TEKNISK RAPPORT • TECHNICAL REPORT

325 • 1994

ISSN 0908-3871

CREEP AND TIME TO FAILURE OF LAMINATED VENEER LUMBER MADE OF SITKA SPRUCE

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Preface

This report summarises the work carried out in fulfilment of Sub-Task 5.2, Section 4 of the EC-Forest project no. MA2B-CT91-0034 entitled “Laminated Lumber Veneer From European Species”. A full report including all test results is available (Vestergaard 1994). The present report contains some information regarding the results from the preceeding Sections 1-3 of the same sub-task. A full report of these sections is also available (Hansen 1993). The research reported has relations to a forthcoming AIR project on duration of load studies. Without jeopardising the present investigation the project was designed to also form a link to this AIR project, for which reason general advise regarding the carrying out of duration of load tests is included.

Abstract

A study of the duration of load and creep properties of 90 beams of laminated veneer lumber (LVL) is presented. 72 beams are experimental LVL of Scottish grown sitka spruce, while the remainder 18 beams are standard LVL beams (Kerto) which were included for reasons of comparison. 55 special designed test rigs were used for the long-term bending tests.

Creep and time to failure data were registered and discussed. No significant mechano-sorptive effect was demonstrated for creep or time to failure. The two parameters of the power creep function are assessed and discussed. A prediction of lifetime based on a fracture mechanics model is attempted. The results from a short-term bending test conducted on the surviving long-term bending test specimens are reported and discussed. The k_{def} and k_{mod} factors related to Eurocode 5 are assessed. Finally, advice and experience gained during the test period are discussed.

1 Introduction

Building Material Laboratory (LBM) is a partner in the EC Forest Programme "Laminated Veneer Lumber From European Species", which has the objective to demonstrate the technical and economic benefit and viability of manufacturing Laminated Veneer Lumber (LVL) using fast growing wood within the Community, that is species, which are abundant and whose resources are being maintained and developed.

French-grown poplar and Scottish-grown sitka spruce were used to manufacture experimental LVL on a commercial scale. In addition, Irish-grown sitka spruce, Danish-grown sitka spruce and French-grown maritime pine were used to manufacture LVL on a Laboratory scale.

The two other partners in the project are Timber Research and Development Association (TRADA), U.K. and Centre Technique du Bois et de l'Ameublement, France.

LBM is responsible for a number of research tasks in the Forest Programme including subtask 5.2 - Creep and Duration of Load Influences - the objective of which is to assess the creep and duration of load behaviour of experimental LVL (Scottish sitka spruce) in comparison with standard LVL (Kerto). Special emphasis is to be placed on the influence of moisture. For a more detailed description reference is made to the Technical Annex of (Vestergaard 1994).

Prior to the present work LBM has carried out the following experiments of subtask 5.2 (Hansen 1993):

1. Modulus of Elasticity (MOE) has been established for each test specimen.

2. Selected groups of specimens were taken to bending failure in a standard short term test.

3. The remaining specimens were tested in a bending creep test at a load within the design range for half a year. The creep parameters of the power law were established for each specimen. Certain groups were tested at 10% moisture content (mc), other at 20 % mc and further groups at a mc varying between 10% and 20%.

The remaining experiments in subtask 5.2, and therefore the main research task for the present work, is:

4. The specimens need to be tested to failure in a duration of load experiment including creep measurements, in the same groups, as mentioned in section 3, with moisture levels at 10%, 20% and varying moisture content.

LBM is also a partner in the EC-AIR project "Duration of Load Effect on Different Sized Beams", which has the objective to establish a new scientific basis for determination of long term performance of reconstituted timber, including glulam and laminated veneer lumber, under load with a duration of a few months. The experiments are planned to start August 1994. This information is needed for the

verification or correction of Eurocode 5, as there is uncertainty regarding the correct value of the long term design stresses for different sized beams.
The AIR project introduces a new loading procedure, in which the load is applied gradually in steps. The first load is chosen low enough to secure that no specimens fail during the first step. This step is included to ensure a simulation of the period of stress peak relaxation taking place during normal periods of relatively high loads, which still causes no failures. LBM was interested in testing this new stepwise loading test procedure, and therefore it was implemented in section 4 of subtask 5.2.

The primary scope of the present work - A determination of k_{mod} and prediction of time to failure on the basis of duration of load test including creep measurements, on experimental LVL (Scottish sitka) and standard LVL (Kerto).

A secondary scope - Testing the Air project test procedure.

2 Background

2.1 Duration of Load

Wood under load looses a significant amount of strength over a period of time. The strength values to be used in design of wood structures for long term permanent loads are approximately 60% of the strength values found in a short term laboratory test.

The background of this 0.60 modification factor originates from the late forties, where duration of load experiments were carried out at the Forest Products Laboratory in Madison, Wisconsin. On the basis of tests on small clear specimens subjected to bending for up to seven years, a stress-lifetime relationship was established, which predicted the 10-years strength to be about 60% of the short term strength. This was termed "the Madison curve" and is illustrated in Figure 1 in a plot of stress level against log time to failure, where stress level is the actual long term load over estimated short term failure load.

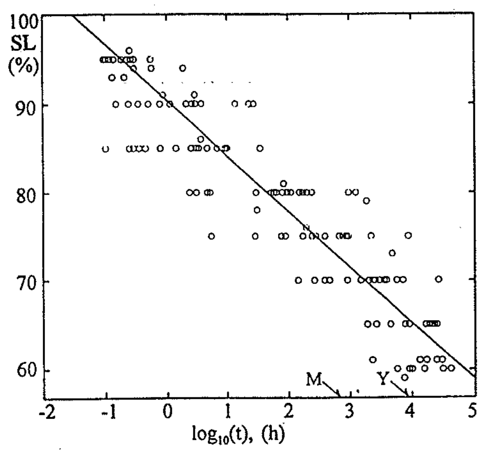

Figure 1. Stress Level (SL,%) as a function of logarithmic time to failure (hours) for small clear specimens subjected to bending (Wood 1951). Y=one year, M=1 month

These first duration of load (DOL) tests on clear specimens were regarded as being valid also for structural timber in spite of the fact that the failure mechanism for structural timber with knots, inclined grain and fissures is quite different from that of clear wood. More than 15 years ago University of British Columbia, Canada commenced DOL tests on structural timber and the preliminary results indicated a much less severe duration of load factor for timber. However, a large number of DOL tests on structural timber have since been carried out both in North America and Europe, and from these it can be concluded that there is no significant evidence for a much less severe modification factor for timber than for clear wood.

Most countries have included this modification factor in their timber design code including the Eurocode 5. In the proposed Eurocode the modification factor k_{mod} is not only reflecting the load duration effect but also including the effect of the relative humidity of the environment.

2.2 The Influence of Moisture Content on Time to Failure

Moisture content has a significant influence on the duration of load behaviour. At the same stress level, beams at high moisture content live shorter than beams at low moisture content (Hoffmeyer 1990). Moisture variation is also known to shorten the time to failure of timber, due to the so-called mechanosorptive effect (Hoffmeyer 1990).

An example of these effects of moisture on DOL behaviour is shown in Figure 2, where results from Hoffmeyer (1990) have been up-dated to cover almost 8 years of load duration (Hoffmeyer 1994). 400 beams of spruce were subjected to bending at constant and varying moisture content. The results indicated a lifetime at the 60% stress level of ½ year, 4 years and 30 years for beams of varying moisture content, 20% moisture content and 10% moisture content respectively. The "Madison curve" predicts a corresponding lifetime of 5 years.

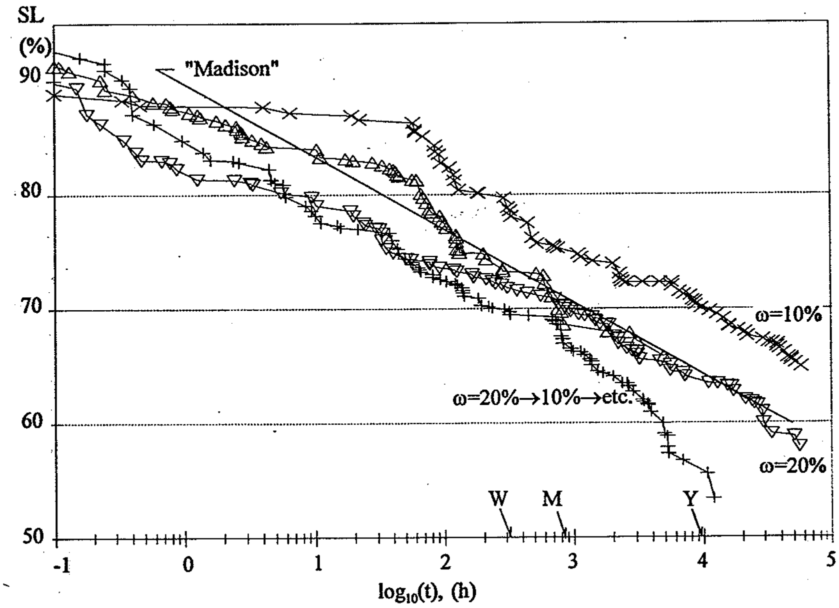

Figure 2. Stress level (%) against logarithmic time to failure (hours) for 50x100mm beams of spruce (Picea abies) subjected to bending at ω=10%, ω=20% and at ω cycling between 10% and 20%. Y=one year, M=one month, W=one week (Hoffmeyer 1994).

2.3 Modelling of Time to Failure

In the present study the time to failure is modelled by a simple fracture mechanics model, which merely uses the elastic-viscoelastic analogy to substitute Youngs modulus by a time dependent modulus. A more detailed description is found in Section 5.1.2.4.

2.4 Creep and Creep Modelling

Creep is defined as the time dependent deformation (strain, deflection or curvature) in a viscous elastic material subjected to a stress σ. In this paragraph creep will be illustrated by using strain as time dependent deformation.

The total strain $\varepsilon(t)$ consists of the following components (Figure 3):

- instantaneous elastic strain ε_i
- delayed elastic strain ε_r, which is recoverable
- viscous strain ε_p, which is irrecoverable

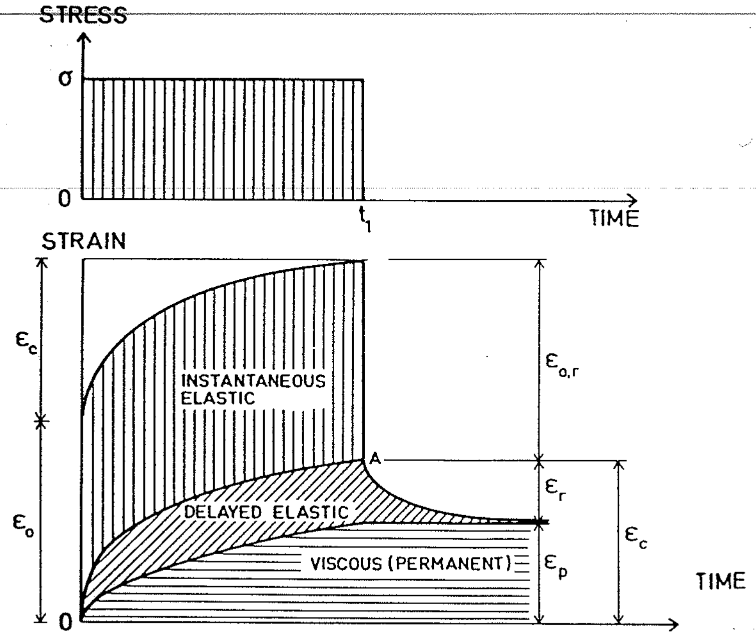

Figure 3. Stress-strain-time diagram for a viscoelastic material (Nielsen 1972).

As shown in Figure 3 the instantaneous elastic strain appears with a constant value immediately upon application of load and is in phase with the stress period, whereas delayed elastic strain and viscous strain exhibit time dependent strain. The time dependent strain ($\varepsilon_r + \varepsilon_p$) is termed creep, ε_c, thus:

$$\varepsilon(t) = \varepsilon_i + \varepsilon_r + \varepsilon_p = \varepsilon_i + \varepsilon_c \quad (1)$$

Equation (1) may be expressed:

$$\varepsilon(t) = \varepsilon_i\,[1 + \phi(t)] = \varepsilon_i\,c(t) \quad (2)$$

where

$c(t) = \varepsilon(t)/\varepsilon_i$ is the normalized creep function
$\phi(t) = \varepsilon_c/\varepsilon_i$ is the creep factor

Many mathematical expressions have been proposed to describe the time dependence of creep in wood, however, the expression most frequently used is the power function (Clouser 1959):

$$\phi(t) = a \cdot t^{b} \quad (3)$$

where

t is time
b is a dimensionless material parameter
a is a material parameter with a dimension of time to the power -b

Alternatively Nielsen (1984) expressed equation (3) by using the doubling time τ:

$$\phi(t) = [t/\tau]^{b} \qquad (4)$$

where $\tau = a^{-(1/b)}$

τ is referred to as the doubling time, due to the fact, that τ is the time at which the total strain has doubled relative to the initial strain.

τ and b can be estimated easily by transforming the power creep function into a straight line in a log-log plot (Figure 4):

$$\log_{10}\phi(t) = -b\log_{10}\tau + b\log_{10}t \qquad (5)$$

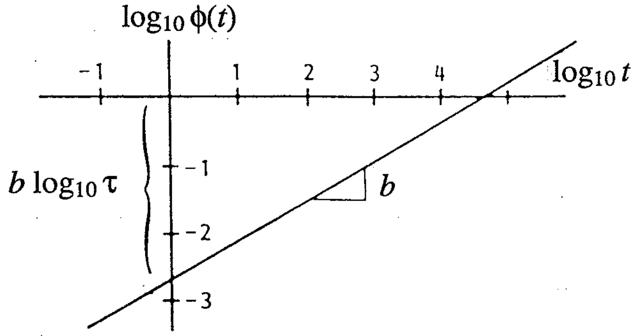

Figure 4. The power creep function $\phi(t)$ transformed into a log-log plot.

2.5 The Influence of Moisture Content on Creep

Moisture variation is known to increase creep in wood (Armstrong and Kingston 1960). This effect was termed mechanosorptive since it is only visible during simultaneous mechanical stress and moisture sorption. An illustration of the influence of varying moisture is seen in Figure 5, which shows bending deflection of small clear specimens.

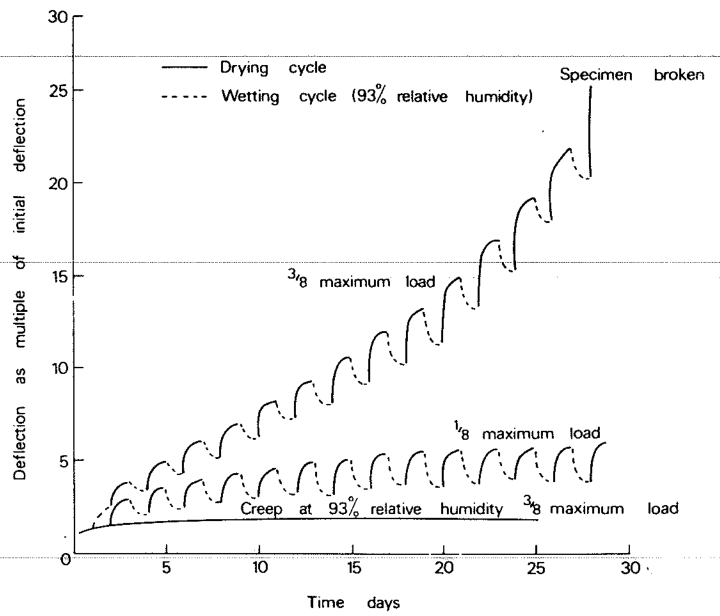

Figure 5. Mechanosorptive creep (Hearmon, Paton 1964).

The most important characteristics of mechano-sorptive effects are the following:

- Deformation increases during desorption (Armstrong, Kingston 1962).
- The first sorption step causes an increase in deformation. All following sorption steps normally cause a decrease of deformation at moderate stresses (Armstrong, Kingston 1962) and an increase of deformation at high stresses (Schniewind 1967).
- The mechanosorptive deformation is time independent and only influenced by the magnitude of moisture change below fiber saturation (Armstrong, Kingston 1962).
- Mechanosorption leads to failure in shorter time and/or lower loads (Schniewind 1967).
- The amplitude of the oscillation of the mechanosorptive creep curve tends to increase linearly with total creep (Hoffmeyer 1990).

3 Material

The material examined in subtask 5.2 is LVL made from Scottish sitka and Norway spruce (Kerto). The LVL was produced by Finnforest OY, Finland and delivered in the dimensions 45x300x6000 mm. All boards were produced from 3.2 mm thick veneers and glued with a modified phenol glue.

At LBM the boards were cut into beams with dimensions 45x95x1800 mm, as shown in Appendix A. LVL beams made from Scottish sitka spruce were numbered 1-216 and the Kerto beams 217-324.

2/3 of the beams were conditioned at 90% RH, 20 °C (group A and B according to Appendix A) and the remaining 1/3 of the beams at 55% RH, 20 °C (group C).

The modulus of elasticity (MOE) in static bending was established for all the beams in accordance with prEN 408.

The short term bending strength was determined for all odd numbered beams according to prEN 408. In order to test the quality of pair matching the even numbered beams 290-324 (Kerto 55% RH) were also tested. The beams of each pair were tested with adjacent edges in tension (Figure 6).

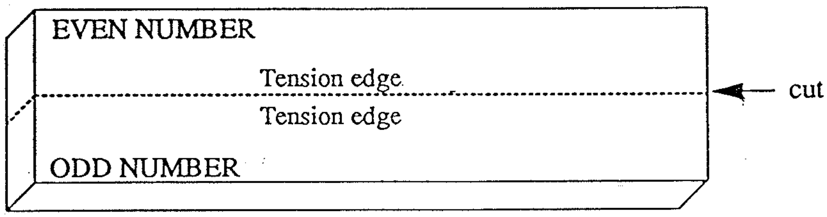

Figure 6. Matching of beams (Bardtrum, Hoffmeyer, Thøgersen, 1994).

The prediction of bending strength based on a non-destructive MOE testing demonstrated a good correlation (Figure 7), whereas an evaluation of short term strength based on pair matching showed poor correlation.

To examine the mechanosorptive creep at low stress levels, long term bending tests were carried out on the remaining even numbered beams. The stress levels were selected to 5 MPa and 15 MPa. The allocation of specimens to the different climates was as shown in Appendix B. Certain groups were tested at 55% RH ("dry"), others at 90% RH ("moist") and further groups at a RH varying between 55% and 90%.

After approximately half a year of creep testing the beams were unloaded and relaxed for a period of one to two weeks, before commencing with the long term failure tests.

Some of the results of tests completed in subtask 5.2 are shown below.

Material	MOE [GPa]			Bending strength [MPa]			Dry density [kg/m^3]			Moisture content [%]		
	No.	Mean	Std.dev.	No.	Mean	Std.dev.	No.	Mean	Std.dev.	No.	Mean	Std.dev.
Sitka 55% RH	72	12,3	0,6	36	49,0	3,9	36	450	17	36	9,9	0,3
Sitka 90% RH	142	10,5	0,6	70	37,1	2,9	70	452	31	70	19,5	0,5
Kerto 55% RH	36	13,3	0,8	36	55,5	5,2	36	463	21	36	9,6	0,6
Kerto 90% RH	72	11,6	0,5	20	40,4	1,7	25	465	16	25	19,6	0,5

Table 1. Results from short term testing (Bardtrum, Hoffmeyer, Thøgersen, 1994).

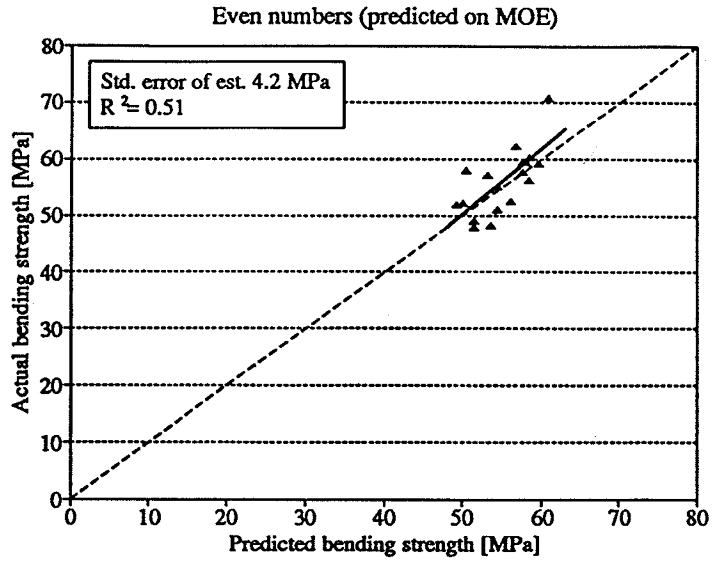

Figure 7. Actual bending strength against bending strength as predicted by MOE (Bardtrum, Hoffmeyer, Thøgersen, 1994).

Creep parameters		Scottish Sitka		Kerto	
Environment	SL [MPa]	b	Thau [days]	b	Thau [days]
55% RH	5	0,077	2E+06	-	-
	15	0,383	26000	-	-
Cyclic	5	0,400	588	0,331	1283
	15	0,575	192	0,540	224
90% RH	5	0,409	2347	-0,116	-
	15	0,389	542	0,583	2206

Table 2. Creep parameters (Hansen 1994).

4 Methods

The experimental work - in retrospect - should have been significantly reduced with respect to the number of creep measurements taken. An alternative procedure is put forward in Section 5.1.4 of this report.

4.1 Long Term Bending

The long term bending tests were carried out in three test rooms. The load was applied gradually in steps corresponding to stress levels (SL) equal to 60%, 68%, 73% and 78% of the average short term bending strength (Table 1). The stress levels for the specimens in varying moisture conditions were determined on the basis of the moist average bending strength. The Scottish sitka spruce specimens subjected to 55% RH were loaded to 68% in the first step. The criterion for establishing these stress levels were to have no specimen failure during the first load step. Each SL was maintained for 4 weeks and the increase of load was accomplished in one step. Applying the load in two steps, as suggested in the EC-AIR project, would be time consuming and furthermore make the creep readings very complicated. The first SL was maintained for 29 days and the second for 27 days (Easter holidays).

The test specimens were conditioned in accordance with subtask 5.2 of the Forest Programme, with relative humidity levels at 55%, 90% and varying RH (Appendix B). The specimens subjected to varying moisture conditions were experiencing moisture environments according to the pattern shown in Figure 8. However, the climate was changed the day after loading and not the same day as shown in Figure 8. This change in loading procedure was encountered to ensure that the specimens were subjected to equal stress and condition in the initial phase, before they are influenced by a climate change.

The specimens subjected to constant climate were sealed in 0.2 mm polyethylene tubing. The climate in the two tests rooms, in which these beams were tested, was kept at a constant at 55% RH. Within the polyethylene tubing of the moist specimens, a 0.05% Rodalon solution was injected to the bottom of the tubing at frequent intervals, in order to maintain 90% RH.

Time (days)		Moisture cycle	Remarks
0	Monday	75% → 55%	Loading and subsequent change of RH over a period of 4 hours
11	Friday	55% → 75%	RH change in 4 hours
14	Monday	75% → 90%	RH change in 4 hours
25	Friday	90% → 75%	RH change in 4 hours
28	Monday	75% → 55%	Next load level and subsequent change of RH over a period of 4 hours
etc.			

Figure 8. Variation pattern of the climate condition (EC-AIR project).

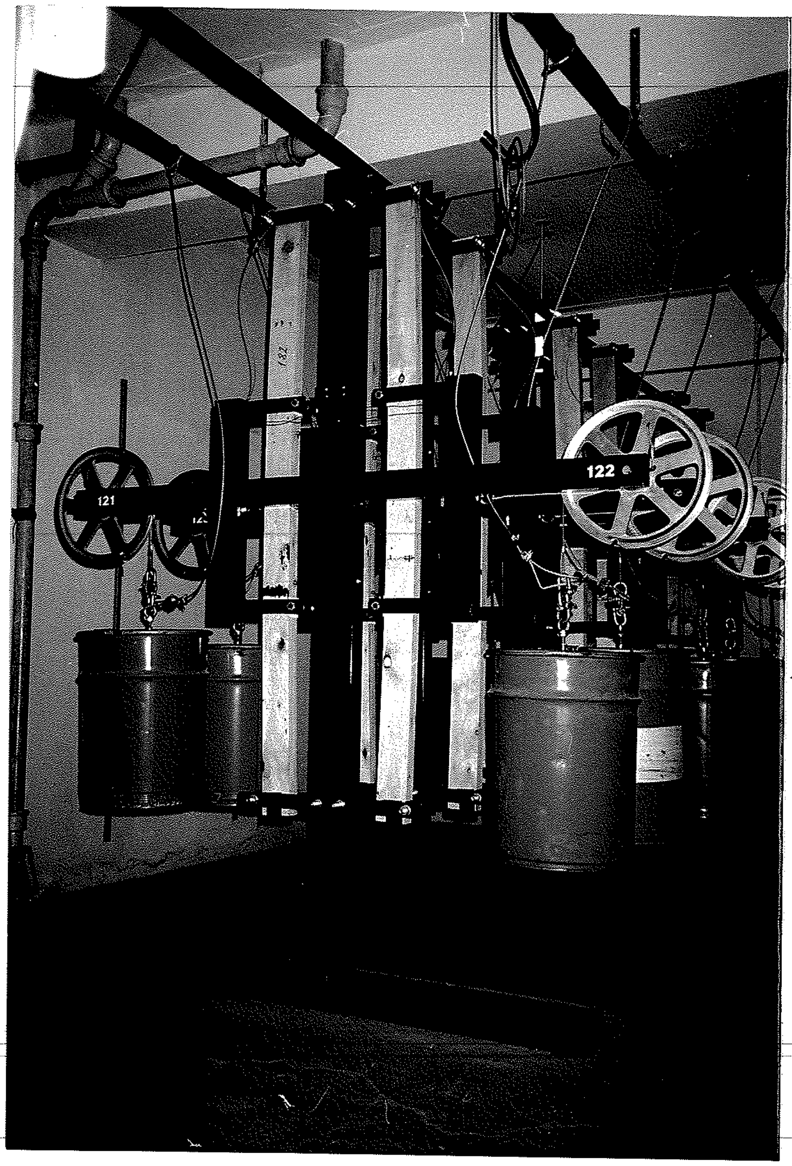

Figure 9. The long term bending test rig.

55 test rigs were used, each capable of testing two specimens at a time, hence most of the beams had a "neighbour" (Figure 9). The load was applied to the specimens through a load lever which was pulled horizontally towards a pulley (ratio 5.16), the latter is turned by the weight of a steel barrel. At the first load step, the barrels were filled with the appropriate amount of steel to an accuracy of ± 0.2 kg. The load was applied by gradually lowering the steel barrels by means of a converted hand-lift-truck. A rate of loading identical to the short term load speed was used, i.e. approximately 2 minutes to full load. Succeeding load increases were accomplished by pouring the appropriate amount of steel chips into the barrels.

The deformation measurements were taken as deflection readings, by means of a digital sliding gage. The readings were taken at three positions: at the center and ±

225 mm off the center of the specimen. The first reading was taken immediately before applying the load and it was followed by readings 30 sec., 2 min., 4 min., 8 min., 16 min. and 3 hrs. after loading. During the first week daily readings were taken, after which the specimens subjected to constant climate were measured twice a week (Monday and Friday). The beams at varying moisture conditions were measured daily during the first load step, however, during the succeeding load steps less frequent reading intervals were used. During moisture change, readings at 0, 2, and 4 hrs. were recorded. The reading of the deflection at the center of the specimen was taken as the reference time.

Upon failure of the long term specimens, the steel barrels were prevented from falling to the floor by a steel wire connected to a steel pipe framework. The stretching of this wire causes the disconnection of the wiring for a timer mounted on the test rig.

Two short sections of Kerto and sitka spruce respectively were placed in each corner of the test room to monitor the corresponding moisture content changes of the beams. The dummies were sealed at the cross sections to imitate the moisture variations of the mid-span of the beams.

For more details concerning the long term bending tests reference is made to the Technical Annex of (Vestergaard 1994).

4.2 Short Term Bending of Surviving Specimens

The surviving test specimens were tested to failure in a short term test in accordance with prEN 408. An Instron test machine (Figure 10) was used. The load was applied at a constant rate leading to failure within 2-3 min.

Figure 10. Short term bending test set-up.

4.3 Moisture Content

A 40 mm disc was cut from each beam, as close to the point of failure as possible. Moisture content was determined by oven-drying at 103 °C.

4.4 Density

The same discs, as mentioned above, were used for the determination of dry density ,ρ_0. Immediately after establishing the oven-dry weight the discs were weighed under water and this weight was taken as a measure of the volume. The discs were not coated with paraffin as a pilot test proved it to be unnecessary.

5 Results and Discussion

Eurocode 5 - Design of Timber Structures - classifies the environmental conditions according to the following three classes:

- Service class 1. Temperature = 20°C and RH of the surrounding air only exceeding 65% for a few weeks per year
- Service class 2. Temperature = 20°C and RH of the surrounding air only exceeding 85% for a few weeks per year.
- Service class 3. Climate conditions leading to higher moisture contents than in Service class 2.

The climate classes used in the present investigation corresponds quite well to the Eurocode 5 climate classes 1, 2 and 3, and the present results are therefore discussed also with respect to the modification factors k_{mod} as defined in EC5.

5.1 Long Term Bending

The results and discussions of the long term bending tests are divided into 4 subparagraphs, Creep, Time to Failure, Climate and Comments. The latter contains a specification of advice and experience gained during the test period with a view to utilizing this experience in the succeeding AIR-Programme.

5.1.1 Creep

A total of more than 24.000 creep observations have been recorded. The three measurements obtained in each reading interval were transformed into one deflection value, by:

$$d(t) = d_{mid\text{-}span} - (d_{upper} + d_{lower})/2$$

where

$d(t)$	is the deflection value over a span of 450 mm
d_{upper}	is the deflection measurement at the upper fitting
$d_{mid\text{-}span}$	is the deflection measurement at the mid-span fitting
d_{lower}	is the deflection measurement at the lower fitting

The first deflection measurements were taken 30 sec. after application of full load. These readings are defined as short term deflection and the corresponding time defined as time=0 for creep measurements.

5.1.1.1 Creep Diagrams

All creep data were transformed into graphs of normalized creep versus time. The normalized creep was determined by:

- 1st load step $c(t) = d(t)_X / d_{i,1}$
- 2nd load step $c(t) = (d(t)_X + d_{i,1}) / (d_{i,1} + d_{i,2})$
- 3rd load step $c(t) = (d(t)_X + d_{i,1} + d_{i,2}) / (d_{i,1} + d_{i,2} + d_{i,3})$
- 4th load step $c(t) = (d(t)_X + d_{i,1} + d_{i,2} + d_{i,3}) / (d_{i,1} + d_{i,2} + d_{i,3} + d_{i,4})$

where

$c(t)$ is the normalized creep
$d(t)_x$ is the time dependent deflection value of the load step
$d_{i,1}$ is the 30 sec.deflection value of the first load step
$d_{i,2}$ is the 30 sec.deflection value of the second load step
$d_{i,3}$ is the 30 sec.deflection value of the third load step
$d_{i,4}$ is the 30 sec.deflection value of the fourth load step
(The "non load" deflection value is subtracted from all the above mentioned deflection values)

By means of linear regression the power creep parameters were determined by transforming the power creep function into a straight line in a log-log plot:

$$\log_{10} \phi(t) = -b \log_{10} \tau + b \log_{10} t$$

where

$\phi(t) = c(t) - 1$
$\log_{10} \phi(t)$ = interscept of the regression line and the ordinate axis
b is equal to the slope of the line
$\tau = 10^{\log10\, \phi(t) / (-b)}$

5.1.1.2 General Trends

A typical set of creep diagrams are shown in Figure 11 overleaf. There is some scatter between the specimens; however, the following general trends can be noted:

- In comparison with the other load steps, the normalized creep function of the first step, surprisingly tends to have the largest value. The reason for this, however, may be found in the loading procedure. When the load is increased, by pouring steel into the barrels, the beams may have experienced "an extra load" caused by the kinetic energy of the plastic bags filled with steel. As a result of this, the initial deflection ($d_{i,2\text{-}3\text{-}4}$) increases, whereby the rate of creep is slowed down and the magnitude of normalized creep is less than expected. The effect of the kinetic energy can also be observed in the log-log plot of the power creep function, by a relatively high creep factor value after loading or in some cases a lack of values, due to negative creep factor values (Figure 15).

- The small variation of normalized creep between the various load steps suggests the behaviour of a linear viscoelastic material. However, in the last load steps, some specimens show a non linearity in which the creep increases dramatically.

- The small oscillation of the creep curves, for beams subjected to constant climate conditions, is caused by the measurement accuracy of the sliding gage.

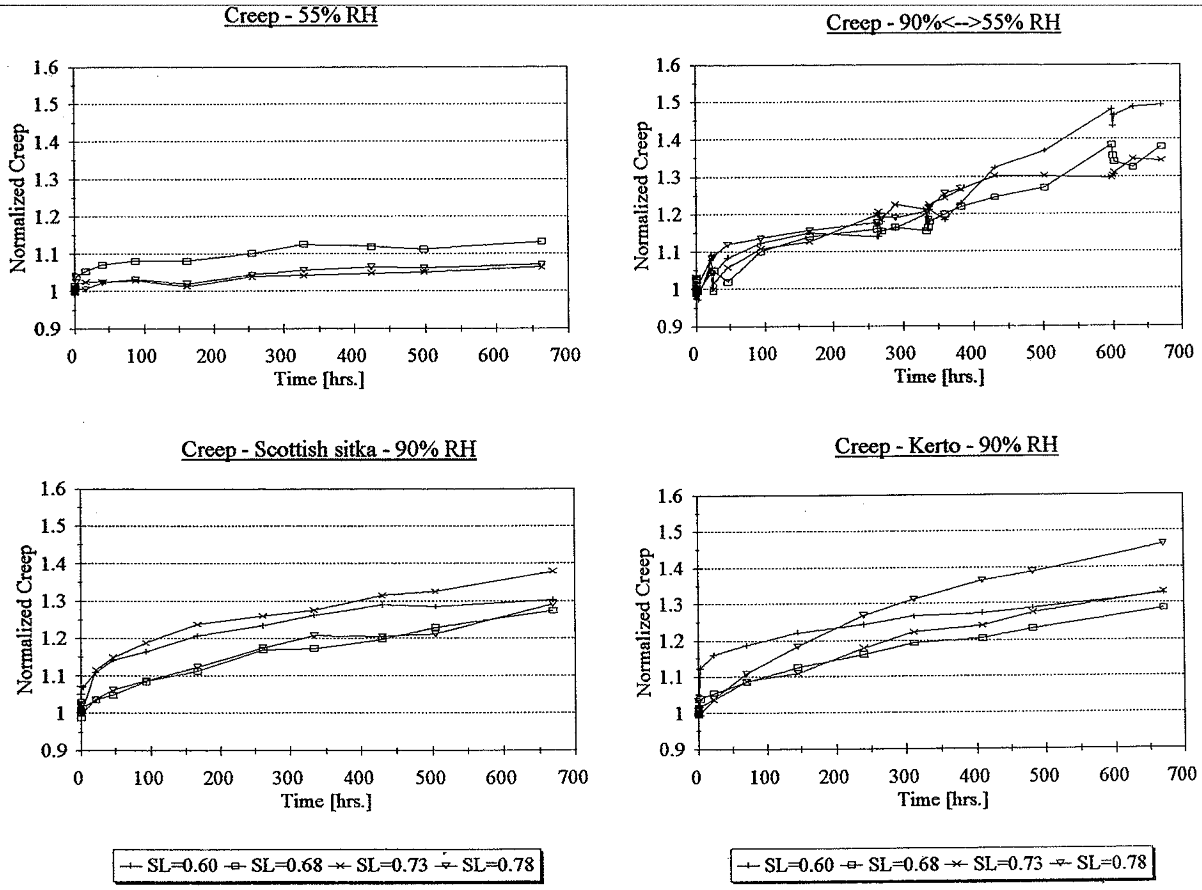

Figure 11. A set of typical creep diagrams for sitka spruce LVL at different moisture conditions. Kerto LVL is included (90% RH) for reasons of comparison

In some of the creep curves a sudden "jump" appeared (Figure 12). The jump is caused by failure of the "neighbouring beam". The influence on the power creep parameters will be discussed in a later paragraph. Figure 12 also shows an example of tertiary creep.

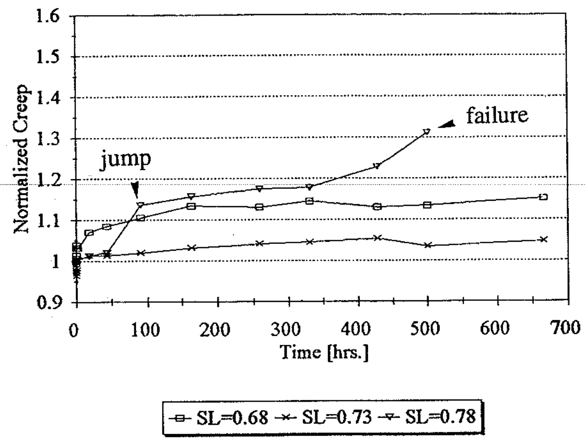

Figure 12. Failure of a neighbouring beam and tertiary creep.

From a registration of type of failure it appears, that when the failure occurred near the load lever support or at the outermost fittings, a relatively smaller deflection value d(t) was measured. Failure near the load lever support or at the outermost fittings can also be detected on the creep curves as a decrease of creep shown in Figure 13.

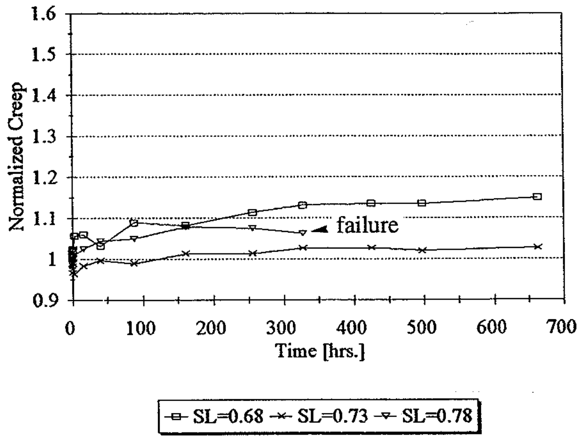

Figure 13. The creep curve influenced by type of failure.

5.1.1.3 Power Creep Parameters

The power creep parameters of each individual test specimen were determined. Maximum coefficient of determination (R^2) and minimum standard error estimate values were used as the criteria for the goodness of fit of the power function. The power creep parameters of each individual specimen were transformed into average values as a function of moisture content, stress level and material. Results are summarized in Tables 3 and 4.

In order to characterize the behaviour of creep on the basis of average values, the influence of type of failure must be discussed. If failure occurs near the load lever support or at the outermost fittings, it produces, low b values and high τ values compared with the other specimens. This behaviour does not always show, due to the fact that it is difficult to determine the correct type of failure. However, if for this reason a significant difference in a set of power creep parameters occurs, then that set has been omitted. The average τ values are calculated on the basis of $\log\tau$.

Scottish Sitka	SL = 60 %			SL = 68 %			SL = 73 %			SL = 78 %		
RH	b	Thau [hrs.]	No.of spec.	b	Thau [hrs.]	No.of spec.	b	Thau [hrs.]	No.of spec.	b	Thau [hrs.]	No.of spec.
55 %	-	-	-	0,29	1,6E+07	17	0,59	1,4E+06	13	0,74	7,4E+04	8
cyclic	0,43	4,8E+04	30	0,67	3,8E+04	30	0,77	4,6E+04	26	0,70	5,2E+03	10
90 %	0,28	3,4E+05	25	0,54	3,7E+04	25	0,73	2,8E+04	20	0,81	2,4E+04	7

Table 3. The power creep parameter values of the Scottish sitka spruce specimens.

Kerto	SL = 60 %			SL = 68 %			SL = 73 %			SL = 78 %		
RH	b	Thau [hrs.]	No.of spec.	b	Thau [hrs.]	No.of spec.	b	Thau [hrs.]	No.of spec.	b	Thau [hrs.]	No.of spec.
cyclic 90 %	0,44 0,30	5,4E+04 6,8E+05	10 8	0,60 0,57	4,3E+04 3,9E+04	10 8	0,73 0,75	5,8E+04 3,7E+04	10 8	0,66 0,69	4,7E+04 2,7E+04	5 7

Table 4. The power creep parameter values of the Kerto specimens.

The following trends can be noted:

- The creep parameters show no significant difference with respect to wood species.
- Varying moisture content results show doubling times, τ, similar to those for constant high moisture, while, on an average, the constant dry beams show higher values than the "moist specimens" at all stress levels.
- Varying moisture content results show b values similar to those for constant high moisture, while, on an average, the dry beams show lower values than the "moist specimens" at all stress levels. This means that normalized creep for dry specimens develops relatively fast in the initial stage and then slows down later. Conversely, normalized creep starts slowly for moist beams, but then develops relatively faster at a later stage.
- It appears that an increase of the stress level causes the power factor, b, to increase and the doubling time, τ, to decrease, although this trend is not generally valid for the moist specimens, for which the doubling time shows indications of stress level independence and a decreasing power factor b during the last load step.

The present results demonstrate a difference compared to the power creep parameters previously determined in section 3 of subtask 5.2 (Table 2). The results from the Section 3 tests (Hansen 1993) suggests an insensitivity of the power creep parameters both to stress levels and moisture conditions, although the doubling time seems to decrease with increasing moisture content and, less significantly, with stress level. This assumption is verified by similar tests (Toratti 1988) on Kerto beams conditioned at either 45% RH or 75% RH and with stress levels within the design range. This test showed, that the power b (≈0.2) is independent of both stress level and moisture conditions, while τ is independent of stress level but moisture dependent ($\tau \approx 10^6$ hrs. at 45% RH and $\tau \approx 10^5$ hrs. at 75% RH).

The results summarized in Tables 3 and 4 demonstrate good agreement with DOL tests (Hoffmeyer, 1990) on 400 beams of spruce subjected to constant or varying climates. Hoffmeyer showed, that τ is very sensitive to climatic conditions. While, on an average, deformation in the compression zone in dry beams takes more than two thousand years to double its initial value, the moist specimens obtain this within a week. The test also indicated that varying moisture content results in a doubling time similar to that of constant high moisture, although the deflection in the mid-span showed τ values nine times less than in constant high moisture content. The power b proved to be less affected by moisture than τ. However, there was a significant difference between the power for dry conditions (b=0.20) and for moist conditions (b=0.30). Finally it appeared that increasing the stress level causes the power factor, b, to increase and the doubling time, τ, to decrease.

5.1.1.4 k_{def} Factor

Eurocode 5 demands a timber construction to be designed and constructed in such a way that the design performance requirements meet both ultimate and serviceability limit states. The general requirements for serviceability limit states in Eurocode 5 demand that the final deformation, u_{fin}, under load should be calculated as:

$$u_{fin} = u_{inst}\,(1+k_{def})$$

where

u_{fin} = final deformation
u_{inst} = instantaneous deformation
k_{def} = a factor which takes into account the increase of deformation with time due to the combined effect of creep and moisture

In the present work the final deformation, u_{fin}, is determined by using the creep factor:

$$u_{fin} = u_{inst}\,[1+\phi(t)]$$

Hence, a set of k_{def} factors corresponding to Eurocode 5 can be calculated as:

$$k_{def} = \phi(t) = [t/\tau]^{b} \tag{4}$$

Prior to presenting the determined k_{def} factors it is necessary to discuss which power creep parameters are to be used in Eq 4. In a later paragraph a set of modification factors, k_{mod}, equivalent to Eurocode 5 are determined on the basis of data from specimen no. 50%. A corresponding procedure would produce a set of misleading k_{def} factors. Instead, the average τ and b values of the stress level in which failure of specimen no. 50% occurred, were implemented in Eq. 4. However, it should be noted that the suggested k_{def} factors are established under an action within the design limit. Therefore, the power creep values established at 5 MPa and 15 MPa were also used in Eq 4, whereby a set of k_{def} factors equivalent to Eurocode 5 were determined. Unfortunately the quality of these power creep parameters were rather poor, due to irregularities in the creep data. 10 years are used as time (t) in Eq 4. The resultant values of $k_{def,10\ years}$ factors are shown in Table 5

It should be noted, that the load-duration class assigned by Eurocode 5 is characterized by the effect of a constant load acting for a certain period of time in the life of the structure. Permanent load class is defined as more than 10 years of accumulated duration of characteristic load and long-term load class 6 months - 10 years. Hence, the determined $k_{def,10\ years}$ is a lower limit for Permanent load class and an upper limit for the Long-term load class.

Material	RH/Service class	DOL-test 5 MPa	DOL-test 15 MPa	DOL-test Sample no. 50%	Eurocode 5 Permanent load class	Eurocode 5 Long-term load class
Sitka	55% / 1	0,63	0,47	1,13	0,60	0,50
Sitka	Cyclic / 2	2,07	5,43	1,64	0,80	0,50
Sitka	90% / 3	1,20	2,09	2,29	2,00	1,50
Kerto	Cyclic / 2	1,41	4,51	1,51	0,80	0,50
Kerto	90% / 3	-	1,34	2,25	2,00	1,50

Table 5. k_{def} factors.

Taking into account the above mentioned uncertainties, the present results do not give a definite answer as to whether or not the k_{def} factors of Eurocode 5 are correct. The k_{def} factors determined in the present work, however, seem to be of the same magnitude as those of the Eurocode 5. The influence of large variations in climatic conditions seems to result in significantly larger k_{def} factors than anticipated by EC5.

5.1.1.5 Initial Deflection

A basic difficulty in describing creep is the assessment of the initial deflection (d_i). In the present work the 30 sec. measurement was used as the initial deflection. However, as an effect of the loading procedure previously discussed in paragraph 5.1.1.2, this value seems to be high. Based on the experience gained, it is recommended to use the measurements after 15 seconds as the initial deflection value and also to change the load procedure, by carefully placing the steel into the barrels - instead of pouring it - during load increase.

5.1.1.6 Dimensional Variations

The dimensional variations, measured on one full moisture cycle, of the "dummy" specimens placed in the variable moisture environment are shown in Figure 14.

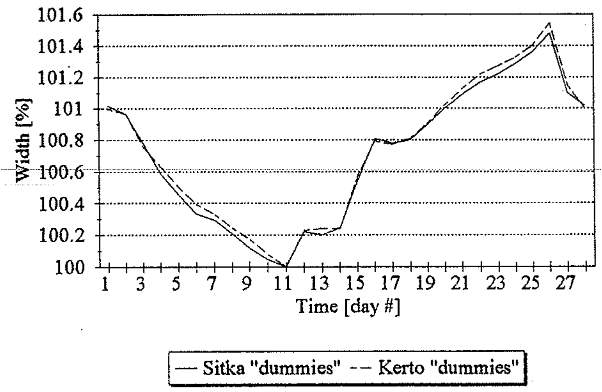

Figure 14. Variation of beam width as a function of time (days) under varying relative humidity conditions

The shapes of the dimensional variation curves are reflecting the climate variation and there is demonstrated no significant difference between the Kerto and Scottish sitka spruce dummies.

The amount of swelling of the beams relative to the radius of the curvature of the beam deflection was so small that no adjustment of deflection readings was necessary.

5.1.1.7 Mechano-Sorptive Effect

The normalized creep diagrams (Figure 11), show the typical features known to characterize the mechano-sorptive effect of timber subjected to the first cycle of varying moisture conditions, whereby:

- Creep increases during desorption.
- Creep increases during the first sorption step and at high stress levels.

With respect to the last feature, it can be discussed which of the two parameters is most significant. If the increase in creep, at load step 2, 3 and 4, is caused by the first sorption step effect, then the diagrams indicate that the specimens are not influenced by their creep history at lower stress levels (Section 2.5).

5.1.1.8 Disturbance of Creep Data Due to Failure in Neighbouring Beams

As mentioned previously, failure of a neighbouring beam can be detected as a jump on the creep curve (Figure15). The fit of the power function is most sensitive in the initial phase, and the influence of a disturbance thus depends on at which time the neighbouring failure occurs. However, the disturbance of the creep data is considerable and should be avoided in future tests.

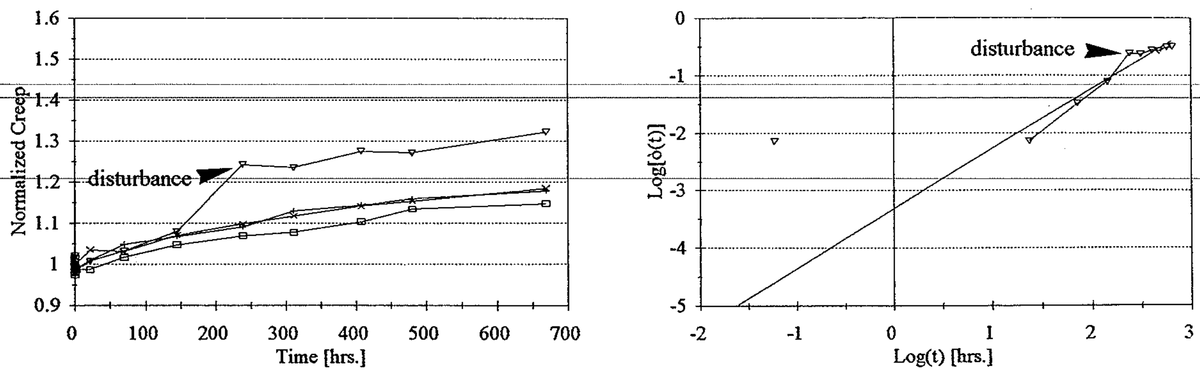

Figure 15. Disturbance of creep data for beam no. 230 due to failure in neighbouring beam

The disturbance is caused by the fact, that upon failure the load lever support is prevented from falling down by a steel wire connected to the top of the test rig (Figure 16). The disturbance can be avoided by connecting the steel wire to the already existing steel framework in the ceiling, hence it must be recommended to take such precaution in future long term bending tests.

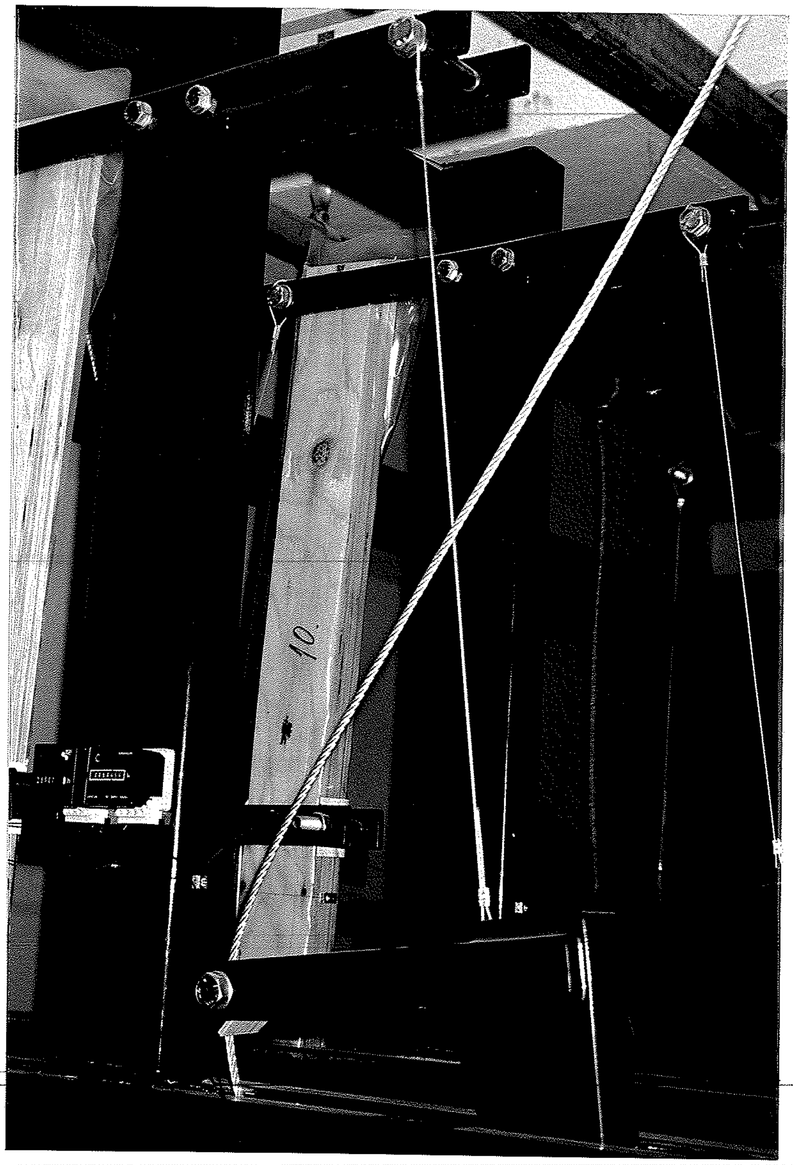

Figure 16. The load lever support.

5.1.1.9 Erroneous Creep Data Due to Incorrect Position of Measurement Fitting

During the test period it was discovered on a few test rigs, that the fittings for the digital gage were in an incorrect position, hence the deflection measurements were disturbed. The influence of the disturbance depends on the angle of the digital gage (Figure 17). Angles (α) between 5-10 degrees were registered, and a corresponding correction of the measured values was carried out.

Although the incorrect position of the fitting has little influence on the normalized creep, it ought to be avoided. Consequently, it must be recommended to move the fitting prior to future tests.

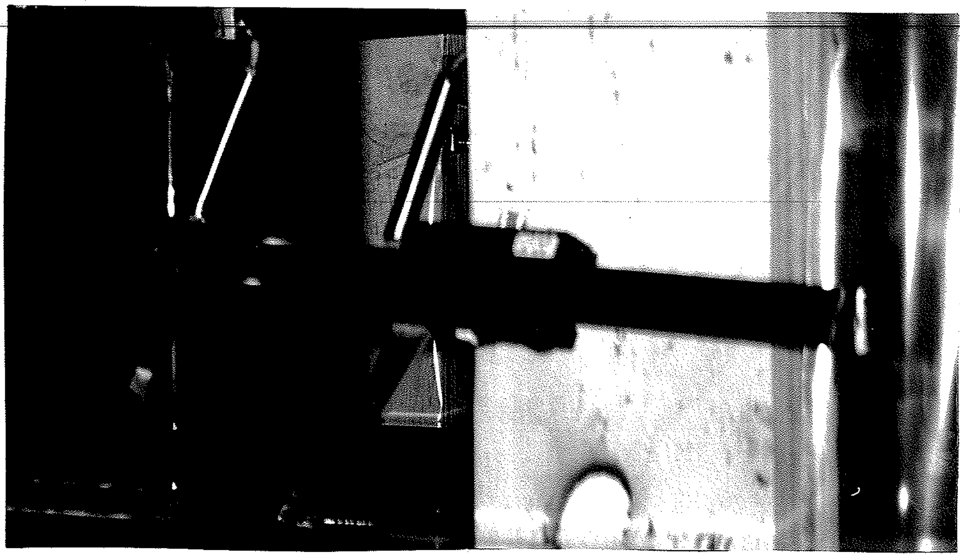

Figure 17. Incorrect position of the fitting.

5.1.2 Time to Failure

5.1.2.1 DOL-curves

Results from the duration of load tests were transformed into a plot of stress level versus logarithmic time to failure. As previously described the stress level was taken as the ratio of actual long-term load to the average short-term failure load. The DOL curves were then determined, by drawing a line through two points. The first point corresponds to the short term results: (SL, time) = (100%, 2 minutes). The second point corresponds to the (SL, time) value for the particular long term loaded specimen which failed as "no. 50%". Figure 18 shows such DOL test results for sitka spruce LVL at 55% constant relative humidity. 17 beams were taken to the same load level, and the beam which fails as number 9 therefore was taken as representative for the median of the population. In this instance the median specimen was loaded to SL=78% and failed after 53,0 hours corresponding to a log(hours) value of 1,72.

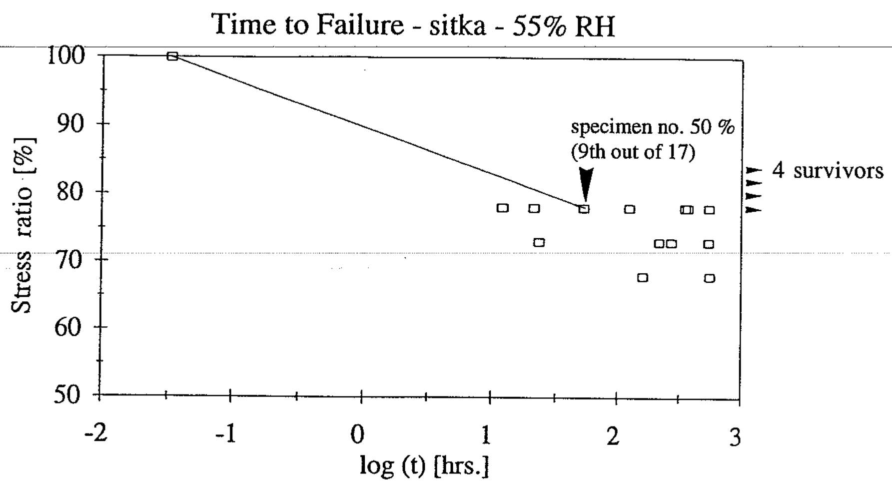

Figure 18. Stress Level (SL) against logarithmic time to failure for experimental sitka spruce LVL. 17 beams are included. Beam no. 9 is taken as representative of the median of the population and used for establishing the DOL relationship.

The DOL-curves for Scottish grown sitka spruce and Kerto are shown in Figures 19 and 20. Superimposed as a reference is the "Madison curve". It must be stressed that the number of Kerto specimens included in two of the test series do not warrant any firm conclusions.

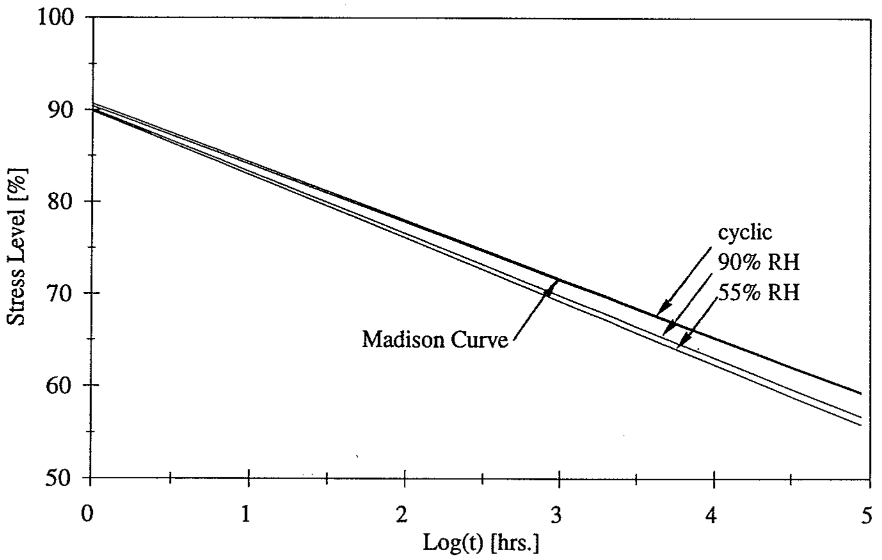

Figure 19. Dol-curves for Sitka spruce LVL

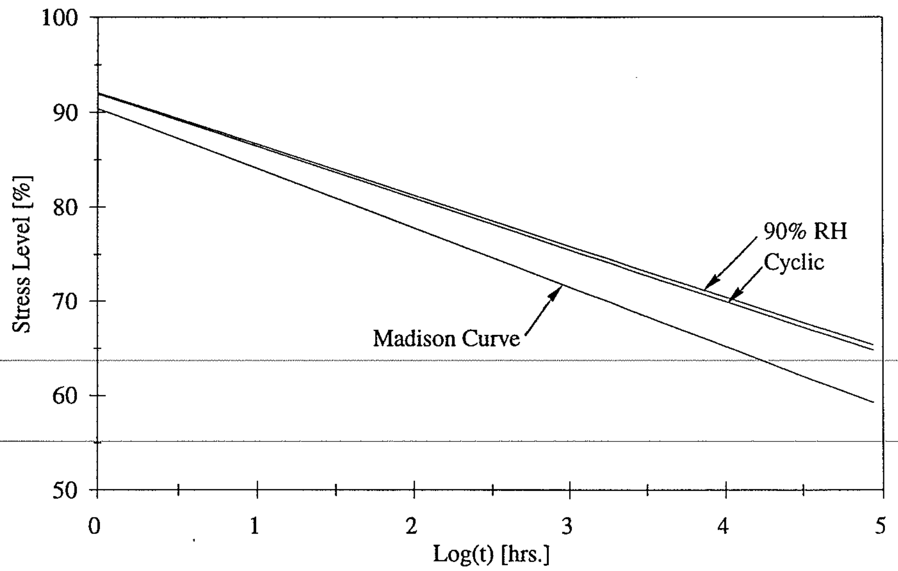

Figure 20. DOL curves for Kerto LVL (based on a small number of specimens!)

The equations for stress level as a function of logarithmic time to failure (t_f) were found to be:

- Sitka 55% RH $\quad SL = 89.85 - 6.87 \cdot \log_{10}(t_f)$

- Sitka Cyclic $\quad SL = 90.66 - 6.32 \cdot \log_{10}(t_f)$

- Sitka 90% RH $\quad SL = 90.05 - 6.74 \cdot \log_{10}(t_f)$

- Kerto Cyclic $SL = 91.90 - 5.48 \cdot log_{10}(t_f)$

- Kerto 90% RH $SL > 92.02 - 5.39 \cdot log_{10}(t_f)$

- *Madison curve-* $SL = 90.40 - 6.30 \cdot log_{10}(t_f)$

It should be noted, that only 4 Kerto test specimens at 90% RH out of 8 failed during the test period, whereby sample no. 50% does not exist. The stress level and time to failure of the 4th specimen was used as the second point for the determination of the DOL-curve

5.1.2.2 General Trends

The following trends can be noted:

- The DOL-effect seems to have a slightly different influence on sitka spruce LVL as compared to Kerto. The effect for Kerto specimens is less than predicted by the traditional "Madison curve" for clear wood, whilst for Scottish sitka specimens it is almost similar. The conclusion regarding the Kerto beams is particularly uncertain due to the few such specimens included

- The load duration has the same *relative* influence on both dry and moist sitka spruce LVL.

- Varying the moisture content does not shorten time to failure, on the contrary, such specimens of sitka spruce LVL proved to be less effected, than the specimens at constant high moisture. Hence, the specimens may not have been fully influenced by the mechanosorptive effect.

The latter trend is in disagreement with all previous DOL-test results. Hoffmeyer (1990) (Figure 2) and Schniewind (1967) showed, that the mere varying of the moisture content while under load shortens time to failure for wooden beams. The present DOL-test results therefore may imply that the specimens have not been fully influenced by the mechanosorptive-effect. In other words, one moisture cycle, at each load step, may not be enough to trigger the full effect of moisture variation. This suggests that the planned loading programme of the related EC-AIR project should be reconsidered. The specimens of the present tests with variable climate have been exposed to a high load only during the moist climate period and to a relatively lower stress level during the dry moisture condition, due to the fact, that the stress level is determined on the basis of the average short-term bending strength of moist specimens. Furthermore, as previously discussed, the DOL-curve shows, that the specimens are not influenced by their creep history at lower stress levels, whereby the specimens subjected to more than one load step may only be influenced by the mechano-sorptive effect of the last load step.

5.1.2.3 k_{mod} Factor

The Eurocode 5 defines the design value X_d of a material, by:

$$X_d = k_{mod} \cdot X_k / \gamma_m$$

where

k_{mod} is a modification factor taking into account the effect on the strength parameters of the duration of the load and the moisture content in the structure.

X_k is the characteristic strength value defined as the population 5-percentile value obtained from the results of tests with a duration of 300s at a temperature of 20°C and a relative humidity of 65%.

γ_m is the partial coefficient for material properties.

In order to determine the set of load duration modification factors, k_{mod}, from the present work, it is necessary to adjust the previously determined DOL-curve equations. The "cyclic moisture" equations and the "moist" equations are all based on the moist average short-term bending strength (37.1 MPa for sitka LVL), whereas the Eurocode 5 uses the dry short-term bending strength obtained from test results as reference. Therefore, to comply with the method used in EC5, the Stress Levels of these equation should be transformed to the "dry" short term strength (49.0 MPa for sitka LVL). The DOL curves modified in this way are given below:

- Sitka 55% RH $SL = 89.85 - 6.87 \cdot \log_{10}(t_f)$

- Sitka Cyclic $SL = 84.44 - 10.53 \cdot \log_{10}(t_f)$

- Sitka 90% RH $SL = 83.42 - 11.22 \cdot \log_{10}(t_f)$

- Kerto Cyclic $SL = 84.17 - 10.72 \cdot \log_{10}(t_f)$

- Kerto 90% RH $SL > 84.41 - 10.55 \cdot \log_{10}(t_f)$

The $k_{mod,10\ years}$ factors calculated from these modified DOL-equations are given in Table 6. It should be noted, that the determined k_{mod} is an upper limit for the Permanent load class and a lower limit for the Long-term load class.

Material	RH/Service class	DOL-test Sample no. 50%	Eurocode 5 Permanent load class	Eurocode 5 Long-term load class
Sitka	55% / 1	0,56	0,60	0,70
Sitka	Cyclic / 2	0,33	0,60	0,70
Sitka	90% / 3	0,28	0,50	0,55
Kerto	Cyclic / 2	0,31	0,60	0,70
Kerto	90% / 3	0,32	0,50	0,55

Table 6. k_{mod} factors.

The k_{mod} factors assigned by Eurocode 5 is in disagreement with the present work, in which the $k_{mod,10\ years}$ shown in Table 6 is considerably lower in all Service classes. Hence the DOL-test conducted by applying the load stepwise according to the AIR project indicates, that the k_{mod} factors in the proposed Eurocode 5 are too moderate.

5.1.2.4 Modelling

Prediction of time to failure was attempted on the basis of a fracture mechanics model (Hoffmeyer 1990):

$$\log_{10} t_f = A\,[\log_{10}\tau + b^{-1}\log_{10}(SLP^{-2} - 1)]$$

where

t_f	=	true time to failure
τ	=	doubling time from power function
b	=	power of the power function
SLP	=	Stress level based on short term bending strength predicted on the basis of individual MOE values
A	=	constant to counter e.g. any difference of measured macroscopic creep and microscopic creep at crack tip.

The power creep data from each individual specimen were used in the equation above, whereby a number of A-factors were established. The A-factors were transformed into mean and standard deviation values as a function of stress level, material, moisture conditions and failure stress level (Tables 7 and 8). The standard deviation expresses the quality of the prediction of time to failure, i.e. the lowest standard deviation in a group of specimens indicates, that the corresponding mean A-factor of that particular stress level gives the best prediction. Prior to discussing the determined A-factor values the following should be noted:

- The power creep parameters τ and b at 5 and 15 MPa were established prior to the present work. Not all parameters are present, due to irregularities in the creep data.
- The parameters from specimens which failed less than 24 hrs. after loading have been omitted.
- The load at which failure took place was used to calculate the stress level based on the predicted short term failure load of individual beams.
- The power creep parameters of the last load step were not used, due to the fact, that the parameters were influenced by the type of failure, as previously discussed.

The average A-factor of the stress level prior to the failure stress level produces the best prediction of time to failure. The A-factor is of the order 1/3 and only slightly higher for variable moisture content than for constant moisture content. The coefficient of variation is of the order 20%. The range of A-factors is surprisingly narrow considering the limited number of specimens represented in the different groups. The A-factor found for LVL seems to be significantly lower than that found for structural timber ($A \approx 1$) by Hoffmeyer (1990)

Moisure	Failure at [SL]	Parameters [SL]	A-factor		No. of specimens
			Mean	Std,dev	
55% RH	68%	15 MPa	0.32	-	1
	73%	5 MPa	0.31	-	1
		60%	0.26	0.02	3
	78%	15 MPa	0.39	0.12	3
		60%	0.23	0.06	5
		68%	0.32	0.07	5
Cyclic	68%	15 MPa	0.45	0.05	2
		60%	0.39	0.02	2
	73%	5 MPa	0.48	0.11	6
		15 MPa	0.51	0.07	6
		60%	0.40	0.06	12
		68%	0.45	0.05	12
	78%	5 MPa	0.40	0.06	6
		15 MPa	0.41	0.08	6
		60%	0.31	0.07	12
		68%	0.37	0.07	12
		73%	0.39	0.07	12
90% RH	68%	5 MPa	0.24	0.01	2
		15 MPa	0.35	0.00	2
		60%	0.29	0.06	4
	73%	5 MPa	0.28	0.05	7
		15 MPa	0.31	0.05	5
		60%	0.27	0.08	12
		68%	0.37	0.06	12
	78%	15 MPa	0.32	0.09	3
		60%	0.27	0.08	3
		68%	0.35	0.10	3
		73%	0.35	0.09	3

Table 7. A-factors for Sitka spruce specimens.

Moisure	Failure at [SL]	Parameters [SL]	A-factor		No. of specimens
			Mean	Std,dev	
Cyclic	73%	5 MPa	0.47	-	1
		15 MPa	0.51	-	1
		60%	0.41	0.01	3
		68%	0.47	0.03	3
	78%	15 MPa	0.48	0.11	3
		60%	0.38	0.06	3
		68%	0.38	0.02	3
		73%	0.36	0.02	3
90% RH	73%	15 MPa	0.45	-	1
		60%	0.26	-	1
		68%	0.48	-	1
	78%	15 MPa	0.30	0.05	3
		60%	0.29	0.03	3
		68%	0.41	0.06	3
		73%	0.43	0.03	3

Table 8. A-factors for Kerto specimens.

5.1.3 Climate

Continuous monitoring of the varying climate conditions during the test period was obtained by means of a Thermohygrometer. Figure 21 indicates, that the target climate conditions was, on the whole, obtained in a satisfactory manner. The temperature in the test rooms was kept at 20-22 °C during the entire test period.

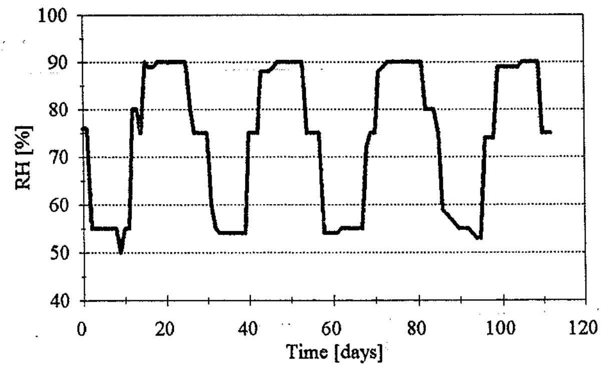

Figure 21. Thermohygrometer readings.

5.1.4 Comments

Loading Procedure

The AIR-project test procedure prescribes, that the first load level must be chosen low enough to ensure no failure in the first full climate cycle. During the present test no specimens failed at SL= 60%, but 8 specimens failed at 68%. Therefore it must be recommended to choose SL= 60% as the first load level for LVL beams.

The AIR-project test procedure also prescribes, that the increase of load must be carried out in two steps in order to more accurately observe the failure load in case the failure takes place before applying the second half of the load increase. If this load increase procedure is used, then an alteration of the loading procedure must be added. A complete record of the deflection measurement, for both steps must be carried out, in order to obtain the necessary initial deflection values. It would be advisable to wait for the 3 hr. test reading, before applying the second half of the load increasement. However, it should be noted that the two-step load increase method will be time consuming, whereby the test capacity will decrease.

In retrospect, a different load procedure would have given more information on the mechanosorptive effect on time to failure. The present data analysis procedure is based particularly on the duration of load behaviour of the one specimen which represents the median time to failure of the tested population of beams. This specimen, which is the average specimen, was referred to earlier as "specimen number 50%". In the present loading procedure no specimen will experience more than one full moisture cycle at the stress level which causes failure. In fact, it is very unlikely that any specimen will fail precisely at the end of a full cycle. Most specimens will fail long before, and some specimens are likely to have experienced no significant moisture change at all. "Specimen number 50%" (the average specimen) could belong to this caterogy of beams. It is therefore recommended that future tests are designed in such a way that the average specimen experiences several moisture cycles. Ideally, "specimen number 50%" should be subjected to at least two full moisture cycles at the stress level which causes failure, and then fail at the earliest during the third moisture cycle.

The design of a test procedure to obtain the pattern as described above is made very difficult because the scatter of times to failure is so large. In the present procedure, all specimens at a particular stress level are loaded to the same nominal bending stress. When the loads are different between specimens, it only reflects the fact that there are differences between cross sectional dimensions of the specimens. As there is a significant scatter of short term strength values, this scatter has to be found also with respect to the true stress level: The weak specimens have been loaded to a relatively high percentage of their individual short term strength while the strong specimens have been loaded to a low stress level relative to their individual short term strength. Therefore, the weak specimens have a short time to failure and the strong specimens live the longest. In order to minimise the scatter, it is suggested to load each specimen individually to meet the target stress level. This necessitates a method for the prediction of short term strength. For the LVL beams a prediction based on the modulus of elasticity seems promising (Figure 7).

In conclusion, the following procedure is suggested:

- Establish the relationship between MOR and MOE for the population in question.
- Calculate the predicted short term strength of the beams that are to be loaded in a DOL test.
- Chose a target stress level I which is as high as possible without causing failure in any specimen during the first moisture cycle.
- Chose a target stress level II which is likely to produce failure of the average beam ("no. 50%") during the fourth moisture cycle.
- Apply to each beam the load corresponding to the target stress level I based on the same beam's predicted short term strength. The load should reflect also any deviation from the nominal size of the cross sectional dimensions.
- Choose a moisture cycle duration of 4 weeks.
- After one full moisture cycle, increase the load individually for each beam to its stress level II.
- Carry out three more moisture cycles to make a total test duration of 16 weeks. Unload and take down the beams.
- If, unexpectedly, less than half of the beams have failed by the end of week no.16 statistical methods such as Gupta (1952) should be applied to estimate the mean and standard deviation of the truncated sample.
- Condition the surviving beams at the same climate as the corresponding short term strength beams and take them to failure in a short term test in order to reveal any damage accumulated during the DOL test .
- The first time a DOL test like this is to be carried out, it may be necessary to run a pilot test in order to estimate the optimal stress levels I and II. This may be done by the stepwise loading procedure already used in the present investigation.

Other Comments

The way in which the deflection values were data processed showed that the number of measurement intervals obtained during the test period were taken too frequently. During the last load step less frequent reading intervals were therefore introduced. It proved to be sufficient. It is recommended to use the reading intervals shown in Table 9 for the AIR project test procedure:

Climate	Mon 1	Tue 2	Wed 3	Thu 4	Fri 5	Sat 6	Sun 7	Mon 8	Tue 9	Wed 10	Thu 11	Fri 12	Sat 13	Sun 14	Mon 15
Variable	0 sec. 15 sec. 30 sec. 1 min. 2 min. 4 min. 8 min. 16 min. 32 min. 3 hrs.	24 hrs. 28 hrs.	48hrs.		96 hrs.			168 hrs.				264 hrs. 268 hrs.	288 hrs.		336 hrs. 340 hrs.
RH	75%	change	55%	55%	55%	55%	55%	55%	55%	55%	55%	change	75%	75%	change
Constant	0 sec. 15 sec. 30 sec. 1 min. 2 min. 4 min. 8 min. 16 min. 32 min. 3 hrs.	24 hrs.	48hrs.		96 hrs.			168 hrs.				264 hrs.			

Climate	Tue 16	Wed 17	Thu 18	Fri 19	Sat 20	Sun 21	Mon 22	Tue 23	Wed 24	Thu 25	Fri 26	Sat 27	Sun 28	Mon 29	No. of Reading Intervals
Variable	360 hrs.			432 hrs.			504 hrs.				600 hrs. 604 hrs.	624 hrs.		672 hrs.	27
RH	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	change	75%	75%	75%	
Constant				432 hrs.										672 hrs.	17

Table 9. Suggested creep reading interval for the AIR project.

Using one hand on the digital gage will encounter an unnecessary error to deflection measurements.

Prior to the DOL-test, all the measurement fittings were attached to the specimens by means of glue and a screw. A better attachment would be obtained by changing the design of the measurement fitting and using two screws instead of one.

The time spent in test rooms should be used as efficiently as possible, i.e. conducting quality tests and weighing the load increasement for the next load step etc. during the climate changes.

Finally, it is a good idea to have necessary data programs ready prior to the test, whereby the measurement interval can be typed into the computer immediately after they have been obtained, which would then serve as a quality control of the data obtained.

5.2 Short Term Bending Test of Surviving Specimens

17 out of the 90 specimens survived the long term bending test. As prescribed in the AIR project test procedure, these 17 surviving specimens were taken to failure in a short term bending test (Table 10).

This procedure was also used by Borg Madsen (1992). Borg Madsen compared the test results with a short term control sample curve (Figure 22). The short term strength of the control and test samples were assumed to be similar (normalized rank). Figure 22 will be used in the following to discuss the test result in the present work.

Short Term Bending Strength					
Material	Beam #	Predicted on MOE	Predicted on pairs	Based on ranking	Tested
Sitka 55% RH	160	50,7	47,3	52,5	44,0
	206	47,2	48,1	52,7	48,9
	220	47,5	43,9	53,0	49,4
	210	49,6	52,4	54,0	52,0
Sitka 90% RH	176	37,7	39,9	38,9	39,8
	172	37,7	43,6	40,1	42,2
	168	37,7	43,6	41,2	42,7
	180	37,7	40,7	43,6	44,4
	164	40,7	45,9	45,9	48,0
Kerto 90% RH	246	33,9	43,6	41,1	33,7
	236	40,3	41,6	41,4	38,7
	218	39,9	37,9	42,6	40,3
	230	40,5	41,1	43,6	43,4

Table 10. Results from the short term bending test (results from varying climate specimens are omitted).

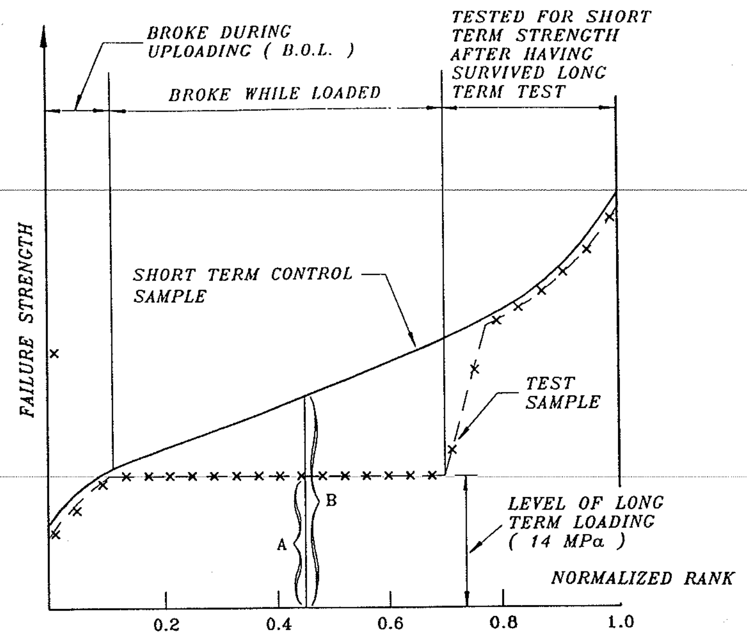

Figure 22. Comparison of short term strength of previously loaded beams with never before loaded beams (Borg Madsen 1992).

The specimens are divided into three groups. To the left are the specimens which broke during uploading. In the present work only one specimen (#114) can be assigned to this group. The specimens that broke while carrying the full load are shown along the horizontal line. The majority of both Kerto and Scottish sitka test specimens are in this group, however, a diagram of the present specimens would show four horizontal lines. Finally, the third group, the ones to the right, are the specimens which survived the long term bending test, but were subsequently broken in a short term test. This part of the curve shows, that the weakest specimens in the group did not match their counterparts on the control curve which indicates that some damage may have been accumulated.

In the present work the short term bending strength was predicted on the basis of both MOE, on the basis of the short term strength of the neighbouring beam and finally on the basis of ranking (Table 10). Two test specimens clearly showed indication of loss in strength compared to the predicted short term bending strength. Table 10 also shows, that the remaining 11 surviving specimens would match up with a short term control sample, i.e. no significant loss in the short term bending strength

5.3 Moisture Content

The moisture content of the test specimens determined from a disc cut close to the failure is given in Table 11.

Material	Climate condition	Moisture content [%]		
		Mean value	Maximum value	Minimum value
Sitka	55% RH	9,9	10,5	9,6
Sitka	Cyclic	15,7	17,8	13,0
Sitka	90% RH	19,0	20,1	16,5
Kerto	Cyclic	15,6	16,9	13,8
Kerto	90% RH	19,3	20,2	18,7

Table 11. Moisture content of the test specimens.

Table 11 shows, that the technique of controlling the climate of the moist specimens by injecting a 0.05% Rodalon solution into the polyethylene tubing has worked as intended. Also, the constant dry specimens are seen to have had a very well defined moisture content. The moisture content of the variable moisture specimens is seen to fluctuate much more, as would be expected.

The moisture content variation of the 8 "dummy" specimens placed in variable moisture rooms are shown in Figure 23. However, it should be noted, that only one full climate cycle was registered. During the three other climate cycles the moisture content prior to all the moisture changes were determined, hence the missing moisture contents are estimated according to Thermohygrometer readings. A full time registration ought to have been carried out, in order to establish the correct variation during the test period.

Figure 23 shows, that the Kerto "dummy" specimens seem to be less affected by the moisture variations. This is confirmed by the fact, that only 60% of the Kerto specimens subjected to varying moisture conditions have failed during the test period, whereas 100% of the Scottish sitka specimens failed. Figure 23 also shows a moisture content variation between 12% and 17%, this agrees with the determined moisture

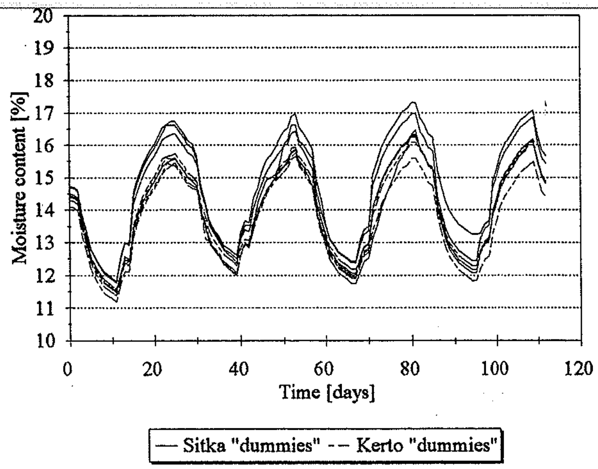

Figure 23. Moisture variation of the 8 "dummy" specimens at varying humidity.

obtained during the test period. The Thermohygrometer readings show, that the correct climate conditions have been present, therefore it must be concluded, that 10 days at high and low moisture is not enough to accumulate 10% and 20% in moisture contents. This last fact might be another reason why a 100% mechanosorptive effect has not been observed.

The moisture variation between 12% and 17% is in agreement with Eurocode 5 Service class 2, hence the determined k_{def} and k_{mod} factors subjected to varying moisture conditions are comparable with Eurocode 5.

5.4 Density

The densities of the test specimens determined from discs cut close to the failure are given in Table 12.

Material	Climate condition	Dry-density [kg/m^3] Mean value	Maximum value	Minimum value
Sitka	55% RH	463	500	445
Sitka	Cyclic	464	520	432
Sitka	90% RH	473	565	430
Kerto	Cyclic	494	515	476
Kerto	90% RH	487	512	467

Table 12. Density of the test specimens.

Table 12 shows, that the mean density value of Kerto specimens is higher than that of Scottish sitka.

It should be noted that the surviving long term bending test specimens have a significant higher density than the average. During the examination of these "high-density" beams it was observed, that the surviving Scottish sitka specimens conditioned at 90% RH all came from one end of the original Scottish sitka LVL-board no.7 with beam numbers 163-180 (see Appendix A). Obviously, the density and strength of these particular beams is quite different from the rest of the Scottish sitka beams. An explanation could be a variation in the production process, in which the veneer used in the first part of board no.7 is from a high density wood.

6 Conclusion

Creep

The creep parameters show no significant difference with respect to wood species.

Varying moisture content results show doubling times, τ, similar to those for constant high moisture, while, on an average, the constant dry beams show higher values than the "moist specimens" at all stress levels.

Varying moisture content results show b values similar to those for constant high moisture, while, on an average, the dry beams show lower values than the "moist specimens" at all stress levels.

An increase of the stress level causes the power factor, b, to increase and the doubling time, τ, to decrease, although this is not generally valid for the moist specimens, for which the doubling time shows indication of stress level independence and a decreasing power factor b during the last load step.

The results do not give a definite answer as to whether or not the k_{def} factors of Eurocode 5 are applicable for LVL. The k_{def} factors determined in the present work, however, seem to be of the same magnitude as those of the Eurocode 5. The influence of large variations in climatic conditions seems to result in significantly larger k_{def} factors than anticipated by EC5.

The normalized creep increased during both desorption and sorption for the specimens subjected to the first cycle of moisture variation.

Failure of a neighbouring beam may in some instances be result in a jump on the creep curve.

Progressive failure near the load lever support or at the outermost fittings can be detected on the creep curve as a decrease of creep.

Duration of load

The DOL-effect has a significantly different influence on sitka LVL as compared to Kerto. The effect for Kerto specimens is less than predicted by the traditional "Madison curve" for clear wood, whilst for Scottish sitka specimens it is similar.

The load duration has the same relative influence on both dry and moist Scottish sitka specimens.

Varying the moisture content does not shorten time to failure, on the contrary, the Scottish sitka showed to be less effected, than the specimens at constant high moisture. Hence, the specimens may not have been fully influenced by the mechanosorptive effect. This is in disagreement with earlier findings and suggests that one moisture cycle at the stress level causing failure may not be sufficient to trigger the full impact of the mechanosorptive effect.

The equations for stress level as a function of logarithmic time to failure were found to be as given below. It should be noted that the stress level is taken relative to the "dry" short term strength for the "dry" DOL specimens. For the "moist" and "varying moisture" specimens the stress level is based on the short term strength of the "moist" specimens.

- Sitka 55% RH $SL = 89.85 - 6.87 \cdot \log_{10}(t_f)$

- Sitka Cyclic $SL = 90.66 - 6.32 \cdot \log_{10}(t_f)$

- Sitka 90% RH $SL = 90.05 - 6.74 \cdot \log_{10}(t_f)$

- Kerto Cyclic $SL = 91.90 - 5.48 \cdot \log_{10}(t_f)$

- Kerto 90% RH $SL > 92.02 - 5.39 \cdot \log_{10}(t_f)$

Prediction of time to failure based on a fracture mechanical model seems promising. This model assumes that failure occurs as soon as cracks start to propagate. It includes a single calibration factor, A, and the three non-destructive parameters SLP (predicted stress level), τ (doubling time), and b (power of the power creep function). The results show that the average A-factor of the stress level prior to the failure stress level produces the best prediction of time to failure. The A-factor is of the order 1/3 and only slightly higher for variable moisture content than for constant moisture content. The coefficient of variation of the A-factor is of the order 20%. The range of A-factors is surprisingly narrow considering the limited number of specimens represented in the different groups. The A-factor found for LVL seems to be significantly lower than that found for structural timber ($A \approx 1$) by Hoffmeyer (1990).

17 out of the 90 specimens survived the long term bending test. A short term bending test conducted on these 17 surviving specimens showed signs of strength loss in approximately 15% of the beams, while the remaining approximately 85% surviving specimens matched up with the predicted short term strength.

The k_{mod} factors assigned by Eurocode 5 is in disagreement with the present work, in which the $k_{mod,10\ years}$ is shown to be considerably lower in all Service Classes. The DOL-tests conducted by applying the stepwise load according to the AIR project indicates, that the k_{mod} factors in the proposed Eurocode 5 are too moderate for the experimental sitka spruce LVL used in the present investigation. The results suggest that particularly the k_{mod} factors for Service Class 3 are too liberal for such structural members which are produced either from virtually defect free wood or from a product using a high degree of defect randomization (LVL). The reason is not so much an underestimation of the DOL effect as it is an underestimation of the strength reducing effect of the high moisture content of such high quality wood.

Loading Procedure

The loading procedure was taken as the one suggested for a large EC-AIR duration of load project to be launched late 1994. The following therefore are comments on that procedure.

It is recommended that future tests are designed in such a way that the average specimen experiences several moisture cycles. Ideally, "specimen number 50%" should be subjected to at least two full moisture cycles at the stress level which causes failure, and then fail at the earliest during the third moisture cycle.

It is recommended to load each specimen individually to meet the target stress level. This necessitates a method for the prediction of short term strength. For the LVL beams a prediction based on the modulus of elasticity seems promising.

In conclusion, the following revised procedure is suggested:

- Establish the relationship between MOR and MOE for the population in question
- Calculate the predicted short term strength of the beams that are to be loaded in a DOL test
- Chose a target stress level I which is as high as possible without causing failure in any specimen during the first moisture cycle.
- Chose a target stress level II which is likely to produce failure of the average beam ("no. 50%") during the fourth moisture cycle.
- Apply to each beam the load corresponding to the target stress level I based on the same beam's predicted short term strength. The load should reflect also any deviation from the nominal size of the cross sectional dimensions.
- Choose a moisture cycle duration of 4 weeks
- After one full moisture cycle, increase the load individually for each beam to its stress level II.
- Carry out three more moisture cycles to make a total test duration of 16 weeks. Unload and take down the beams.
- If, unexpectedly, less than half of the beams have failed by the end of week no.16 statistical methods such as Gupta (1952) should be applied to estimate the mean and standard deviation of the truncated sample.
- Condition the surviving beams at the same climate as the corresponding short term strength beams and take them to failure in a short term test in order to reveal any damage accumulated during the DOL test .
- The first time a DOL test like this is to be carried out, it may be necessary to run a pilot test in order to estimate the optimal stress levels I and II. This may be done by the stepwise loading procedure already used in the present investigation

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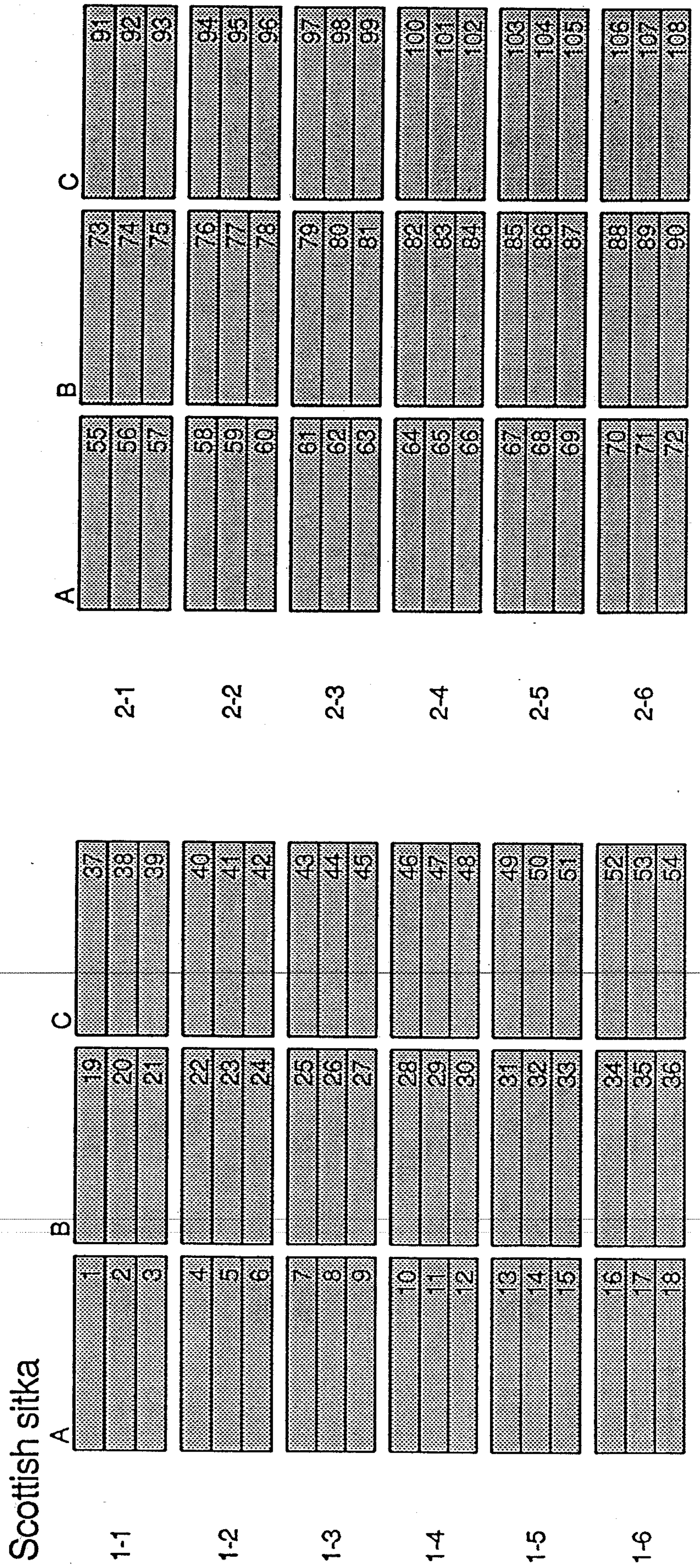
Scottish sitka
A
B
C
1-1
1-2
1-3
1-4
1-5
1-6
2-1
2-2
2-3
2-4
2-5
2-6
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36
37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54
55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72
73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90
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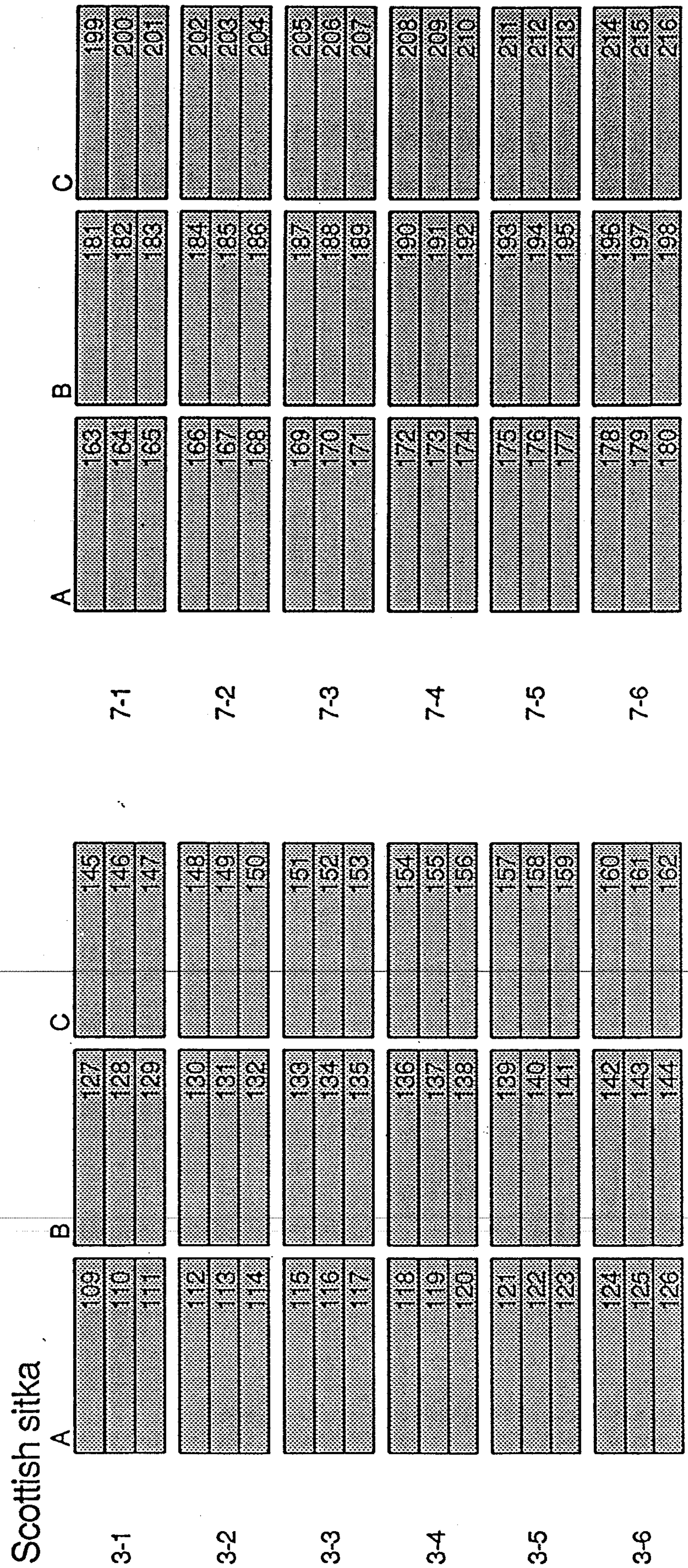
Scottish sitka
A
B
C
3-1
109 110 111
127 128 129
145 146 147
3-2
112 113 114
130 131 132
148 149 150
3-3
115 116 117
133 134 135
151 152 153
3-4
118 119 120
136 137 138
154 155 156
3-5
121 122 123
139 140 141
157 158 159
3-6
124 125 126
142 143 144
160 161 162
7-1
163 164 165
181 182 183
199 200 201
7-2
166 167 168
184 185 186
202 203 204
7-3
169 170 171
187 188 189
205 206 207
7-4
172 173 174
190 191 192
208 209 210
7-5
175 176 177
193 194 195
211 212 213
7-6
178 179 180
196 197 198
214 215 216

KERTO (Norway spruce)

	A	B	C
1	217 218 219	253 254 255	289 290 291
2	220 221 222	256 257 258	292 293 294
3	223 224 225	259 260 261	295 296 297
4	226 227 228	262 263 264	298 299 300
5	229 230 231	265 266 267	301 302 303
6	232 233 234	268 269 270	304 305 306
7	235 236 237	271 272 273	307 308 309
8	238 239 240	274 275 276	310 311 312
9	241 242 243	277 278 279	313 314 315
10	244 245 246	280 281 282	316 317 318
11	247 248 249	283 284 285	319 320 321
12	250 251 252	286 287 288	322 323 324

90 Long Term Bending Test Specimens

Number	55 % RH (10% MC)		90-55-90-55-... % RH		90 % RH (20% MC)	
Scottish Sitka	9	8	15	15	12	13
KERTO	-	-	5	5	4	4

No.	55 % RH (10% MC)		90-55-90-55-... % RH		90 % RH (20% MC)	
Scottish Sitka	38	42	20	22	2	6
	48	52	24	26	10	14
	92	94	28	30	18	36
	98	102	32	34	56	60
	106	146	76	78	64	68
	150	154	80	82	72	74
	160	200	84	86	110	114
	204	206	88	90	118	126
	210		128	130	140	142
			132	134	144	164
			136	138	168	172
			182	184	176	180
			186	188		198
			190	192		
			194	196		
KERTO	-	-	254	256	218	220
			260	262	226	230
			266	268	236	240
			276	278	246	248
			282	284		