood Science and Technology 9, pp. 189 - 205.

Ranta-Maunus, A. 1989. Analysis method for creep of timber beams. Espoo, The Mechanics of Structures 22, 1, pp. 13 - 30.

Saarelainen, U. 1981. Wood constructions 1. Wood material. Helsinki, Wood Information Association. 62 p. (In Finnish).

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