VTT RESEARCH NOTES 1899

Duration of load effect on LVL beams

Part 2. Long term load tests under constant and cyclic humidity

Alpo Ranta-Maunus, Shankare Gowda & Markku Kortesmaa

VTT Building Technology

TECHNICAL RESEARCH CENTRE OF FINLAND
ESPOO 1998

ISBN 951–38–5290–3 (soft back ed.)
ISSN 1235–0605 (soft back ed.)

ISBN 951–38–5291–1 (URL: http://www.inf.vtt.fi/pdf/)
ISSN 1455–0865 (URL: http://www.inf.vtt.fi/pdf/)

JULKAISIJA – UTGIVARE – PUBLISHER

Valtion teknillinen tutkimuskeskus (VTT), Vuorimiehentie 5, PL 2000, 02044 VTT
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Technical editing Maini Manninen

Libella Painopalvelu Oy, ESPOO 1998

Ranta-Maunus, Alpo, Gowda, Shankare & Kortesmaa, Markku. Duration of load effect on LVL beams. Part 2. Long term tests under constant and cyclic humidity [Kertopuun pitkäaikaislujuus. Osa 2. Pitkäaikaiset kuormituskokeet]. Espoo 1998, Technical Research Centre of Finland, VTT Tiedotteita – Meddelanden – Research Notes 1899. 34 p. + app. 30 p.

UDC 694:624.072.2:624.042.1
Keywords structural timber, laminated wood, life (durability), laminated veneer lumber, loads (forces), bending tests

ABSTRACT

A research study on the long term load effects of Kerto laminated veneer lumber (LVL) was carried out at VTT in co-operation with other partners of a European project. Before the start of the long term tests, short term reference tests on Kerto LVL beams were completed (Fonselius and Ranta-Maunus 1996). The selection of load levels for the long term tests were determined based on the short term strength results.

The results of long term bending experiments made by VTT are published in this report. A total of 40 LVL beams were loaded under long duration loading. Nearly structural size beams were loaded to failure under monthly increasing stepwise loading under controlled humidity conditions, including both constant (85 % RH) and cyclic humidity.

The bending stress at failure when extrapolated to 6 months load duration was 67 to 75 % of the short term strength of similar beams having the same moisture content, which is equal or better than predicted by Madison curve (67 %).

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TIIVISTELMÄ

Tutkimus koskee kertopuun lujuuden riippuvuutta kuormitusajasta ja on osa kantavien puupalkkien pitkäaikaislujuutta koskevaa eurooppalaista projektia. Tässä VTT:n osuudessa määritettiin aluksi pitkäikaiskokeiden lähtökohdaksi kertopuun lyhytaikaislujuus, joka on raportoitu edellisessä osassa (Fonselius ja Ranta-Maunus 1996). Tämä julkaisu sisältää pitkäaikaiskokeiden tulokset.

Yhteensä 40 lähes rakenteellista kokoa olevaa palkkia kuormitettiin syrjällään ja kuormaa lisättiin portaittain neljän viikon välein. Kahdessa koesarjassa ilman suhteellinen kosteus oli vakio 85 % ja kahdessa vaihtuva 55 ja 90 %:n välillä.

Koesarjojen keskimääräiset kuormitustaso-murtumisaikatulokset ekstrapoloitiin logaritmisella aika-asteikolla puolen vuoden kuormitusta vastaaviksi. Tällöin murtumisen aiheuttava taivutusjännitys on 67…75 % lyhytaikaislujuudesta samoissa olosuhteissa. Tuloksen mukaan kuormitusajan vaikutus kertopuun lujuuteen on sama tai pienempi kuin puumateriaaleille perinteisesti käytetyn Madison-käyrän puolen vuoden kuormitukselle antama arvo 67 %.

PREFACE

A large research project (Number AIR2-CT941057) concerning the duration of load effect on different sized timber beams was initiated in 1994 as an EC-AIR project (European Community Agriculture and Fisheries, including agro-industry, food-technology, forestry, acquaculture and rural development) with a joint co-operation of five EC countries. The five countries involved in the project are, Finland, Sweden France, Denmark and Germany. The contact persons and the corresponding participating laboratories from these countries are respectively:

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The main objective of the project was to investigate the behaviour of different sized wooden beams under short term and long term loading conditions under normal and cyclic relative humidity and moisture content environment.This report includes the long term bending test results of LVL beams obtained by VTT (Task A2).

The work is supported by European Community (EC), Technology Development Centre of Finland (TEKES) and Finnforest Oy and their help is gratefully acknowledged.

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1 INTRODUCTION

A joint research program on the duration of load effect on different sized timber beams was initiated in 1994 as a EC-AIR project with the co-operation of five EC member countries. The main aim was to investigate both short term and long term strength of straight, notched and curved timber beams subjected to both constant and varying humidity conditions. The research results will help in establishing new scientific basis for the development and modification of Eurocode 5.

The short term reference tests on the duration of load effect on LVL beams has been completed and published (Fonselius and Ranta-Maunus, 1996). The test results of curved glulam beams have been published in the form of reports for both short and long term tests (Gowda and Ranta-Maunus, 1996, Gowda, Kortesmaa and Ranta-Maunus, 1998).

Laminated veneer lumber (LVL) is produced by gluing veneers parallel to each other, while plywood veneers are glued usually at right angles to each other. The veneers are made by peeling logs with thicknesses ranging from 1 to 5 mm. The production and its subsequent use of LVL is on the increase in recent years all over the world. In Finland it is called Kerto-LVL, which is a laminated veneer lumber product manufactured by Finnforest Oy. The main laminated veneer lumber products produced are Kerto-S, Kerto-T and Kerto-Q. The most common product is Kerto-S and the veneers in this group are long-grained.

In this part of the research, assessment of factors which affect the long term behaviour of LVL beams are studied under different loading and environmental conditions. An interesting part of this AIR research project is the new loading procedure that is followed in loading of the beams during long term testing. Normally, in case of long term loading the beams are loaded at certain required load level and kept constant until specimen failure occurs. However, in the present case, the loading method consist of applying the load in stages rather than keeping it constant for many months. After four weeks of test duration, the load is increased in a systematic way. Similarly, the humidity of the testing environment was also varied cyclically from 55 % to 90 % during a period of 28 days.

This report documents the results of tests on long term load effects on LVL beams under varying and as well as constant climatic conditions carried out in VTT during the 1994-97 period. Also a new theoretical model for long term bending strength based on strain energy has been developed and published as part of this project (Hanhijärvi, 1997). Results of other project partners concerning LVL will be published separately (Andreasen & Hoffmeyer, 1997).

2 EXPERIMENTAL PROGRAMME

2.1 DETAILS OF MATERIAL

Kerto-LVL is a laminated veneer lumber product manufactured by Finnforest Oy. Material and sampling has been described in the publication of Fonselius and Ranta-Maunus (1996). The moisture content, the density, the bending strength and modulus of elasticity were determined in accordance with the European standard EN 408. The mean density of the material used in this research is 523 kg/m^3. The bending specimen and the test set-up are shown in Figure 1. To minimise local indentation metal plates having length as long as the nominal depth of the beam were inserted between the beam, the supports and loading heads.

Four series of short term bending tests on LVL specimens (A, B, C and D in Table 1), have been carried out with 20 specimens in each series and 10 specimens in series F. The results are reported in a separate report (Fonselius and Ranta-Maunus, 1996). In this research project, four long term test series were performed with 10 specimens in each series. The details of long term test series along with dimensions of specimens and humidity conditions under which they are tested are summarised in Table 2. An additional series (P) of short term tests are also included in this report.

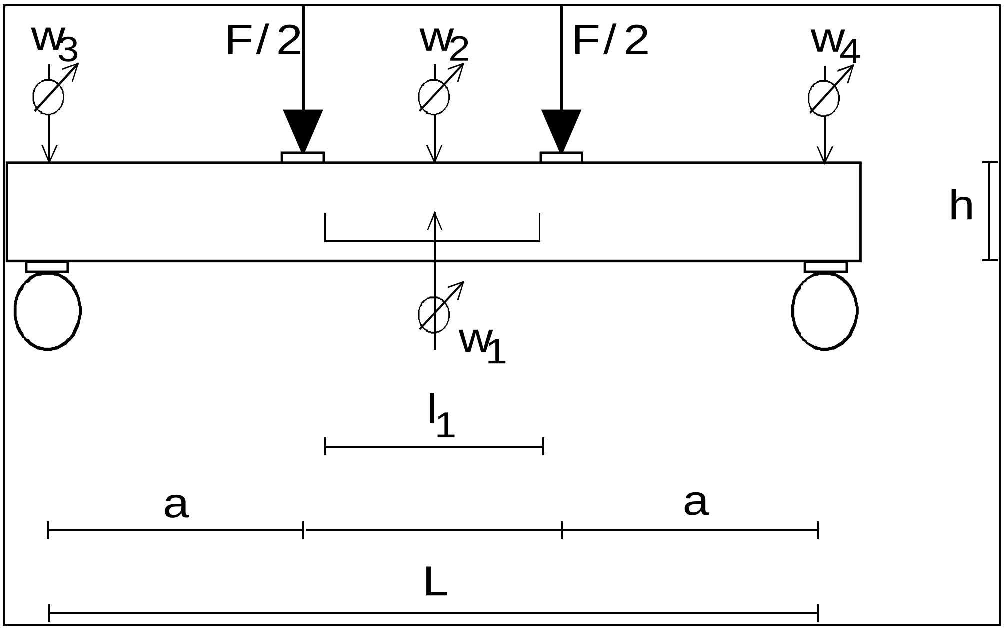

Figure 1. The specimen and test set-up in short term bending.

Dimensions of specimens are non standard except series C. The reason is that the same length of constant moment span (L-2a in Table 1) was wanted for different heights of beams in order to determine the pure height effect under short and long term loading. Pure length effect can be studied by comparison of series A and C. This specimen is expected to produce 3 % higher bending strength values for 300 mm high beams than a standard specimen having 1800 mm long constant moment span.

Table 1. Test series of LVL in bending including also short-term tests reported by Fonselius and Ranta-Maunus (1996). See Fig. 1.

Series	Sub-task	Load duration	h mm	L mm	a mm	L-2a mm	l_1 mm	RH %
A	A2,1	short	100	2000	350	1300	1000	65
B	A2,1	short	100	2000	350	1300	1000	(85)
C	A2,1	short	100	1800	600	600	500	65
D	A2,3	short	300	3900	1300	1300	1000	65
E	A2,2	long	100	2000	350	1300	1000	55 ↔ 90
F	A2,3	short	300	3900	1300	1300	1000	->90
G	A2,4	long	300	3900	1300	1300	1000	55 ↔ 90
H	A2,5	long	300	3900	1300	1300	1000	85
N	A2,5	long	300	3900	1300	1300	1000	85, sealed
P	A2,3	short	300	3900	1300	1300	1000	85

2.2 MOISTURE CYCLING

Two first long term test series (E, G) were made under cyclic humidity conditions (55 to 90 % RH). Humidity cycles for all series are illustrated in later sections of this report. Humidity cycle length was 28 days. Two last long term test series (H, N) having beam height 300 mm were loaded under constant relative humidity of 85 %. The aim of test series H is to study the failure stress under long term loading, whereas the loading of test series N was interrupted so that the residual short term strength could be tested for the stronger half of the beams.

Table 2. Long term test series of LVL specimens.

Test series	t x h x L	RH
E (A2,2)	75 x 100 x 2000 mm	cyclic 55<->90 %
G (A2,4)	75 x 300 x 3900 mm	cyclic 55<->90 %
H (A2,5a)	75 x 300 x 3900 mm	constant 85 %
N (A2,5b)	75 x 300 x 3900 mm	constant 85 %, sealed

Each long term testing was continued for 28 days under stepwise increased stress level until at least 50 % of the specimens had failure. A few weeks later the remaining specimens were tested to failure under short term ramp loading.

Load is applied by a spring system. The stress relaxation during loading has been measured in some test series and the load has been adjusted to the nominal value weekly.
Results will be analysed with respect to the following aspects:

1. Bending stress and time to failure for each specimen is recorded.
2. Cumulative distributions of the bending strength including both the data of beams failed under long term test and the testing of remaining specimens under short term loading.
3. Load level vs. time-to-failure graphs will be presented based on the behaviour of the medium strong beam.
4. Remaining strength after long term loading will be analysed in comparison to the predicted short term strength by the use of ranking method.

Four types of small samples having different dimensions were used to measure the moisture content in the wood material during moisture cycling. For some samples one side was sealed, while other samples had no sealing on all sides to facilitate for free moisture movement. The measurement of variation of moisture in LVL wood samples with no end sealing for sample D is shown in Figure 2, while other curves for samples A, B, and C with different end conditions are shown in Appendix A. The letter K represents Kerto and the numbers 15, 30 and 60 are the width of samples in millimeters.

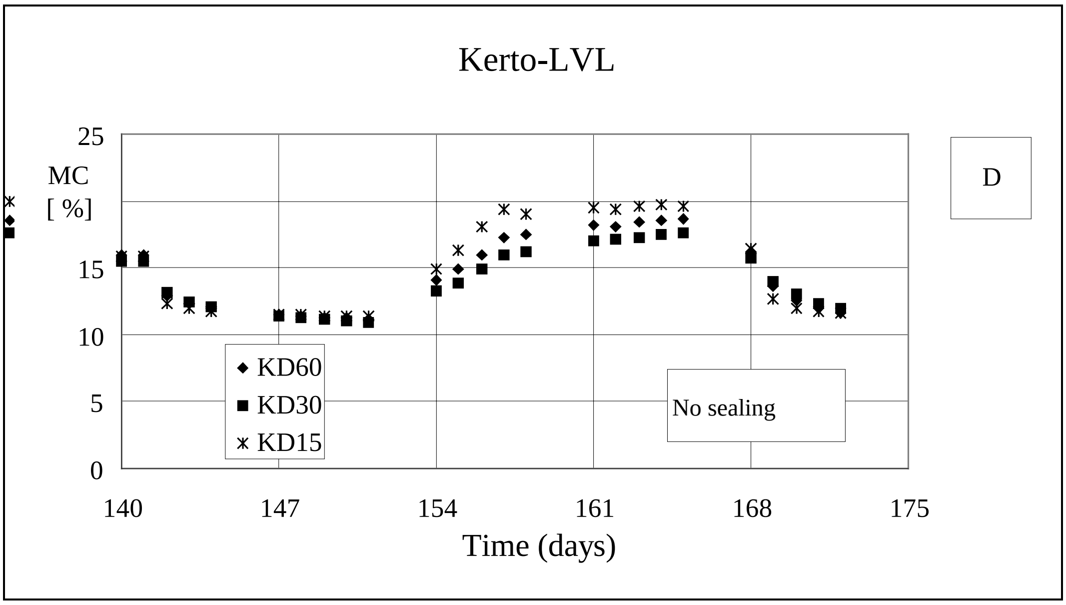

Figure 2. Measurement of variation of moisture in LVL wood material.

2.3 DETAILS OF LOADING AND MEASUREMENTS

A total of four series of tests (LT-A2-E2, LT-A2-G4, LT-A2-H5a, LT-A2-N5b), having ten specimens in each series were carried out under incremental load and cyclic or constant relative humidity conditions. The short term test results were used as a basis for selecting the load levels for the long term tests.

To carry out the long term tests on LVL beams, special test frames were designed and built according to the requirements. The specimens were tested under four point bending tests. The two load positions in the central section of the beam were kept at 1300 mm apart. The schematic of loading and supporting positions for the first series is shown in Figure 3, while for the other series with longer spans is shown in Figure 4.

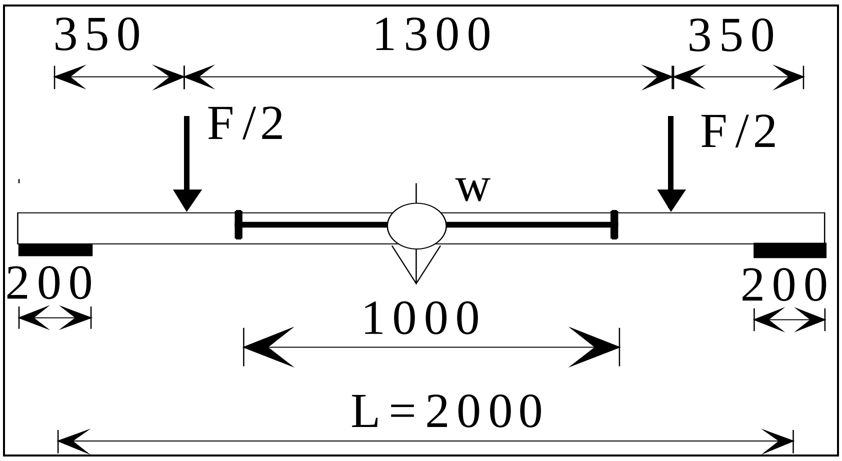

Figure 3. Schematic of loading and supporting positions for LT-A2-S2 series.

The creep deformations of the beams during the test period were measured in the central section (1000 mm) of the beams using dial gauges. The deformations were measured at regular intervals with an automatic computer controlled data acquisition system.

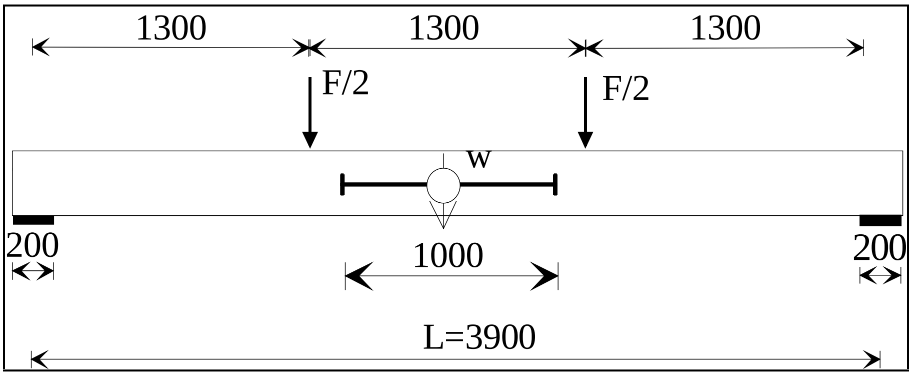

Figure 4. Schematic of loading and supporting positions for longer span series.

All the beams were loaded with a heavy-duty spring system and the load was applied through hydraulic jacks at two load positions. Since it was decided to apply the load in increments at several stages, the first load level was selected very low, such that no specimens would fail during loading or during the first two weeks after load application. The first load level induced an initial bending stress of about 20 to 25 MPa. The photograph of test set-up and loading system is shown in Figure 5.

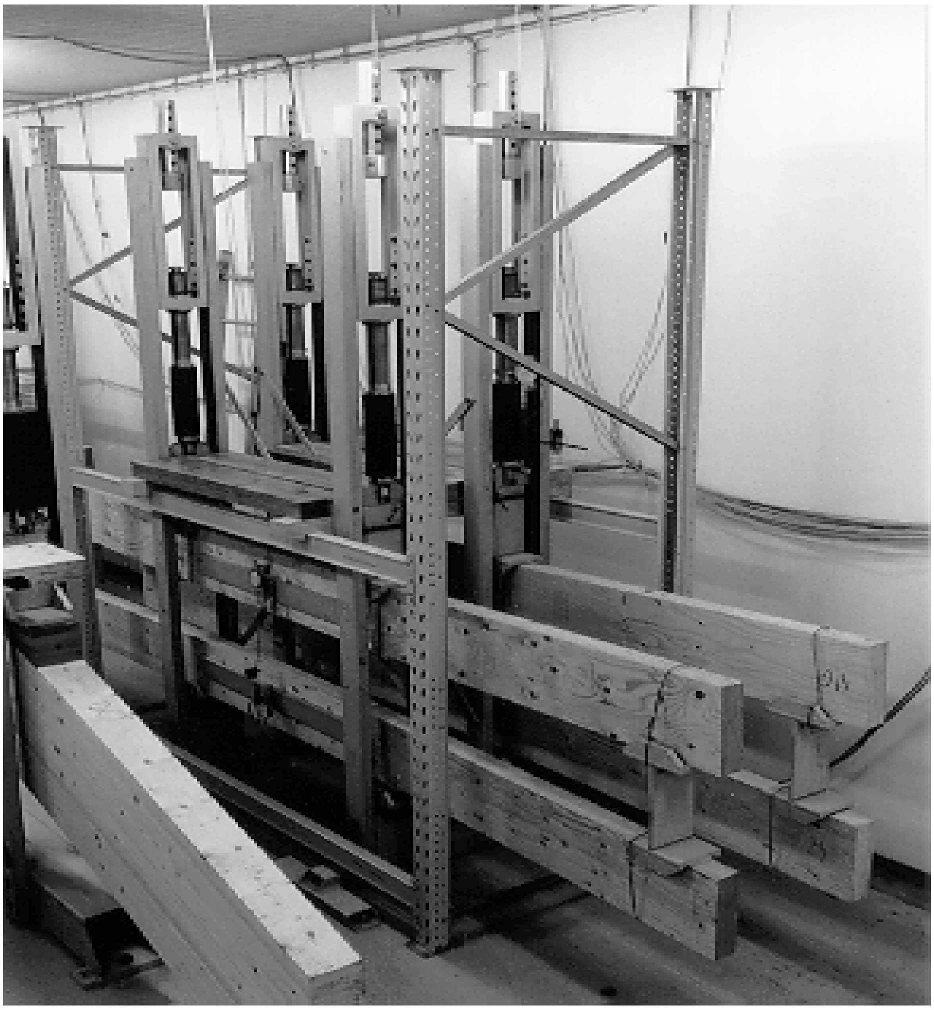

Figure 5. Photograph of test set-up and loading for LVL series.

3 TEST RESULTS

3.1 SHORT TERM EXPERIMENTS

The measured individual results of reference short term tests on LVL specimens are given in a separate report (Fonselius and Ranta-Maunus, 1996). In addition, a new series of specimens has been loaded at a high moisture content (P). A summary of the test results of all LVL beams tested in short term loading is given in Table 3, where series F and P both have been also considered as a combined one test series.

All the beams were broken by bending on tension side between the two load points. During the tests no failure was recognised on the compression side of the beams. However, it should be noted that the load-deflection curves of the beams in series F which were stored in the relative humidity of 90 %, are not as linear as the beams in series D which were stored at a relative humidity of 65 %. The same difference is found among the beams which were stored at a relative humidity of 85 % for series B and the beams stored at a relative humidity of 65 % for series A.

Table 3. Summary of results in short term bending tests.

Series	Number	Mean or Stdev	ω %	$\rho_{\omega,\omega}$ kg/m^3	$\rho_{0,\omega}$ kg/m^3	f_m N/mm^2	E_m N/mm^2	E_{mapp} N/mm^2
A	20	Mean	10.6	520	471	53.7	13566	12863
		Stdev	0.3	9	9	3.6	639	470
B	20	Mean	12.0	523	467	51.2	13356	12510
		Stdev	0.3	10	9	4.1	445	411
C	20	Mean	10.5	523	473	57.5	13382	12866
		Stdev	0.3	11	11	4.3	571	401
D	20	Mean	10.5	525	475	50.1	13319	12149
		Stdev	0.4	9	9	4.1	482	287
F	10	Mean	15.4	530	468	47.1	12163	11159
		Stdev	1.0	6	7	3.4	476	412
P	10	Mean	14.1	525	460	45.7	12242	11130
		Stdev	0.2	7	6	1.8	580	600
F+P	20	Mean	14.8	528	464	46.4	12202	11144
		Stdev	0.8	7	7	2.7	518	502

3.1.1 Statistical distributions

Within each series the cumulative function $F(f_m)$ of the bending strength f_m was modelled by the two-parameter Weibull distribution

$$F(f_m) = 1 - e^{-V\left(\frac{f_m}{m}\right)^k} \qquad (1)$$

where V is the volume of the specimens, *m* is the scale parameter and *k* is the shape parameter. By rearranging Equation (1) to the form

$$\ln(f_m) = \ln\left(\frac{m}{V}\right) + \frac{1}{k}\ln\left(-\ln\left(1 - F(f_m)\right)\right) \qquad (2)$$

the logarithm of bending strength $\ln(f_m)$ can be solved using the linear regression equation

$$\ln(f_m) = A + B\ln\left(-\ln\left(1 - F(f_m)\right)\right) \qquad (3)$$

where the constant *A* is equal to $\ln(m/V)$ and the slope *B* is equal to $1/k$. The value of $F(f_m)$ was found by ranking all the bending strength values within each series and divide the rank number n_{rank} with the amount of specimens n_{tot}. Finally, from the achieved value the inverse of two times the amount of specimens were subtracted. Hence $F(f_m)$ was given by the equation

$$F(f_m) = \frac{n_{rank}}{n_{tot}} - \frac{1}{2n_{tot}} \qquad (4)$$

The individual bending strength values and the modelled two-parameter Weibull distribution for each series are presented in Figure 6. To make it easier to compare the series to each other the cumulative functions are presented together in Figure 7. The constant *A*, slope *B* and correlation coefficient *R* of equation (3) are given in Table 4.

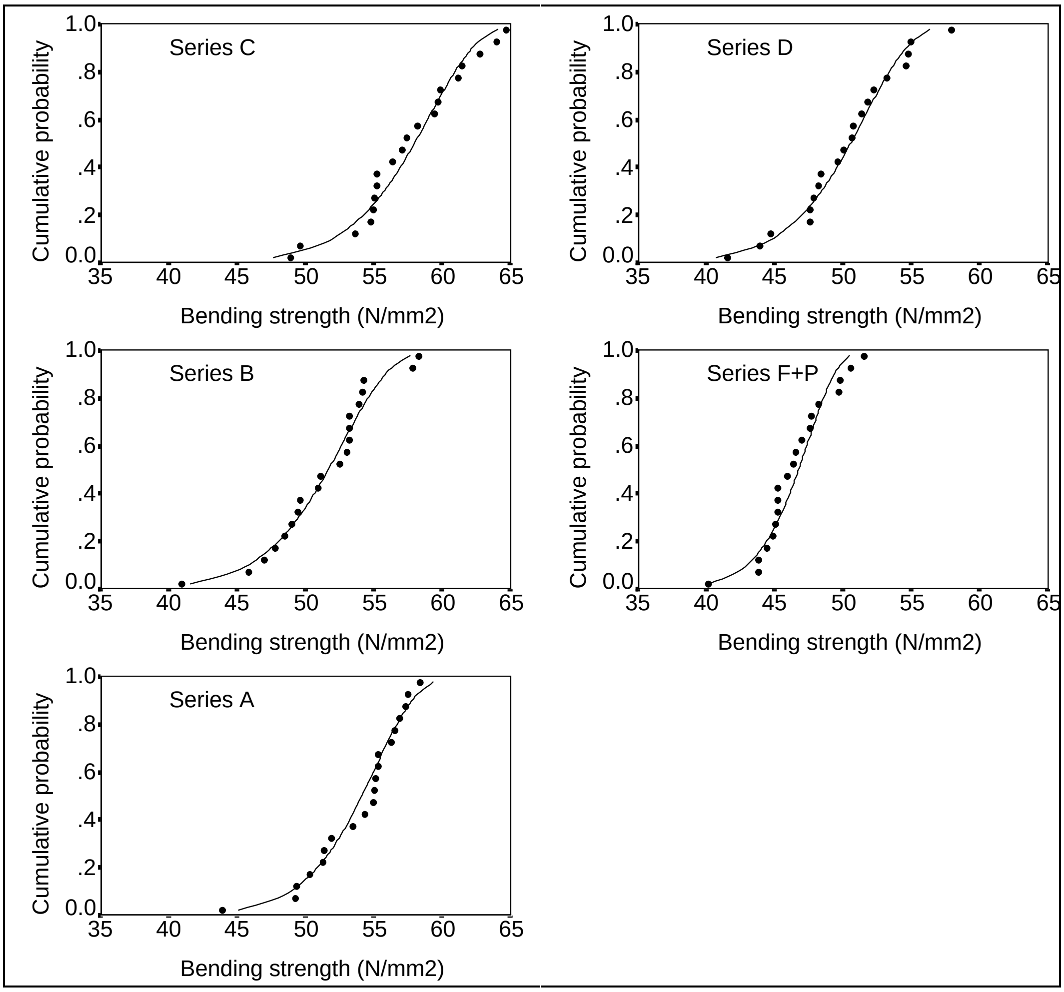

Figure 6. Cumulative functions of the short term bending strength for series A, B, C, D and F+P.

Within each series the fifth percentile of bending strength was estimated in different ways. If the bending strength is assumed to follow the two-parameter Weibull distribution the fifth percentile $f_{m,W05}$ is given by equation (3). If the bending strength is assumed to follow the normal distribution the fifth percentile $f_{m,N05}$ is given by

$$f_{m,N05} = f_{m,mean} - 1.645 f_{m,stdev} \qquad (5)$$

where $f_{m,mean}$ is the mean value of bending strength and $f_{m,stdev}$ is the standard deviation of bending strength.

When lognormal distribution is used, the fifth percentile $f_{m,ln05}$ can be calculated by

$$f_{m,\ln 05} = e^{(\ln f_{m,mean} - 1.645 V_m)} \qquad (6)$$

when V_m= coefficient of variation is small or it can be calculated by the use of the definition of lognormal distribution having cumulative distribution function:

$$F(x) = \Phi\left(\frac{\ln(x) - m_y}{\sigma_y}\right) \tag{7}$$

where Φ is the standard normal distribution (Gauss) cumulative function,

$m_y = \ln(m_x)-0.5\ln(1+V_x^2)$ is the mean of lognormally distributed values

$\sigma_y = (\ln(1+V_x^2))^{0.5}$ is the standard deviation of lognormal distribution, and m_x is the mean and V_x is the C.O.V. of normal distribution.

The fifth percentile values are given in Table 4. As a complement the mean value $f_{m,N50} = f_{m,mean}$ as well as the fiftieth percentiles $f_{m,ln50}$ and $f_{m,W50}$ of bending strength are also included.

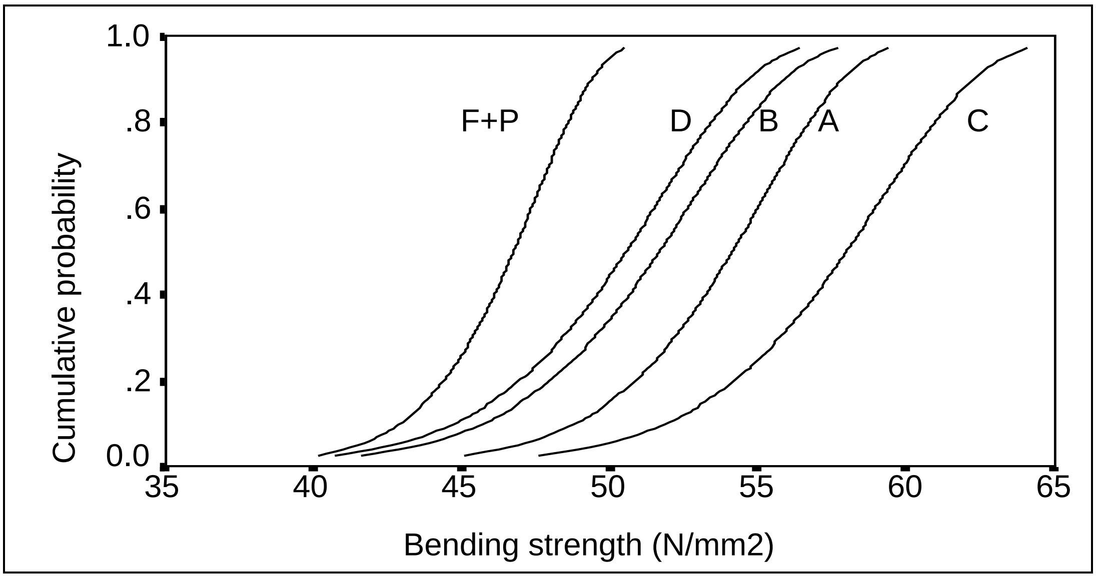

Figure 7. Cumulative Weibull functions of the short term bending strengths. See Table 4b on next page for explanation of test series A, B, C, D and F+P.

Table 4a. Summary of fitted results of short term tests with LVL: normal distribution, lognormal and 2-parametric Weibull. A and B are coefficients in eqn (3).

Series	A	B	R	$f_{m.mean}$ N/mm^2	$f_{m.ln50}$ N/mm^2	$f_{m.W50}$ N/mm^2	$f_{m.N05}$ N/mm^2	$f_{m.ln05}$ N/mm^2	$f_{m.W05}$ N/mm^2
A	4.0119	0.0552	0.983	53.7	53.6	54.2	47.8	48.0	46.9
B	3.9691	0.0653	0.987	51.2	51.0	51.7	44.4	44.7	43.6
C	4.0821	0.0594	0.979	57.5	57.3	58.0	50.4	50.7	49.7
D	3.9472	0.0652	0.988	50.1	49.9	50.6	43.4	43.7	42.7
F	3.8835	0.0595	0.991	47.1	47.0	47.5	41.6	41.8	40.7
P	3.8367	0.0273	0.872	45.7	45.7	45.9	42.7	42.9	42.8
F+P	3.8619	0.0457	0.967	46.4	46.3	46.8	42.0	42.1	41.5

Table 4b. Summary of essential variables in different test series.

Series	Load duration	beam height mm	constant moment span mm	ω %	RH %
A	short	100	1300	10.6	65
B	short	100	1300	12.0	(85)
C	short	100	600	10.5	65
D	short	300	1300	10.5	65
E	long	100	1300		55 ↔ 90
F	short	300	1300	15.4	->90
G	long	300	1300		55 ↔ 90
H	long	300	1300		85
N	long	300	1300		85, sealed
P	short	300	1300	14.1	85

3.2 LONG TERM EXPERIMENTS

3.2.1 Small beams under cyclic humidity

Specimens in this series LT-A2-E2 (Task:A2,2 E) had dimensions of 75 x 100 x 2200 mm, each having a volume of 0.0165 m^3. First, specimens were exposed to cyclic relative humidity without any load for 56 days. The cyclic variation was varied from 75➢90➢75➢55➢75. After 56 days, the load was applied incrementally in a step-wise fashion and each incremental load was kept constant for 28 days. The first load level induced a bending stress of about 20 N/mm^2 in the beams. When the first cycle was completed, the next four consecutive load cycles were applied gradually and no failure of beams occurred during this period (139 days). Then the sixth load increment was applied after 139 days. During this period, about five specimens failed and the rest did not fail. After this stage, the test was discontinued by terminating the load on the remaining specimens. The details of failure stress levels and the load duration days are given in Table 5.

Table 5. Load duration time of Kerto-LVL beams ($b \cdot h = 75 \cdot 100$, $L = 2200$).

Specimen	Designation	σ_b (MPa)	Time from start of cycle	Total loading time
LT-A2-E2-1	44E			*
LT-A2-E2-2	46E			*
LT-A2-E2-3	45E			*
LT-A2-E2-4	43E			*
LT-A2-E2-5	47E	35.7	5 s	140 d
LT-A2-E2-6	48E	35.7	26 d	166 d
LT-A2-E2-7	40E			*
LT-A2-E2-8	49E	35.7	8 d	148 d
LT-A2-E2-9	41E	35.7	19 d	159 d
LT-A2-E2-10	42E	35.7	8 d	148 d

* These specimens did not fail and discarded after 168 days.

The graphical representation of load duration and the failure stress levels for five specimens in LT-A2-E2 series is shown in Figure 8. The step-wise loading increment followed during testing is shown in Figure 9, while the variation of cyclic relative humidity is shown in Figure 10.

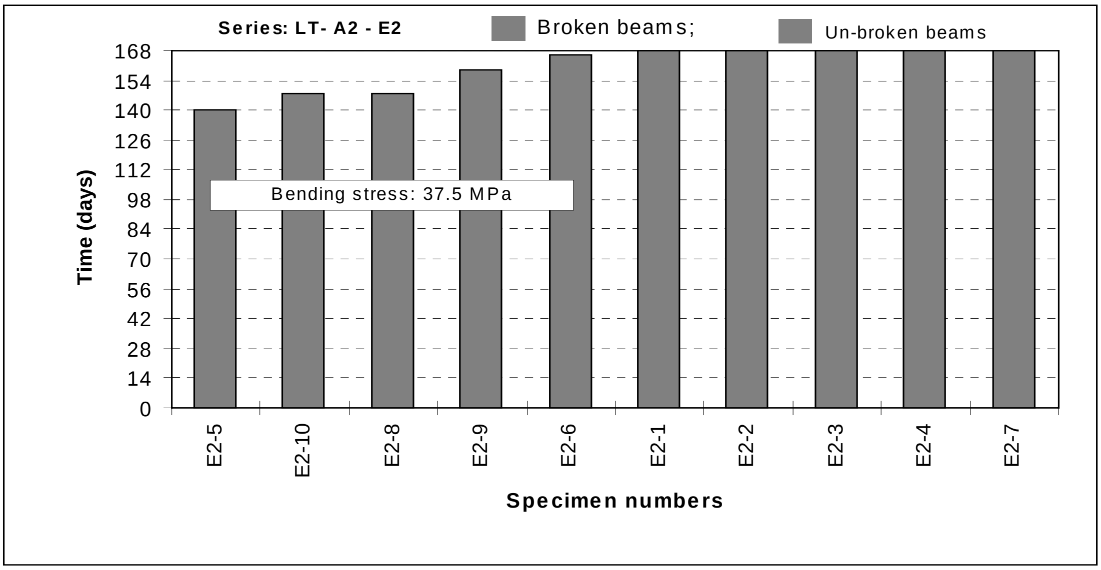

Figure 8. Load-duration and failure stress levels of specimen series LT-A2-E2.

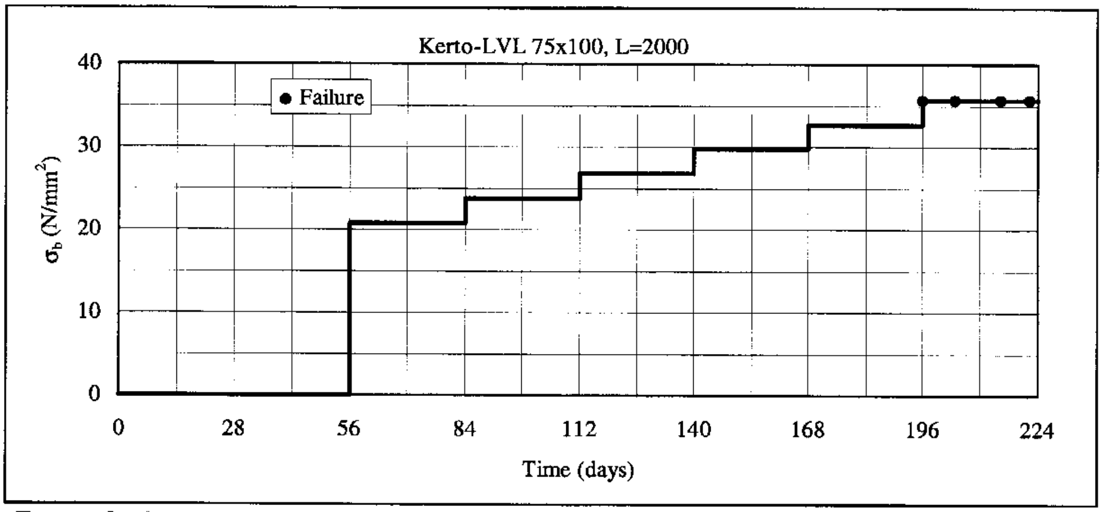

Figure 9. Step-wise loading pattern used for specimen series LT-A2-E2.

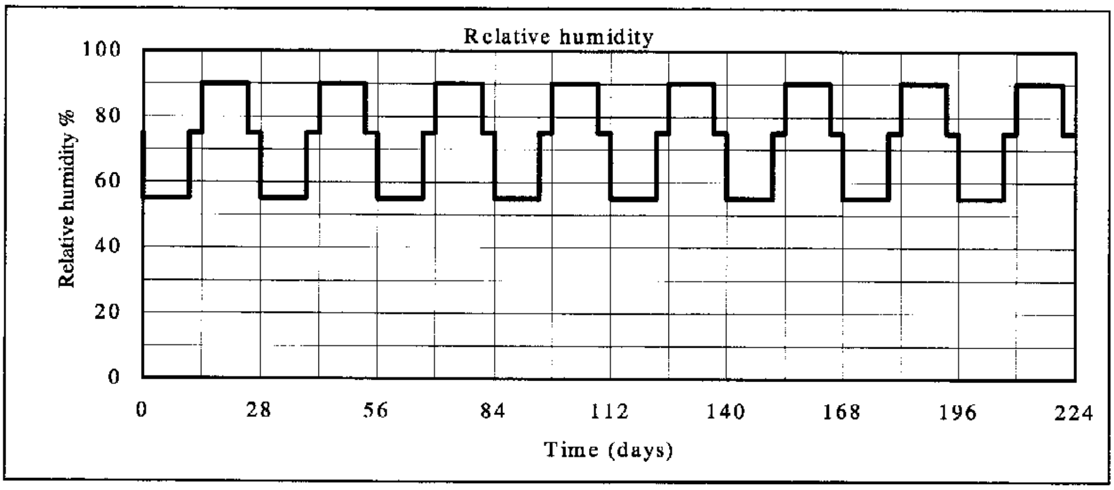

Figure 10. Cyclic relative humidity variation for Series LT-A2-E2.

3.2.2 Large beams under cyclic humidity

Specimens in this series LT-A2-G4 (Task:A2,4 G) had dimensions of 75x300x4100 mm, each having a volume of about 0.1 m^3. First, specimens were exposed to cyclic relative humidity without any load. The cyclic variation of relative humidity was selected to vary from 75➢90➢75➢55➢75. The first step-wise incremental load induced a bending stress of about 20 N/mm^2 in the beams. This level was kept constant for 28 days. When the first cycle was completed, the second stage of loading was applied raising the stress level to 30 MPa. No failure of beams occurred for a period of 112 days. Next the third incremental load was applied and the stress level was increased to 33.5 MPa. During the load increase the first specimen failed, and 3 days later the second. After this period, the stress level was increased to 37 MPa and at this stage three more beams failed but rest did not fail. After 161 days the load was terminated. The details of load duration and failure stress for different beams are given in Table 6. Moisture content values (ω) given in Table 6 are references for densities, and are not the moisture content values at time of failure.

Table 6. Load duration of Kerto-LVL beams($b \cdot h = 75 \cdot 300$, $L = 4100$).

Specimen	Series	σ_b (MPa)	Time from start of cycle	Total loading time	Density (kg/m³)		ω %
					$\rho_{\omega,\omega}$	$\rho_{0,\omega}$	
LT-A2-G4-1	42G	37.0	17 d	157			
LT-A2-G4-2	44G			*	508	456	11.3
LT-A2-G4-3	45G	37.0	14 d	154 d	513	461	11.2
LT-A2-G4-4	43G			*			
LT-A2-G4-5	48G			*			
LT-A2-G4-6	40G	33.5	3 d	116 d	512	461	11.0
LT-A2-G4-7	41G			*			
LT-A2-G4-8	46G			*			
LT-A2-G4-9	49G	37.0	21 d	161 d	514	463	11.0
LT-A2-G4-10	47G	30.0	28 d	113 d	514	462	11.1
Mean					512	461	11.1

* Specimens did not fail and discarded after 168 days.

The load duration of specimens for this series is shown in Figure 11, while the incremental step-wise bending stress used during testing period is shown in Figure 12. The cyclic variation of relative humidity for this series is shown in Figure 13. There was a gap of 21 days without any load on the beams during the testing period due to some problems in the loading system. The details of moisture sample dimensions and other data for this series is given in Appendix B.

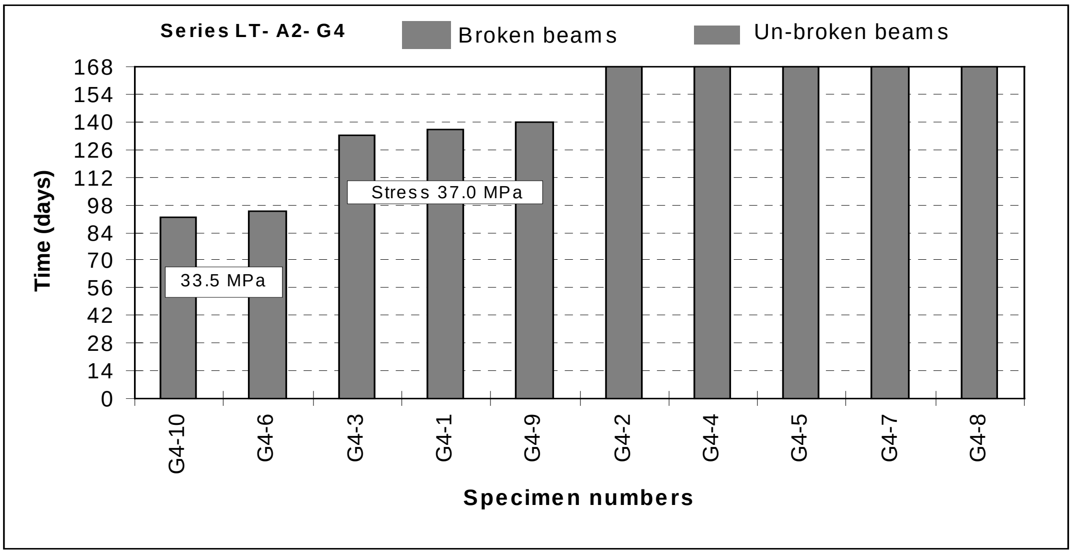

Figure 11. Load-duration of specimen series LT-A2-G4.

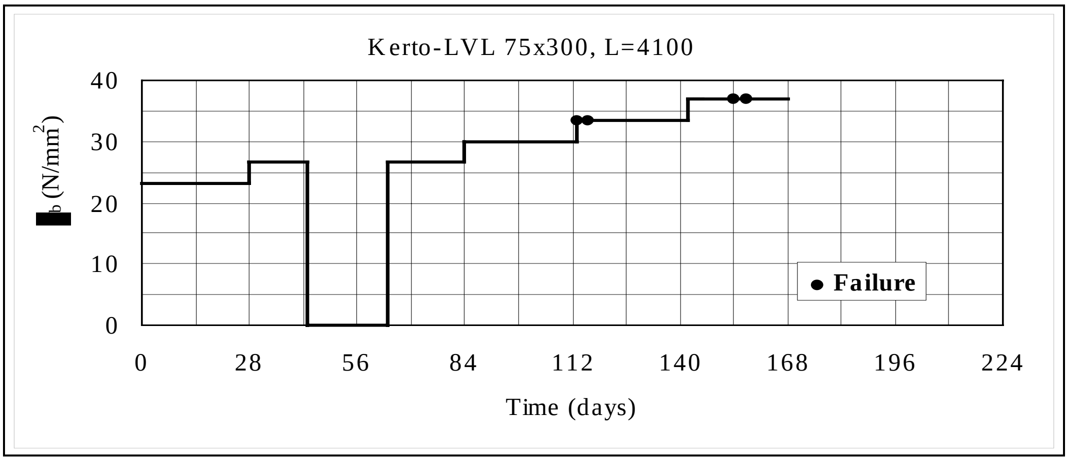

Figure 12. Step-wise loading pattern used for specimen series LT-A2-G4.

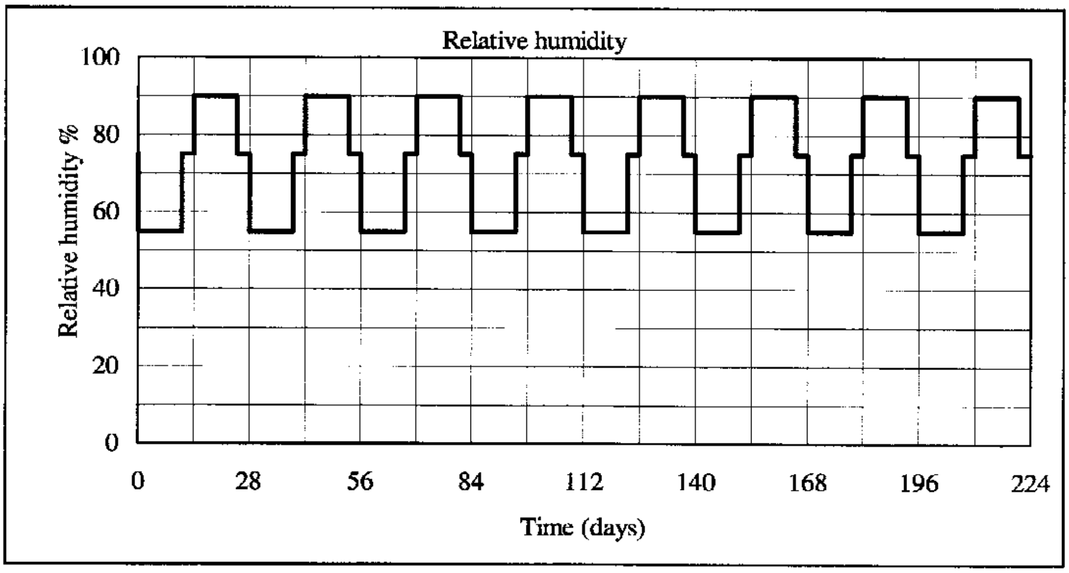

Figure 13. Cyclic relative humidity variation for Series LT-A2-G4.

3.2.3 Large beams under constant humidity

The specimens in this LT-A2-H5a (Task: A2,5a H) series had dimensions of 75 x 300 x 4100 mm and a volume of about 0.1 m^3. The ends of the beams in this series were sealed to control the moisture movement in the specimens. The relative humidity was kept constant during testing at nominal level of 85 %. Obviously the relative humidity was in practice lower, because the average moisture content after test was 13.1 %. The loading was made in two series: 5 specimens (1 to 5) starting at load level 27 MPa and the other 5 specimens (6 to 10) starting at 30 MPa.

When the next incremental load was applied and the stress level was increased to 33.5 MPa, the failure in beams started to happen as the number of days continued to increase. After this period, the stress level was increased to 37 MPa and at this stage two more beams failed. The unbroken beam was loaded to failure by ramp loading. The details of load duration and failure stress of different beams are shown in Table 7.

Table 7. Load duration of Kerto-LVL beams ($b \cdot h = 75 \cdot 300$, L = 3900)

Specimen	Series	σ_b (MPa)	Time from Start of cycle	Total loading time	Density (kg/m^3) $\rho_{\omega,\omega}$	$\rho_{0,\omega}$	ω %
LT-A2-H5a-1	43H	37.0	9 h	84 d	517	458	12.9
LT-A2-H5a-2	44H	37.0	5 h	84 d	525	467	12.5
LT-A2-H5a-3	42H	33.5	21 d	78 d	520	462	12.6
LT-A2-H5a-4	41H	37.0	5 d	88 d	536	475	12.9
LT-A2-H5a-5	45H	37.0	5 d	88 d	528	470	12.4
LT-A2-H5a-6	48H	33.5	13 d	68 d	528	466	13.2
LT-A2-H5a-7	47H	33.5	14 h	57 d	522	462	13.2
LT-A2-H5a-8	46H	33.5	14 d	70 d	521	463	12.6
LT-A2-H5a-9	40H	33.5	9 d	65 d	534	472	13.1
LT-A2-H5a-10	49H	41.1 [1)]			515	457	12.8
Mean					525	465	13.1

[1)] Ramp loading to failure after long term loading was terminated.

The stepwise loading pattern and the stress levels for this series is shown in Figure 14. The constant relative humidity graph is shown in Figure 15. The details of moisture sample dimensions and other data for this series is given in Appendix B.

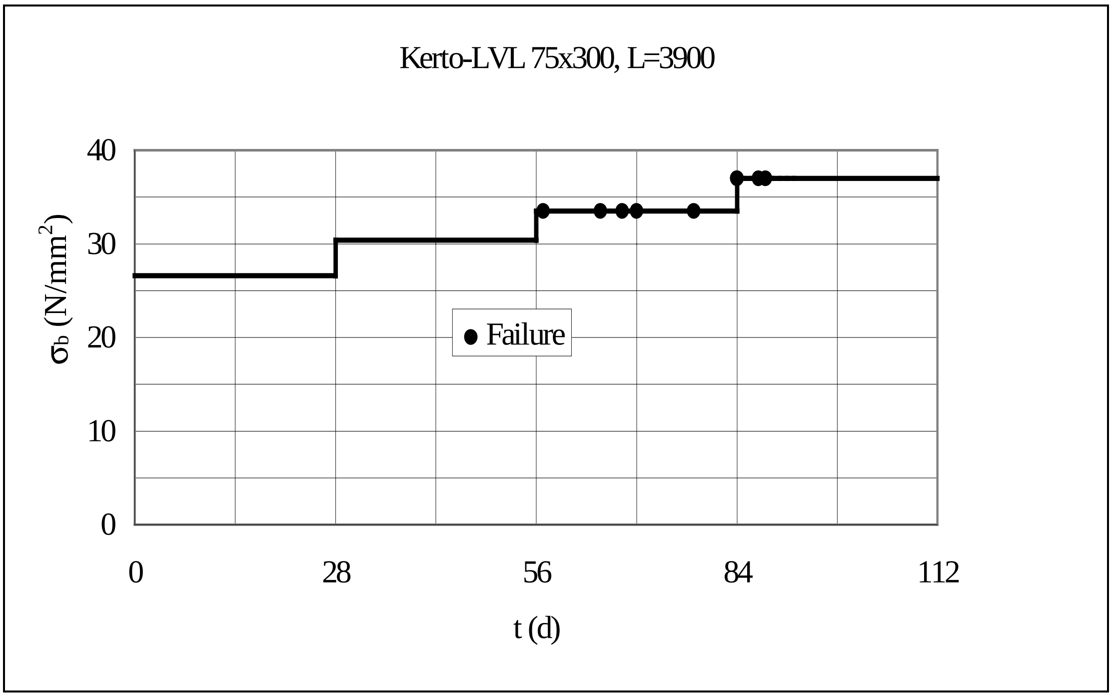

Figure 14. Step-wise loading pattern used for specimen series LT-A2-H5a.

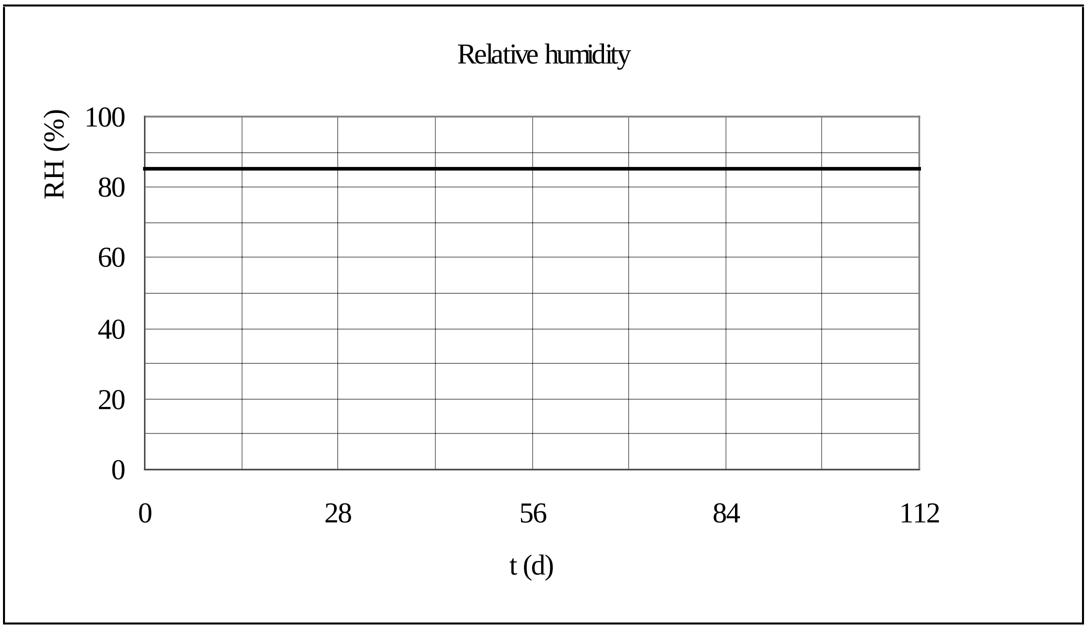

Figure 15. Constant relative humidity used for specimen series LT-A2-H5a.

3.2.4 Large sealed beams for residual strength

The specimens in this series LT-A2-N5b (Task:A2, N) had dimensions of 75x300x4100 mm and a volume of about 0.1 m^3. The relative humidity was kept constant at nominal level of 85 % throughout the test period. Specimens were coated by a vapor barrier to control moisture movement. The loading of specimens was made in two parts: specimens 1 to 5 were loaded first, starting at stress level 30 MPa. Load was removed from the remaining specimens at the end of load step period when the stress level was 37 MPa. During the second stage, specimens 6 to 10 were loaded starting at a stress level of 33.5 MPa. The details of load duration and failure stress for different beams are given in Table 8. The load duration plot for these specimens is given in Figure 16, while step-wise loading pattern and the relative humidity graphs are given in Figures 17 and 18 respectively.

Table 8. Load duration of Kerto-LVL beams ($b \cdot h = 75 \cdot 300$, L = 3900, sealed).

Specimen	Series	σ_b (MPa)	Time from start of cycle	Total loading time	Density (kg/m^3)		ω
					$\rho_{\omega,\omega}$	$\rho_{0,\omega}$	%
LT-A2-N5b-1	51N	41.1[1)]			523	462	13.4
LT-A2-N5b-2	50N	42.5[1)]			527	465	13.3
LT-A2-N5b-3	58N	37.0	9 d	65 d	541	478	13.1
LT-A2-N5b-4	55N	33.5	21 d	49 d	525	463	13.4
LT-A2-N5b-5	54N	48.1[1)]			539	474	13.7
LT-A2-N5b-6	53N	37.0	2 d	30 d	533	470	13.4
LT-A2-N5b-7	56N	50.1[1)]			542	478	13.6
LT-A2-N5b-8	52N	37.0	9 d	37 d	524	461	13.6
LT-A2-N5b-9	57N	37.0	3 d	31 d	533	470	13.4
LT-A2-N5b-10	59N	47.9[1)]			548	483	13.6
Mean					534	470	13.5

[1)] Ramp loading to failure after long term test

Specimens 51N, 50N, 54N, 56N and 59N did not fail for 11 days at a load level 37 MPa. After this period all these beams were ramp loaded to failure and their corresponding bending strength is given in Table 8. During long term testing, the load duration allowed was until the occurrence of 50 % failure of specimens and the stress level at this stage was 37.0 MPa. After this the long term loading was discontinued.

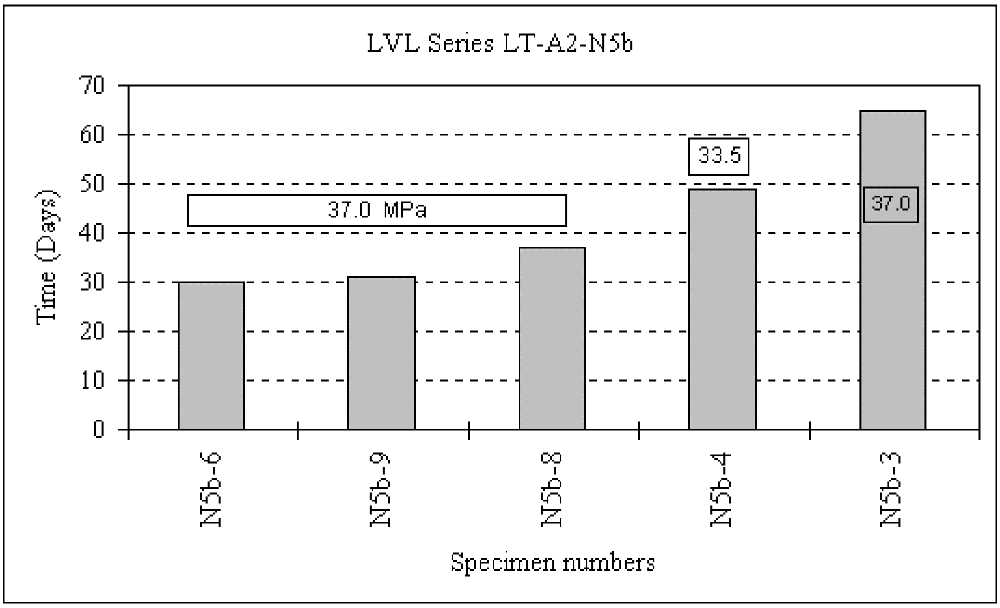

Figure 16. Load-duration plots for specimen series LVL LT-A2-N5b.

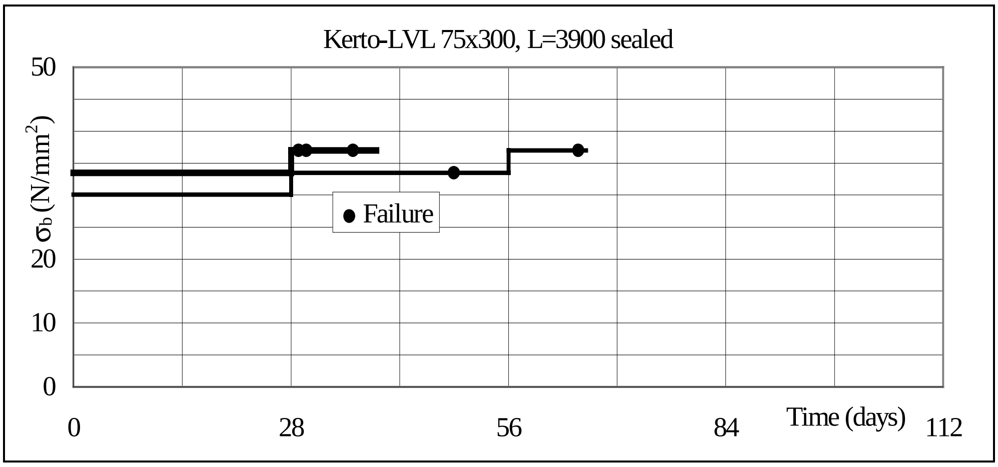

Figure 17. Step-wise loading pattern used for series LT-A2-N5b.

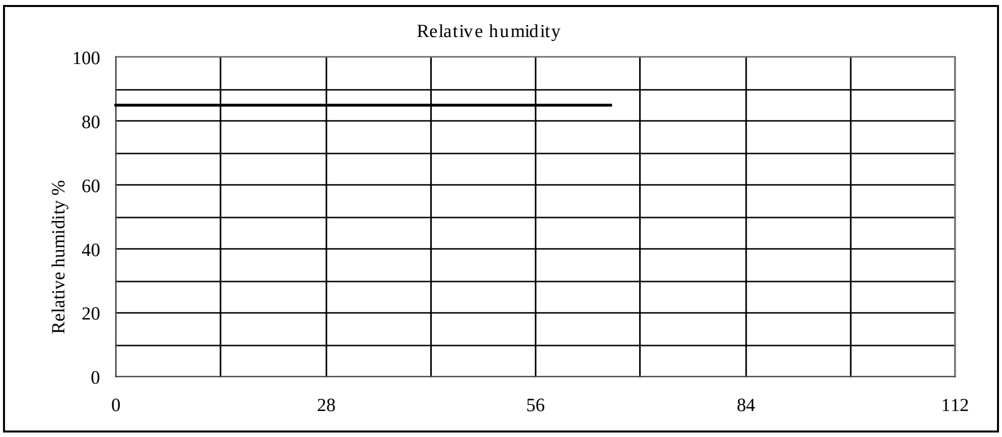

Figure 18. Constant relative humidity used for series LT-A2-N5b.

3.3 ANALYSIS OF RESULTS

The four series of long term tests with LVL specimens which have been completed under stepwise increasing loading are given in Table 9. The long term testing was continued for 28 days at each stress level until at least 50 % of the specimens had failure. In series N, when the loading stress level was 37 MPa the test was terminated after 11 days and a few weeks later the remaining specimens were tested to failure under short term ramp loading.

Table 9. Long term test LVL specimen series.

Test series	Height	RH
E (A2,2)	100 mm	cyclic 55<->90 %
G (A2,4)	300 mm	cyclic 55<->90 %
H (A2,5a)	300 mm	constant 85 %
N (A2,5b)	300 mm	constant 85 %, sealed

Bending stress and time to failure for each specimen was given in previous chapters. In addition, further results are analysed as follows:

1. Cumulative distributions of the bending strength including both the data of failures under long term test and the testing of remaining specimens under short term loading.
2. Load level vs. time-to-failure graphs based on the data of the 5th weakest specimen (out of 10).
3. Remaining strength after long term loading.

All long term test values of 300 mm high beams are illustrated in Figure 19 as a cumulative probability plot. The short term strength of the survived specimens are also shown for comparison. The data indicates clearly that two weakest of the non-failed specimens have been effected by the long term loading. They failed on the stress level of 88 % of their predicted short term strength, whereas the strongest specimens after constant 85 % RH testing (N) had kept the strength practically unchanged.

In changing climate (G) also the strongest specimens were weaker than predicted, which may indicate the effect of changing moisture content or the test specimens in group G have been weaker than the reference short term group due to statistical variation.

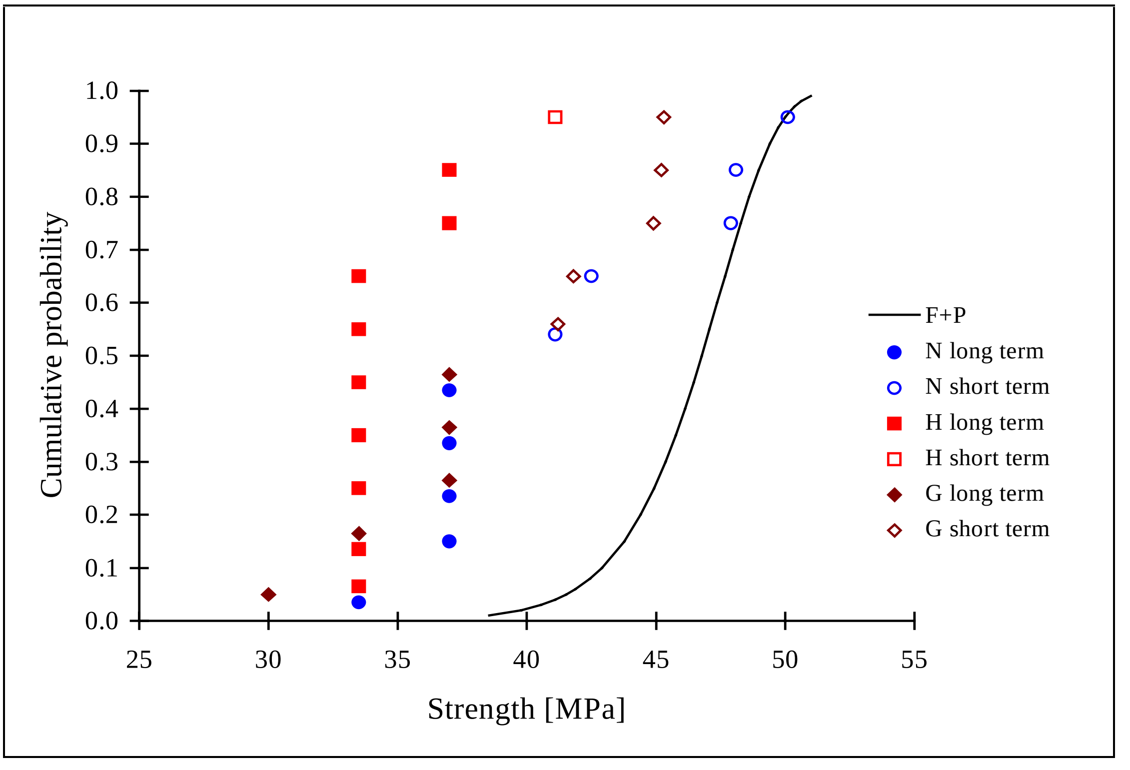

Figure 19. Cumulative probability of failure vs. stress under long term testing of 300 mm high LVL including the ramp loading data of survived beams. The curve is the short term reference strength distribution at 85 % RH. G series was loaded under cyclic humidity, H at 85 % RH and N at 85 % RH with sealed specimens.

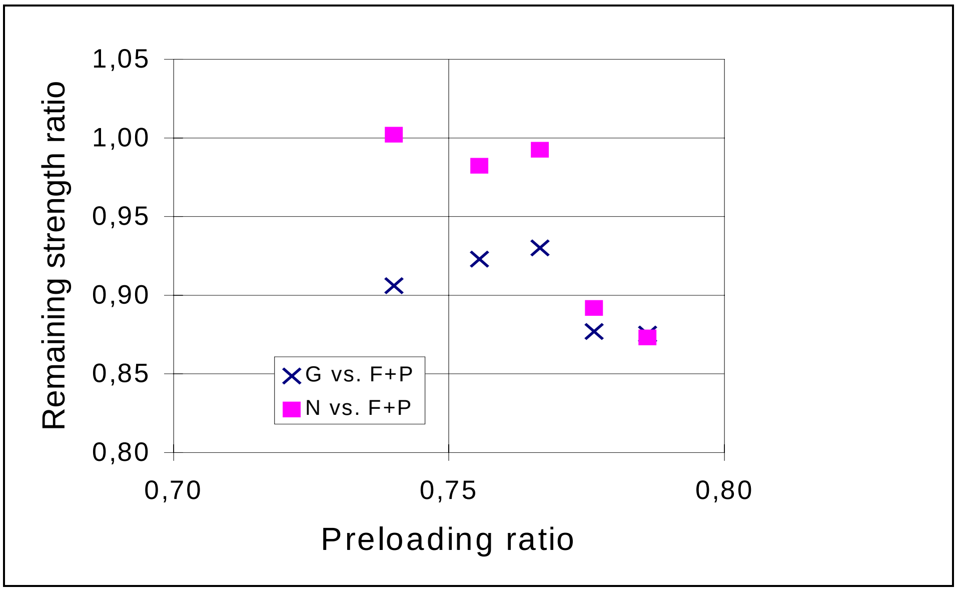

Figure 20. The effect of 4 week loading to remaining residual strength of LVL.

The residual strength values in series G and N have been plotted in Figure 20 against the maximum stress during the preceeding long term loading. Both values are given as a ratio of stress to the predicted short term strength according to ranking method and Weibull distribution fit to the combination of test series F&P. Results indicate that the preloading stress ratio approaching 0.8 has a clear effect on strength, whereas a value of 0.75 has much less effect if any.

The long term strength values are lowest at constant humidity (85 %, series H), higher under cyclic humidity (G), and still a little higher at constant humidity (85 %, N) when the beams were painted (vapor barrier). This indicates that the small changes of humidity in a nominally constant climate (H) may have a noticeable influence to the strength.

Table 10 gives a summary of the time-to-failure results. Time to failure is that of the 5th specimen to fail, and stress ratio is the ratio of stress during failure (nominal stress for the period) to the 45 percentile short term strength at similar moisture content.

The same information is illustrated in Figure 21. The conclusion is that the test cycle is slightly less damaging to 300 mm high beams than the constant 85 % RH. Increasing beam height (100 vs. 300 mm) has a beneficial effect to the duration of load effect under cyclic climate. The extrapolation of stress ratios for the load duration of 6 months are also given in Table 10. Values obtained are similar to those obtained for glued laminated timber in this project (Andreasen & Hoffmeyer, 1997). Both values are more severe than those given in Eurocode 5 for medium term loading (k_{mod} = 0.8 in service class 2).

Table 10. Time-to-failure of the 5th weakest LVL beam (out of 10) or 10th weakest out of 20 in combimed series H+N. k_{DoL} is the ratio of stress at failure to the estimated short term strength of the specimen under similar moisture conditions and k_{mod} is the ratio of stress at failure to the estimated short term strength of the specimen under standard conditions (65 % RH).

Test series	E/B	G/(F+P)	H/(F+P)	N/(F+P)	(H+N)/(F+P)
b x h [mm]	75x100	75x300	75x300	75x300	75x300
Humidity [%]	55<->90	55<->90	85	85 sealed	85
Time-to-failure [days]	26	21	13	9	3
Stress ratio k_{DoL}	0.72	0.80	0.72	0.80	0.80
k_{DoL} for 6 months	0.67	0.75	0.64	0.73	0.68
k_{mod} for 6 months	0.60	0.69			0.63

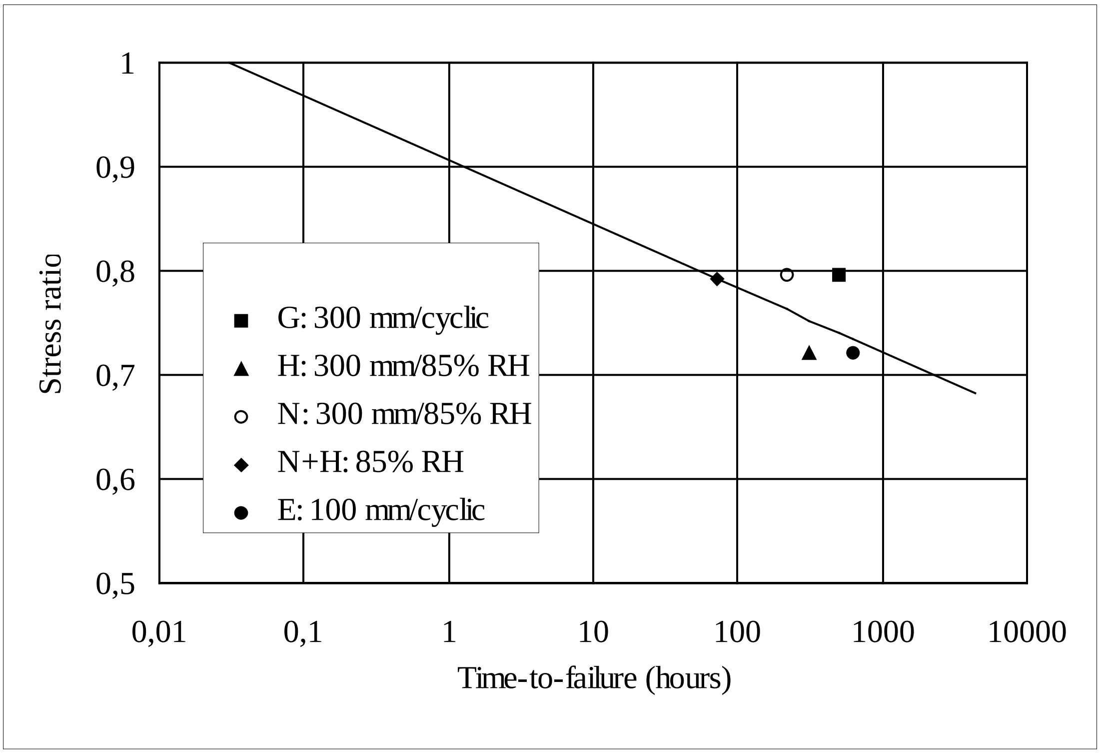

Figure 21. Stress ratio vs. time-to-failure of LVL specimen series.

4 DISCUSSION

The results of reaction forces and deflections measured during long term testing are discussed in this section. The graphical variation of reaction force versus time for all the series is given in Appendix C. As an example, the measured reaction force versus time for series LT-A2-H is given in Figure 22.

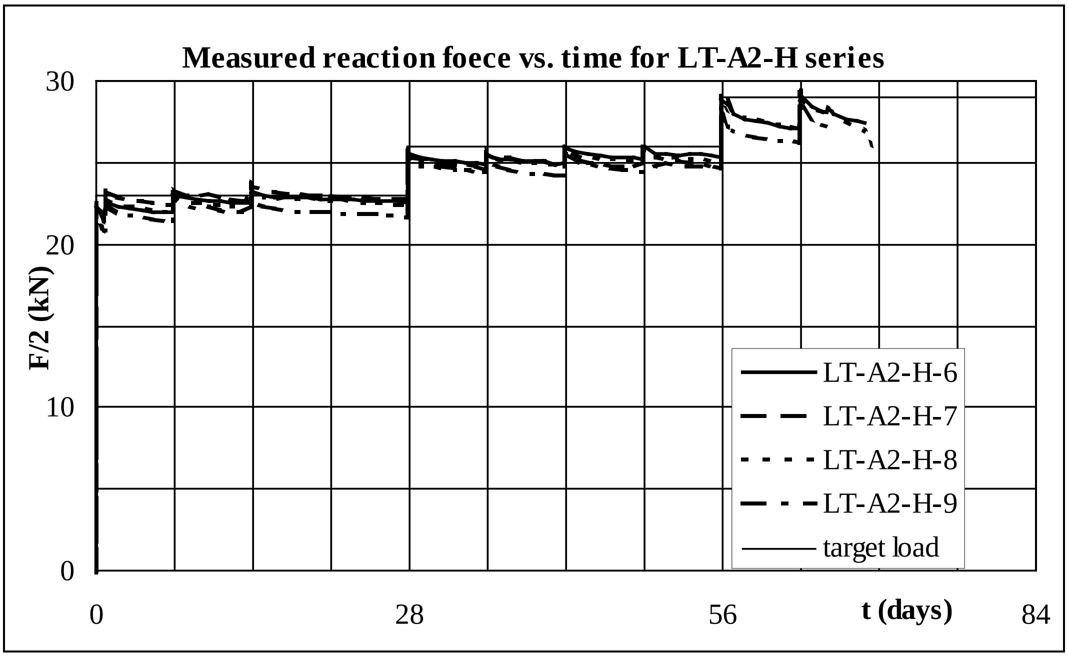

Figure 22. Measured reaction force versus time for LVL series LT-A2-H.

Figure 22 shows the measured reaction force at the support during the long term loading of H series along with the reference target values for all the specimens. As can be seen in the graph, the measured reaction force at the support decreases as the time reaches the 28 days cycle. This is due to continuos creeping of beams under load during experiment. Loads have been corrected to the nominal value once a week. The measurement illustrates that load applied to the beams was not constant, and therefore the duration of load results may not be identical to those obtained under ideal constant load conditions.

The deflection versus time plots for LVL beams in series H is shown in Figure 23. The graph indicates that the deflection measurement was not reliable in all cases. The reason is due to the fact that some of the transducers did not work during experiment at high humidity. In appendix D the lines represent data measured using instruments, while the points represent manually measured values. Manual measurements were added to the program when the problems with electrical measurements were realised. The deflection measurement results are not considered very useful, because of the doubtful reliability of the data. However they are documented in Appendix D.

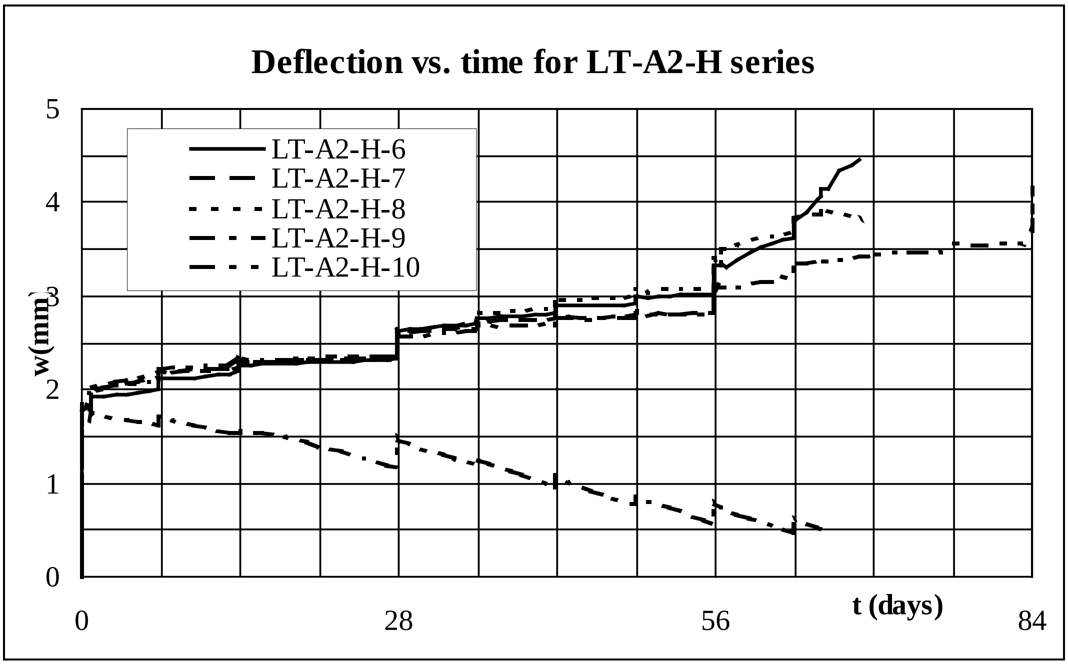

Figure 23. Deflection versus time for LVL specimen series LT-A2-H.

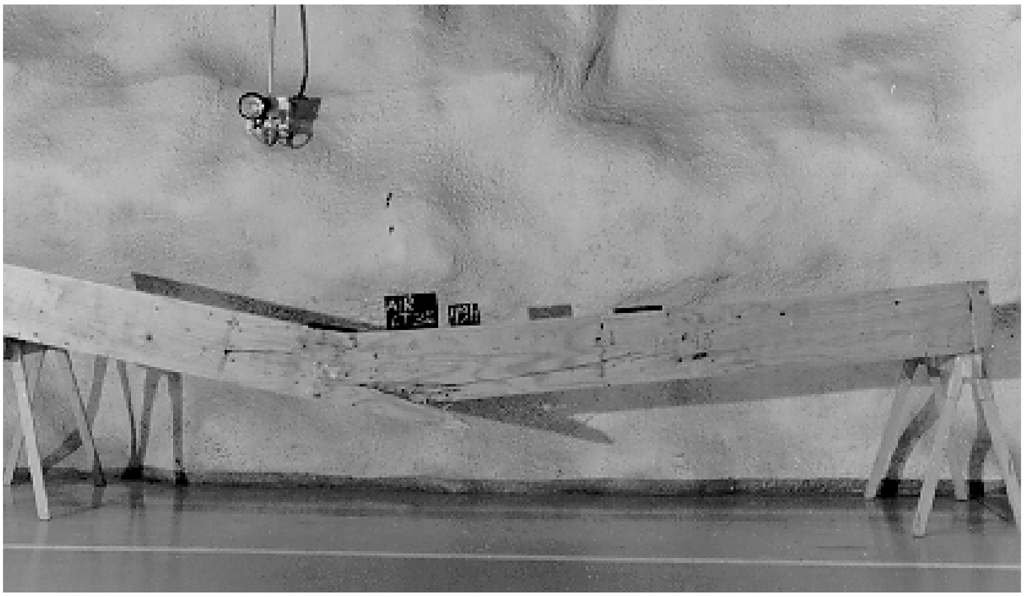

Figure 24. Failure behaviour of beam 49H in LT-A2-H5b series.

The photographs of failure behaviour of specimens for all the series are given in Appendix E. As an example, failure behaviour for beam 49H is shown in Figure 24.

5 CONCLUSIONS

Duration of load experiments were conducted with structural size cross-sections of 75 x 300 mm, at constant (nominally 85 % RH, measured 13.5 % MC) and at cyclic climate. The variation between 55 and 90 % RH with cycle length of 28 days produced less severe duration of load effect than constant moisture content. Most severe strength reduction was obtained in case of smaller cross-section, 75x100 mm, when the cyclic humidity resulted in the same k_{DoL}-factor as given by the traditional Madison curve.

When stress ratios are extrapolated to 6 months and compared to k_{mod}-factor given in Eurocode 5 for medium term load duration (0.8), it will be noticed that duration of load effect observed in experiments with wooden materials is more severe than that adopted in Eurocode 5. A new proposal can be made when results of all partners in this project are combined.

In conclusion, it can be stated that duration of load behaviour of LVL is very close to that observed for solid wood. Under cyclically changing climate, however, LVL showed higher long term strength than was expected on the basis of sawn timber results. Especially the larger coss-section is less sensitive to weekly or monthly humidity variation.

All failures under long term load took place at the load level of 0.7 to 0.8 times the actual short term strength of the specimen, based on ranking method. When testing the remaining strength of the survived specimens, it was clearly indicated that long term load level exceeding 0.77 times the short term strength had an influence on the residual strength, reducing it by 10 %. It has to be noticed, however, that all these numbers depend on the test arrangement:

- maximum duration of load at one stress level was 28 days,
- increase of load by 10 % per load step, and
- long term loading was made by a spring system, the consequence being that the nominal load was not maintained, instead the load was relaxing and corrected weekly to the nominal value, which is expected to result in somewhat higher values for long term strength than would be in load controlled case.

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Fonselius, M. and Ranta-Maunus, A. 1996. Duration of load effect on LVL beams. Part 1. Short term reference tests. Espoo: VTT Research Notes 1789. 23 p. + app. 17 p.

Gowda, S. and Ranta-Maunus, A. 1996. Duration of load effect on curved glulam beams. Part 1. Short term reference tests. Espoo: VTT Research Notes 1741. 66 p. + app. 11 p.

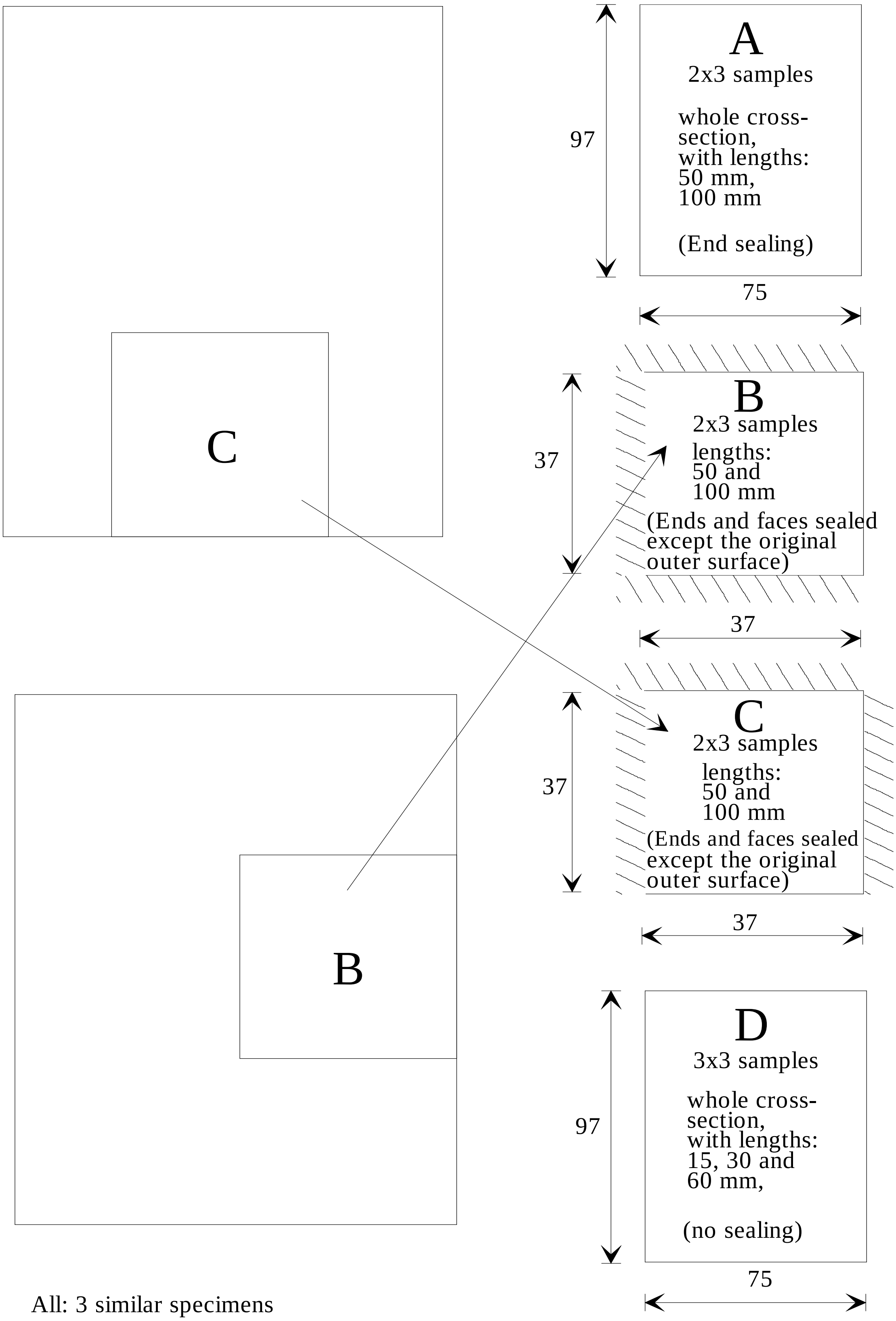
Gowda, S., Kortesmaa, M. & Ranta-Maunus, A. 1998. Duration of load effect on curved glulam beams. Part 2. Long term load tests and analysis. Espoo: VTT Publications 334. 76 p. + app. 28 p.

Hanhijärvi, A. 1997. Development of a computational method for analysis of the strength reduction of LVL-beams due to long-term loading and variable environment. COST Action E8 Conference, Copenhagen 16. - 17.6.1997.

MOISTURE MEASUREMENTS

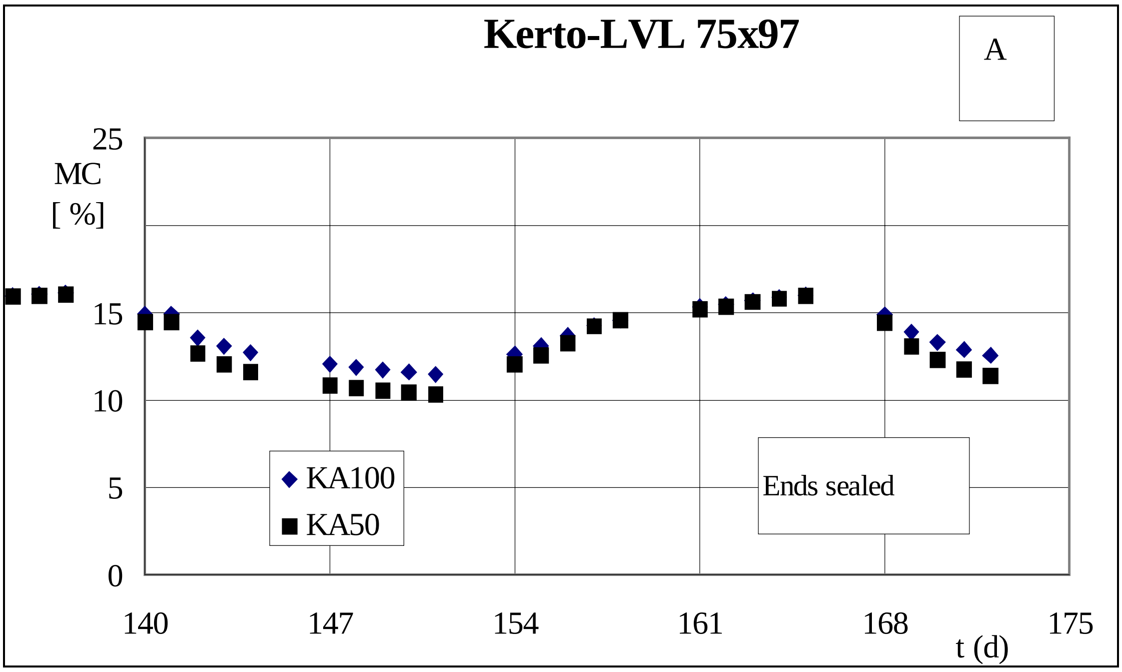
Appendix A

LVL Moisture samples

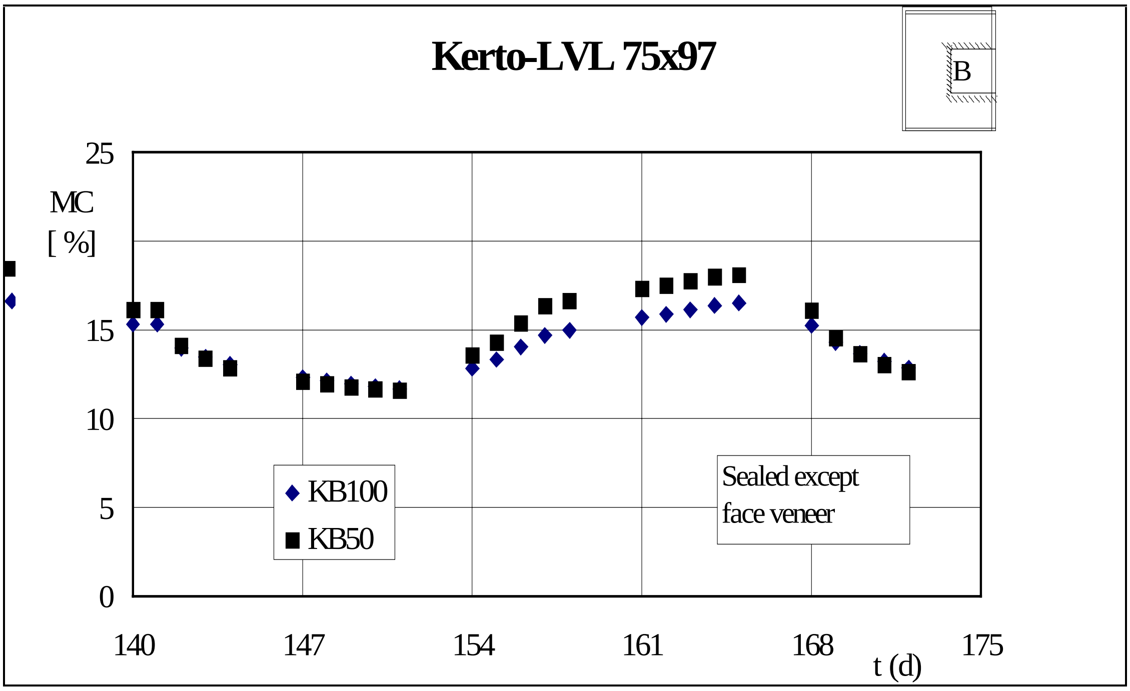


All: 3 similar specimens

Variation of moisture in LVL samples



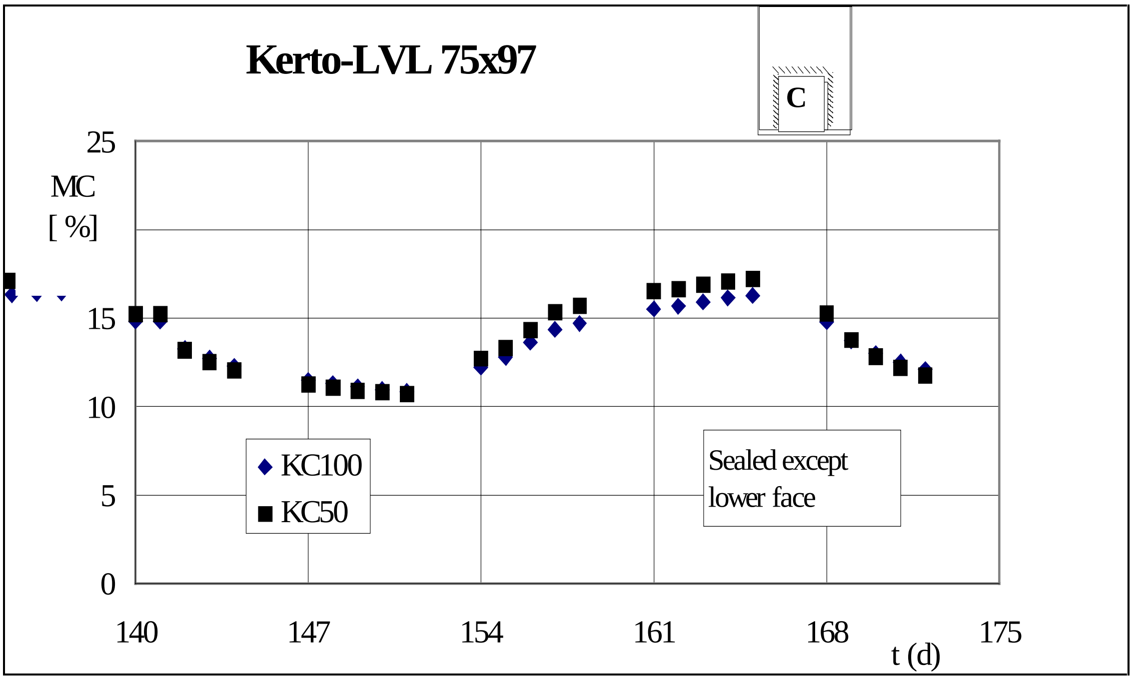
Variation of moisture in LVL samples.



Variation of moisture in LVL samples.

Appendix A3

Variation of moisture in LVL samples



Variation of moisture in LVL samples.

INDIVIDUAL SPECIMEN DATA

Appendix B

Measurements of additional short term test series P:

ID	ω %	$\rho_{\omega,\omega}$ kg/m^3	$\rho_{0,\omega}$ kg/m^3	f_m N/mm^2	E_m N/mm^2	E_{mapp} N/mm^2
50P	14.2	513	450	45.0	12376	11508
51P	14.2	520	455	44.9	12165	11154
52P	14.0	519	455	49.8	11237	9872
53P	13.8	525	461	46.5	11727	10417
54P	14.0	537	471	47.0	13201	11872
55P	13.8	525	462	45.2	12041	11395
56P	14.4	530	464	45.9	13012	11673
57P	14.2	526	461	43.8	11894	10907
58P	14.1	533	467	45.2	12481	11343
59P	14.2	524	459	43.8	12286	11160
Mean	**14.1**	**525**	**460**	**45.7**	**12242**	**11130**
Stdev	0.2	7	6	1.8	580	600
Number	10	10	10	10	10	10

Density and moisture content values for LVL beams failed in long term test: Series G and H.

Number	Beam	Height (mm)	Width (mm)	Length (mm)	Weight before ovendry (kg/mm3)	Weight after ovendry (kg/mm3)	Density before ovendry ρ_u	Density after ovendry ρ_0	Moisture content u (%)
9	48H	259.59	75.88	24.90	258.81	228.63	528	466	13.2
10	47H	259.16	76.80	24.71	256.91	227.05	522	462	13.2
11	46H	259.19	77.10	25.15	262.07	232.75	521	463	12.6
12	40H	259.46	76.37	24.88	263.47	232.93	534	472	13.1
13	49H	259.50	77.46	25.62	265.42	235.33	515	457	12.8
9	43H	259.44	76.32	25.09	256.79	227.35	517	458	12.9
10	44H	259.86	76.05	25.34	263.12	233.88	525	467	12.5
11	42H	259.71	76.59	25.17	260.14	231.08	520	462	12.6
12	41H	259.34	77.63	25.09	270.94	239.94	536	475	12.9
13	45H	259.28	77.13	25.46	268.69	239.08	528	470	12.4
10	44G	259.26	76.50	25.37	255.40	229.52	508	456	11.3
11	45G	259.59	76.84	25.49	260.79	234.46	513	461	11.2
14	40G	259.15	76.67	25.67	260.95	235.11	512	461	11.0
17	49G	259.61	77.23	25.20	259.80	234.01	514	463	11.0
18	47G	259.54	77.11	24.40	250.78	225.82	514	462	11.1
Mean							**520**	**464**	**12.2**

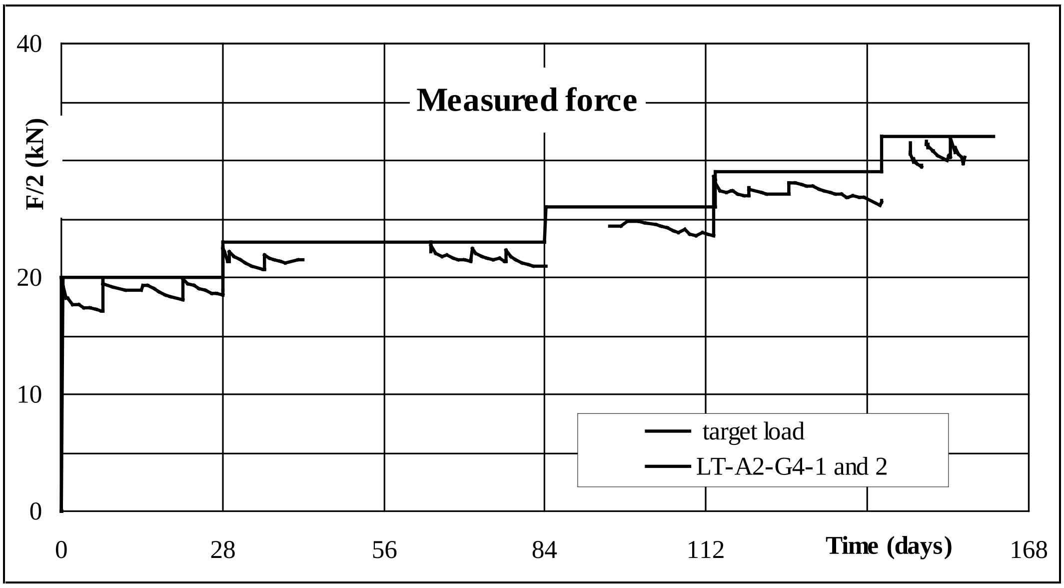
Density, moisture content, strength and stiffness values for LVL beams failed in ramp loading after long term test:

ID	ω %	$\rho_{\omega,\omega}$ kg/m^3	$\rho_{0,\omega}$ kg/m^3	f_m N/mm^2	E_m N/mm^2	E_{mapp} N/mm^2
41G	14.1	514	450	45.3	11106	10504
42G	14.1	515	452	45.2	10572	9745
43G	14.2	537	470	44.9	11331	10056
46G	14.2	530	464	41.2	11149	9770
48G	14.2	530	464	41.8	11152	10039
Mean	**14.1**	**525**	**460**	**43.7**	**11062**	**10023**
Stdev	0.0	10	9	2.0	287	306
Number	5	5	5	5	5	5

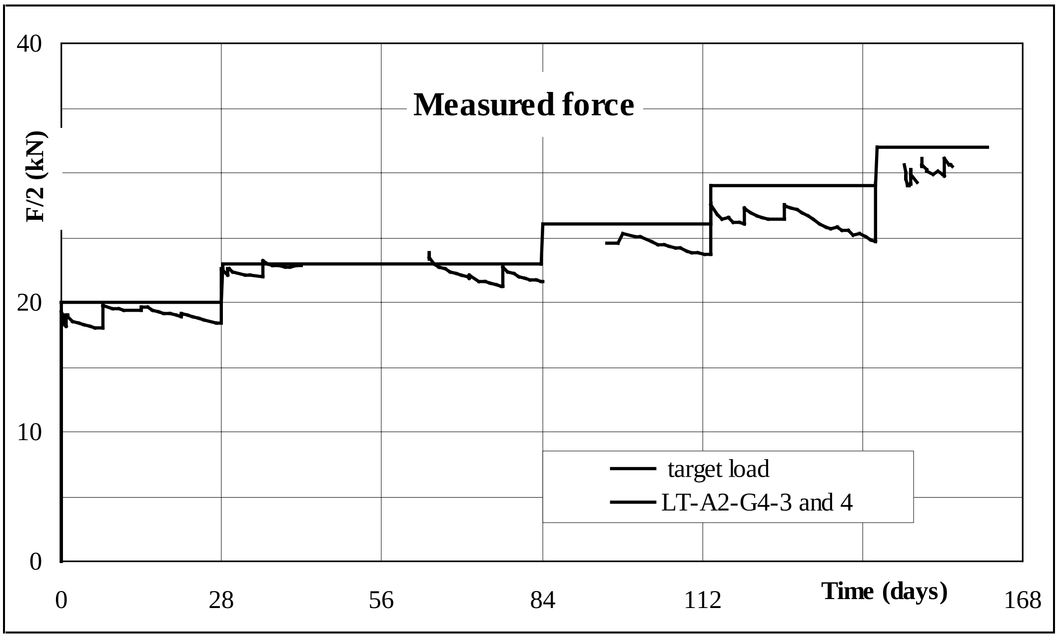
ID	ω %	$\rho_{\omega,\omega}$ kg/m^3	$\rho_{0,\omega}$ kg/m^3	f_m N/mm^2	E_m N/mm^2	E_{mapp} N/mm^2
50N	13.3	527	465	42.5	10682	10092
51N	13.4	523	462	41.1	10219	9799
54N	13.7	539	474	48.1	12686	11130
56N	13.6	542	478	50.1	12496	10672
59N	13.6	548	483	47.9	11490	10447
Mean	**13.5**	**536**	**472**	**46.0**	**11515**	**10428**
Stdev	0.2	11	9	3.9	1085	515
Number	5	5	5	5	5	5

Moisture content values are based on a 25 mm high sample taken from the tensile edge of the beam indicating the mean moisture content in most stressed area being 1/6 of the total volume of the beam.

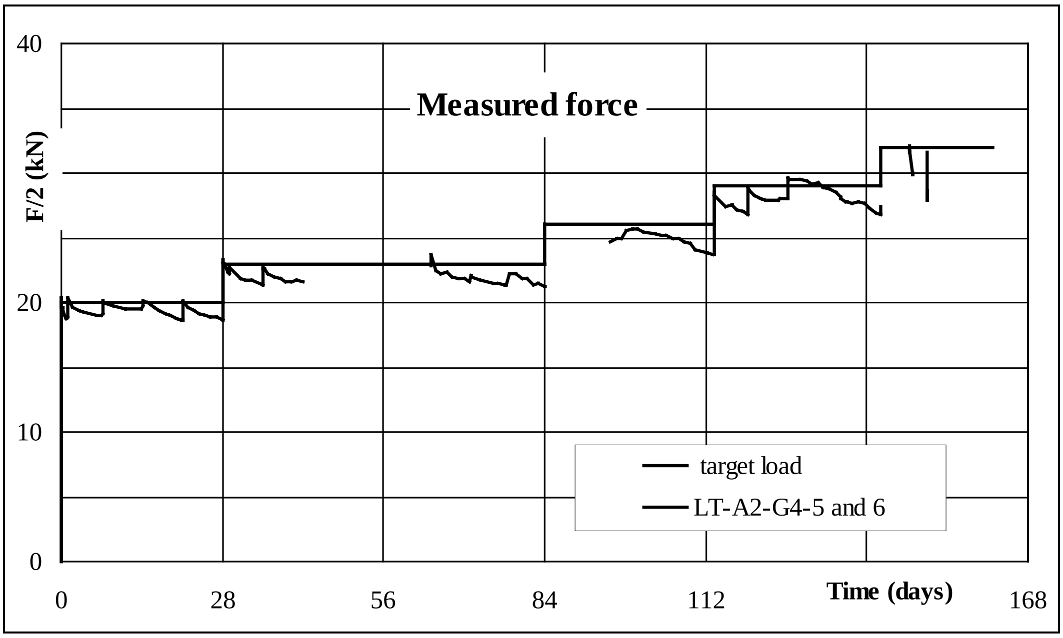
Measured reaction force vs. time for LT-A2-G4 series



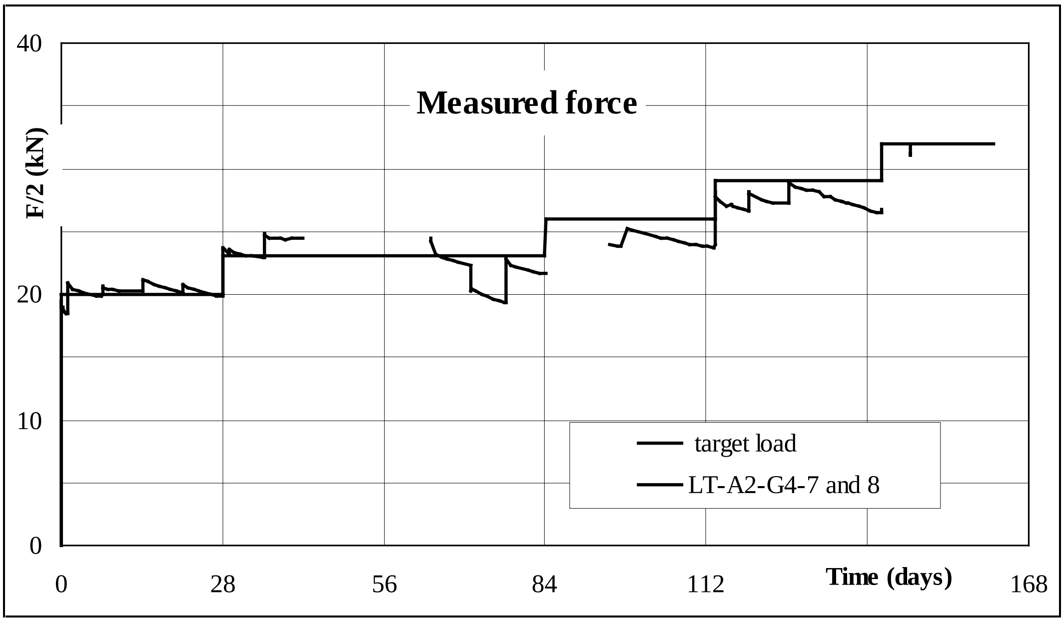
Measured reaction force versus time for specimens LT-A2-G4-1 and 2.



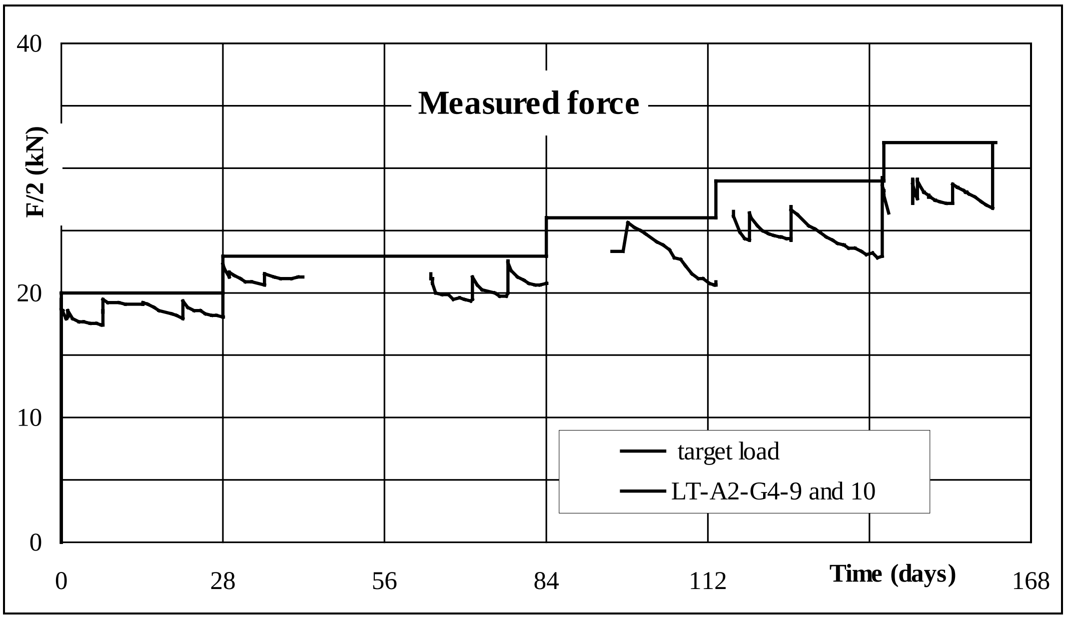
Measured reaction force versus time for specimens LT-A2-G4-3 and 4.



Measured reaction force versus time for specimens LT-A2-G4-5 and 6.

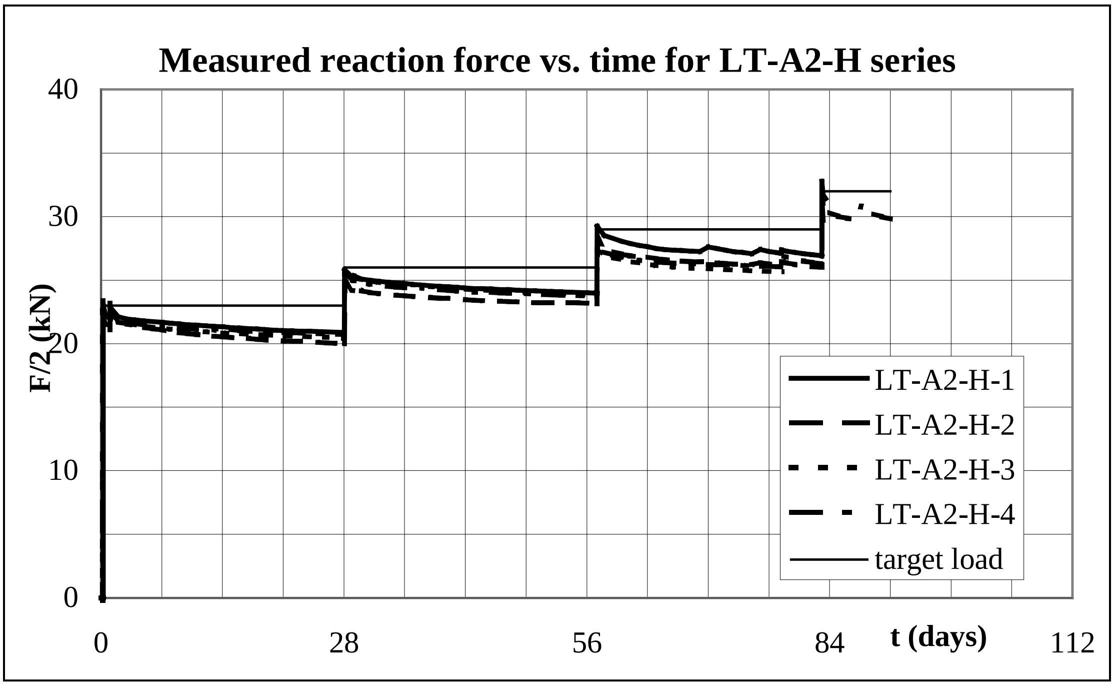


Measured reaction force versus time for specimens LT-A2-G4-7 and 8.

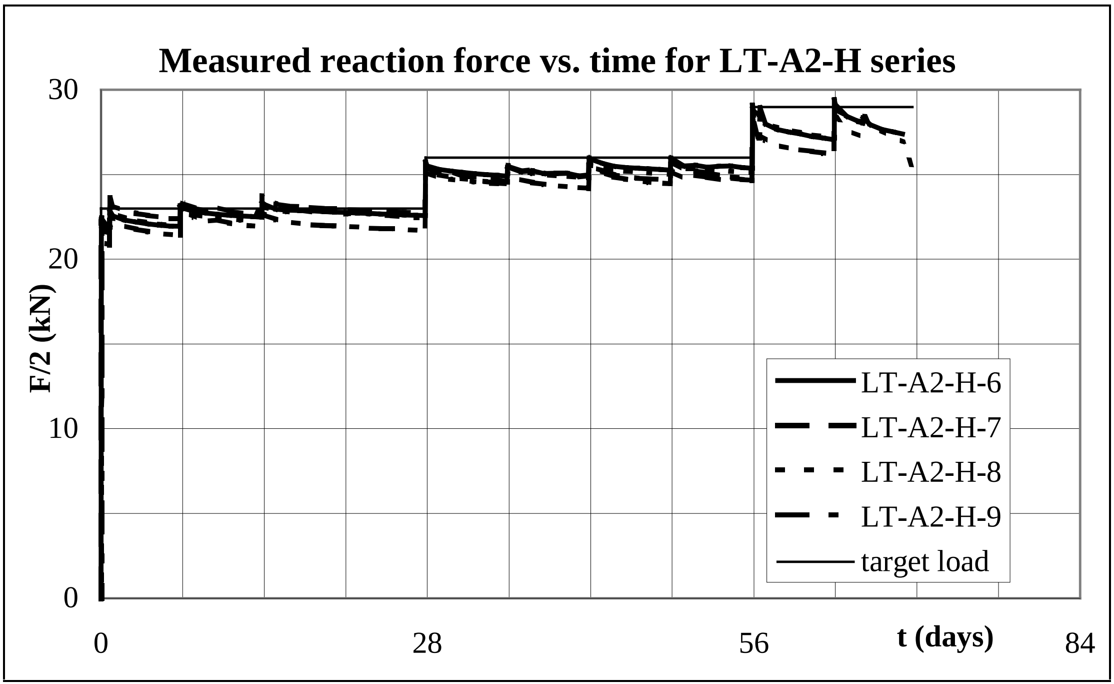


Measured reaction force versus time for specimens LT-A2-G4-9 and 10.

Measured reaction force vs. time for LT-A2-H series

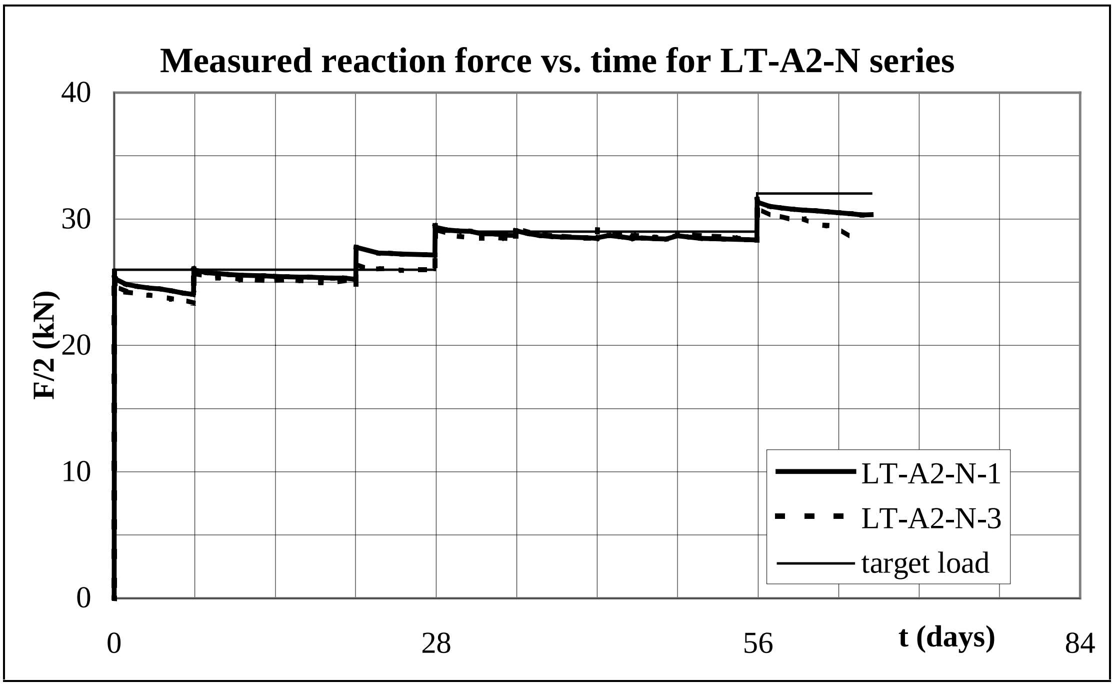


Measured reaction force vs. time for specimen H1 to H4 in LT-A2-H series.

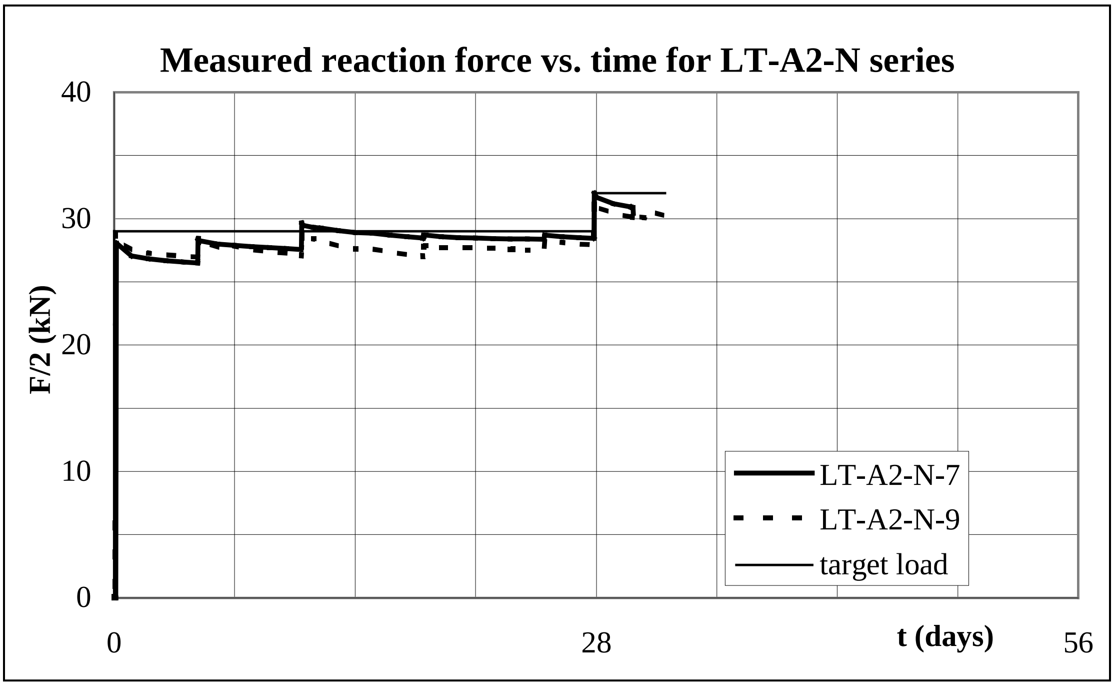


Measured reaction force vs. time for specimen H6 to H9 in LT-A2-H series.

Measured reaction force vs. time for LT-A2-N series

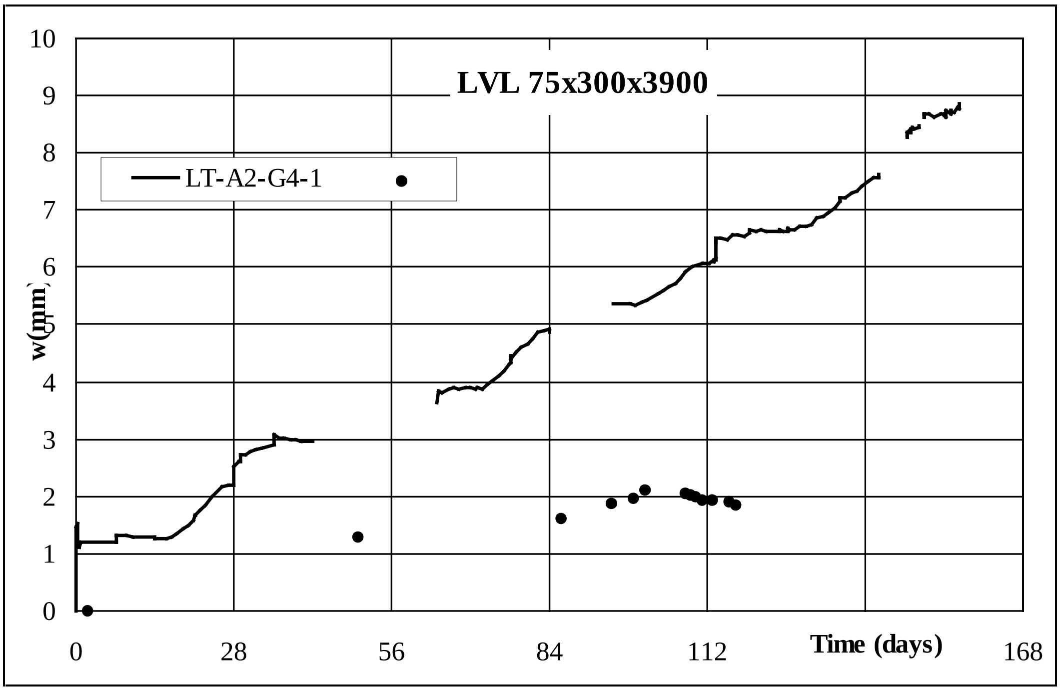


Measured reaction force vs. time for specimens N1 & N3 in LT-A2-N series.

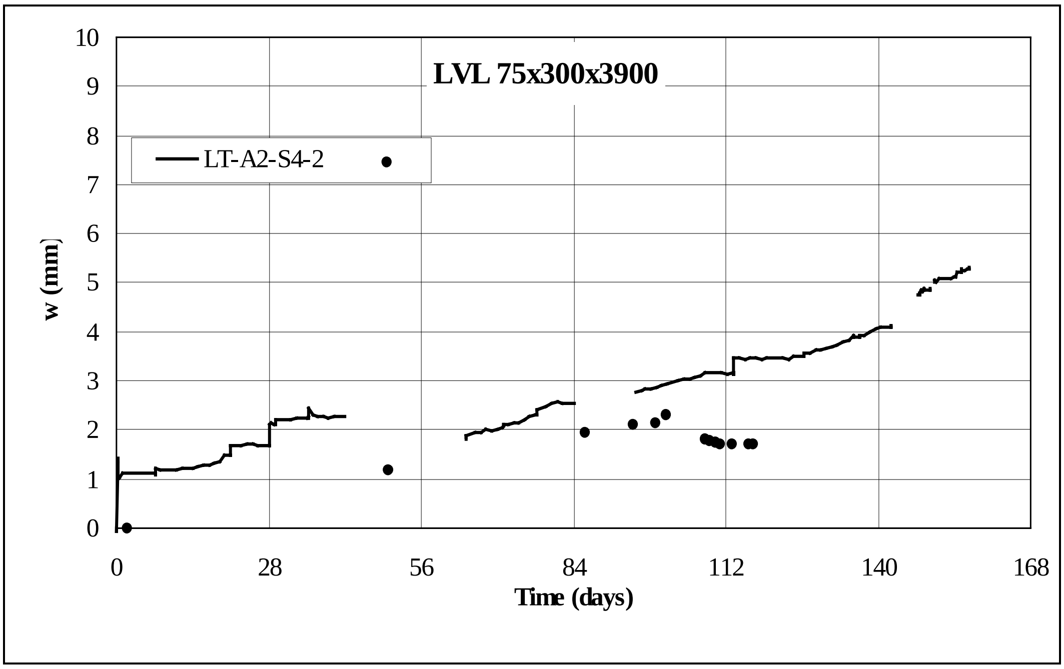


Measured reaction force vs. time for specimens N7 & N9 in LT-A2-N series.

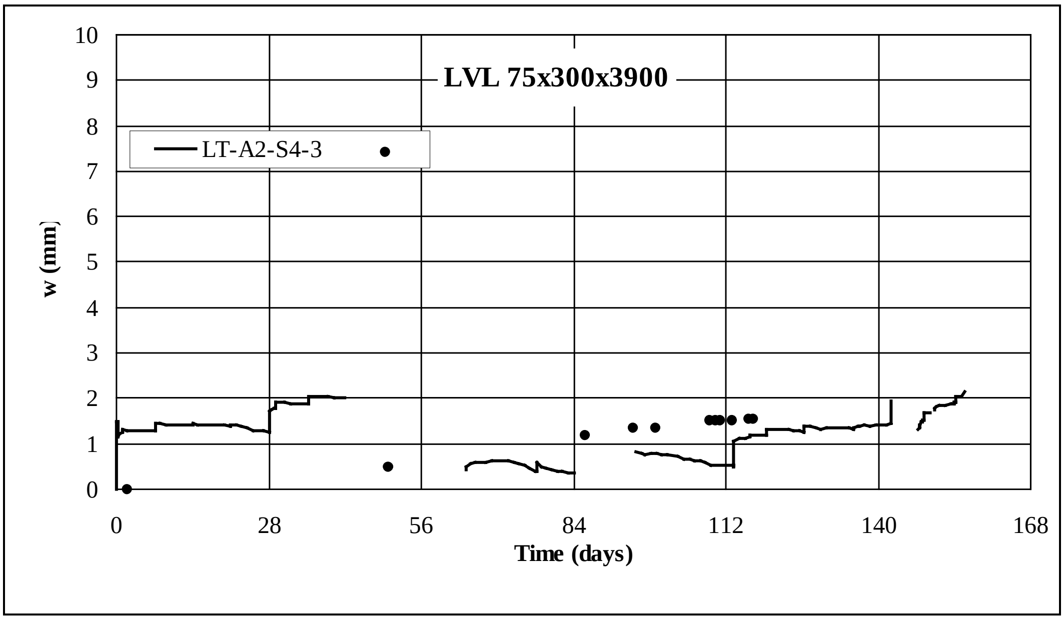
Deformation versus time for LT-A2-G4 series



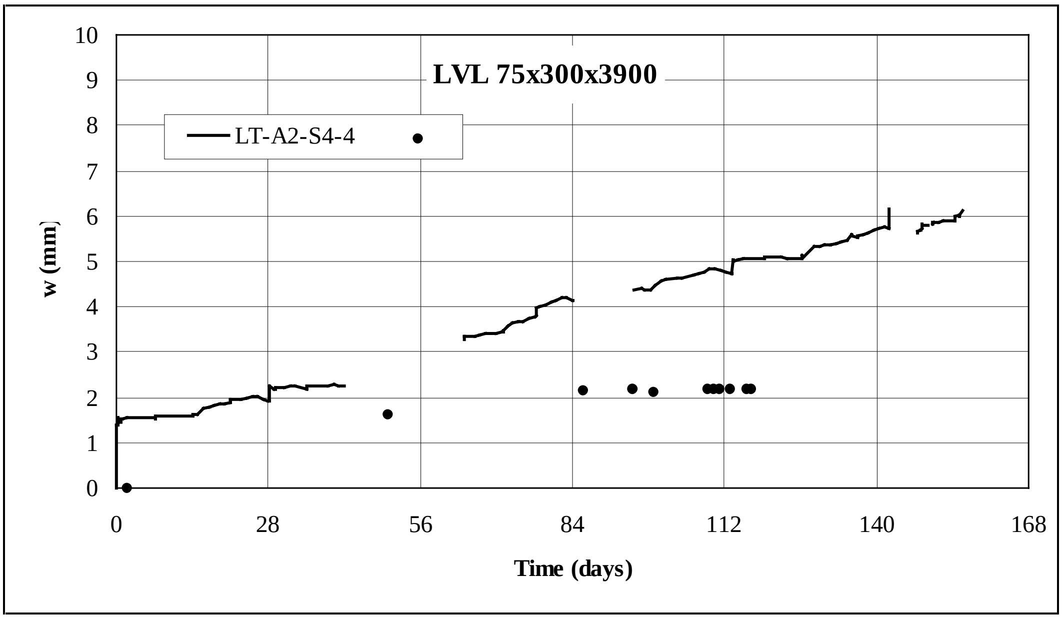
Long term creep deformation versus time for specimen LT-A2-G4-1.



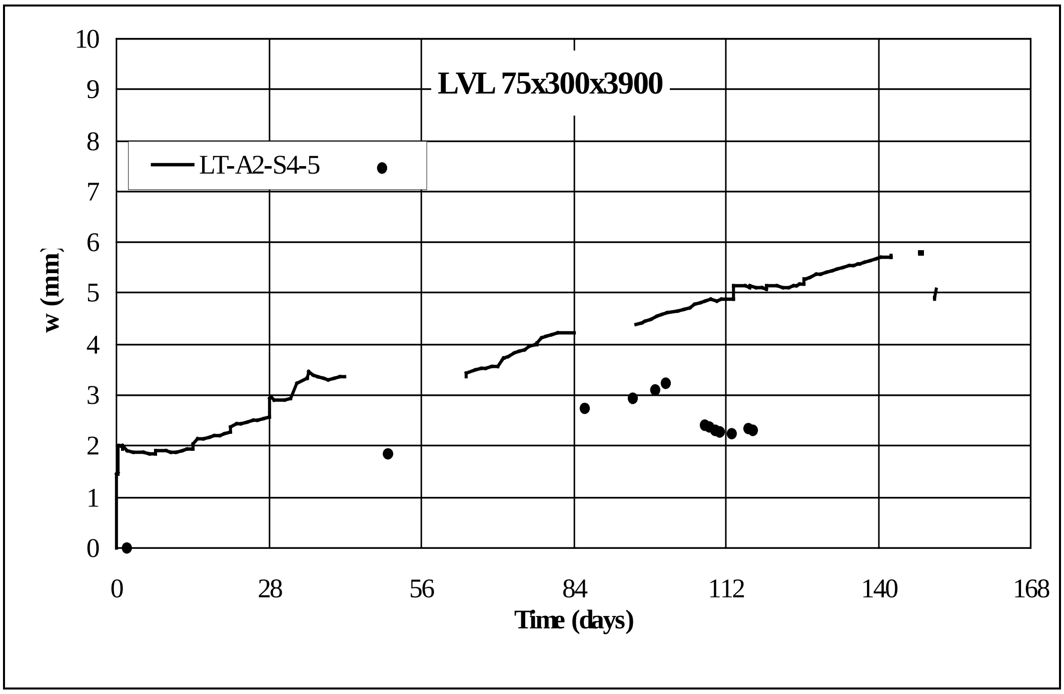
Long term creep deformation versus time for specimen LT-A2-G4-2.



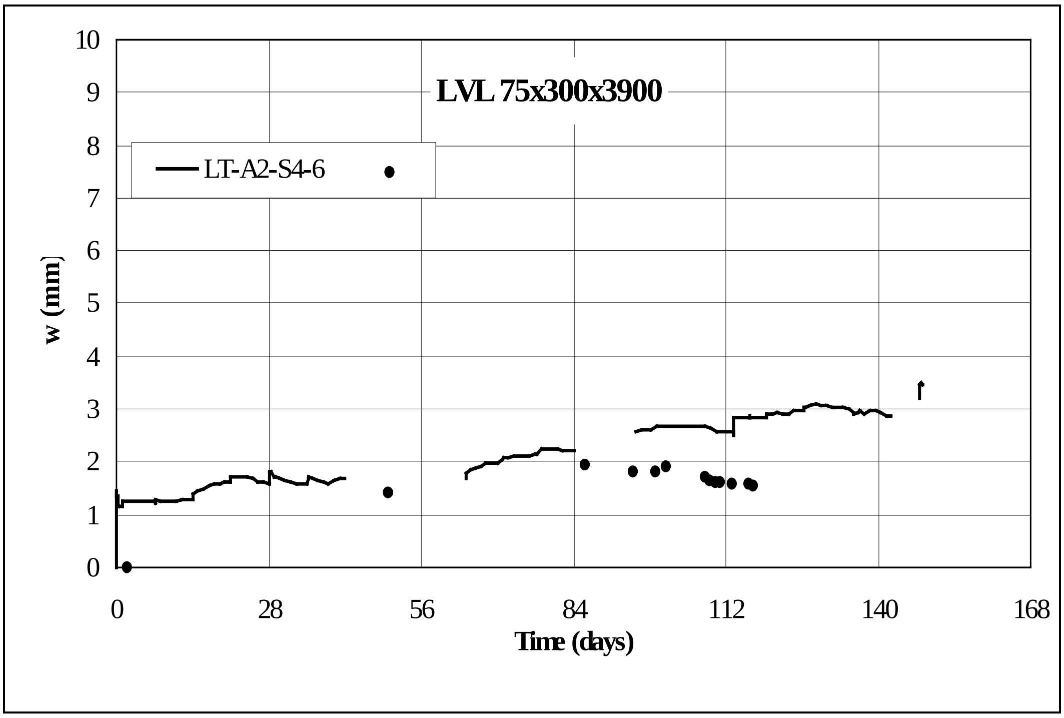
Long term creep deformation versus time for specimen LT-A2-G4-3.



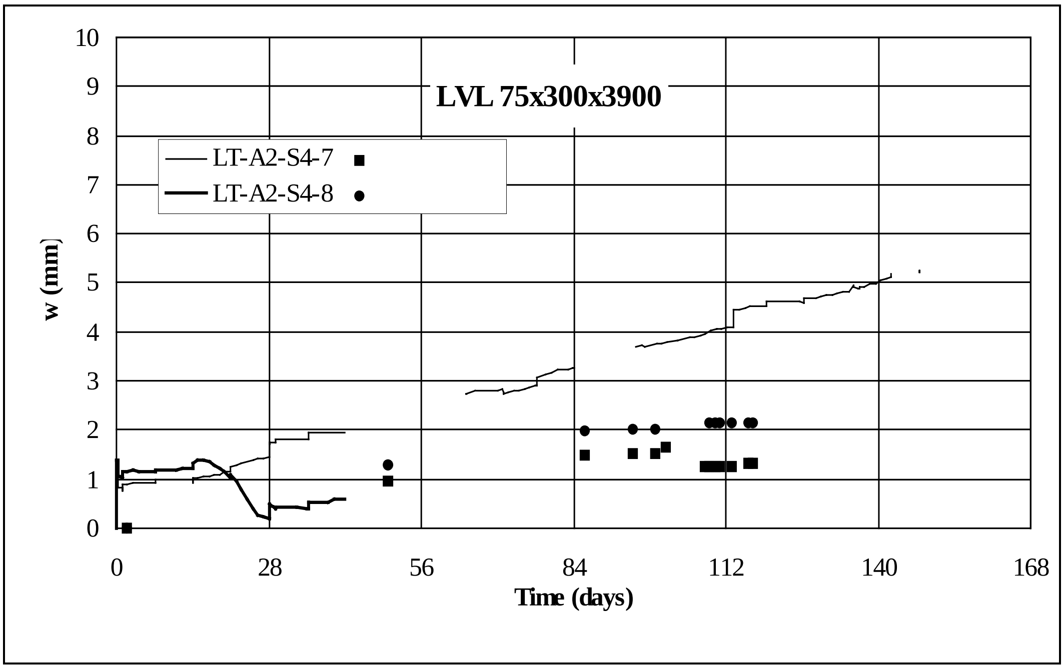
Long term creep deformation versus time for specimen LT-A2-G4-4.



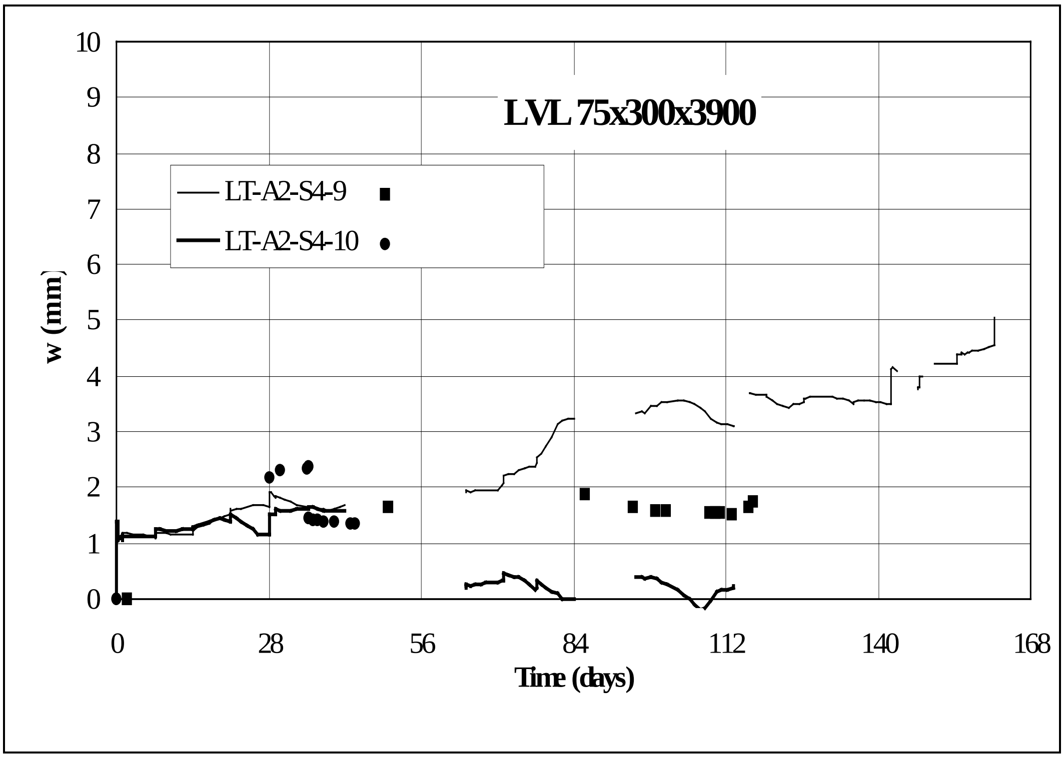
Long term creep deformation versus time for specimen LT-A2-G4-5.



Long term creep deformation versus time for specimen LT-A2-G4-6.

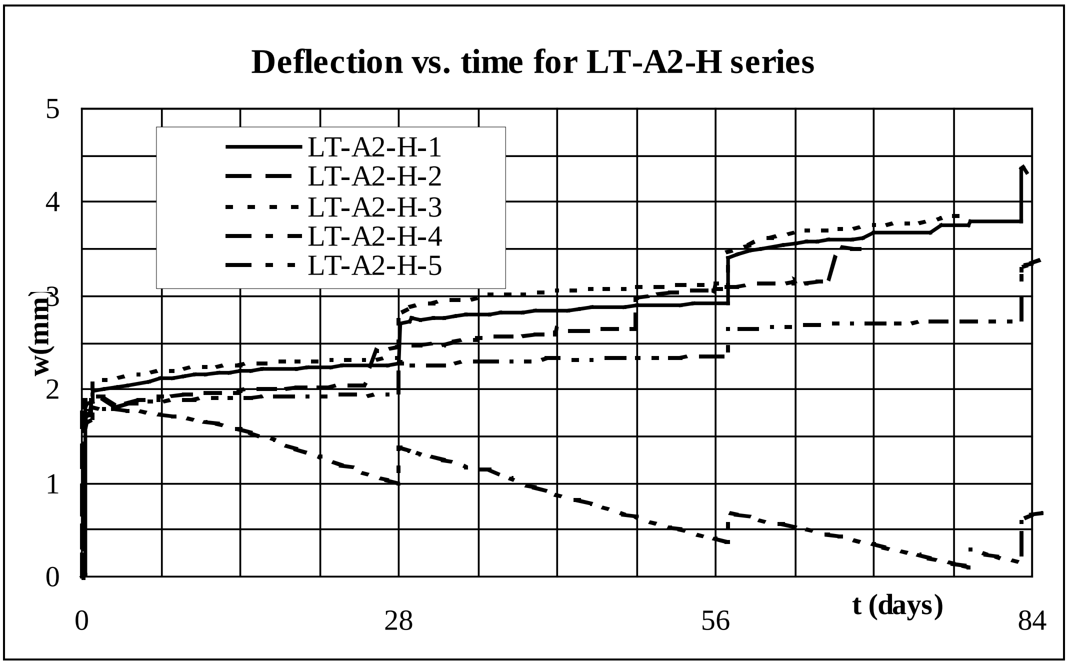


Long term creep deformation versus time for specimen LT-A2-G4-7 and 8.

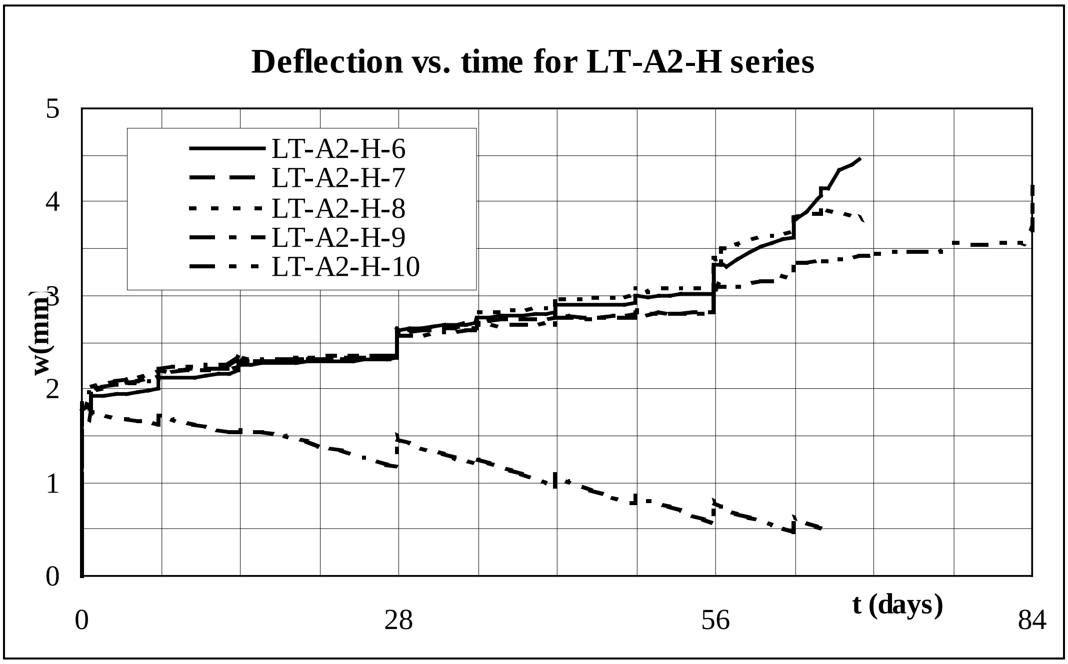


Long term creep deformation versus time for specimen LT-A2-G4-9 and 10.

Deformation versus time for LT-A2-H series

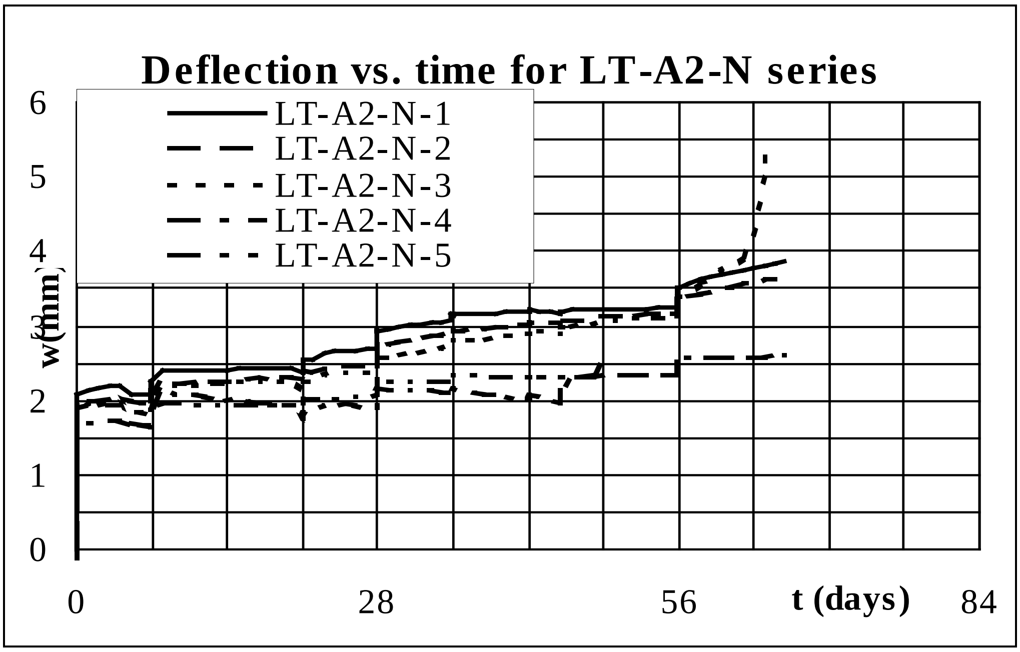


Long term creep deformation vs. time for specimen H1 to H5 in LT-A2-H series.

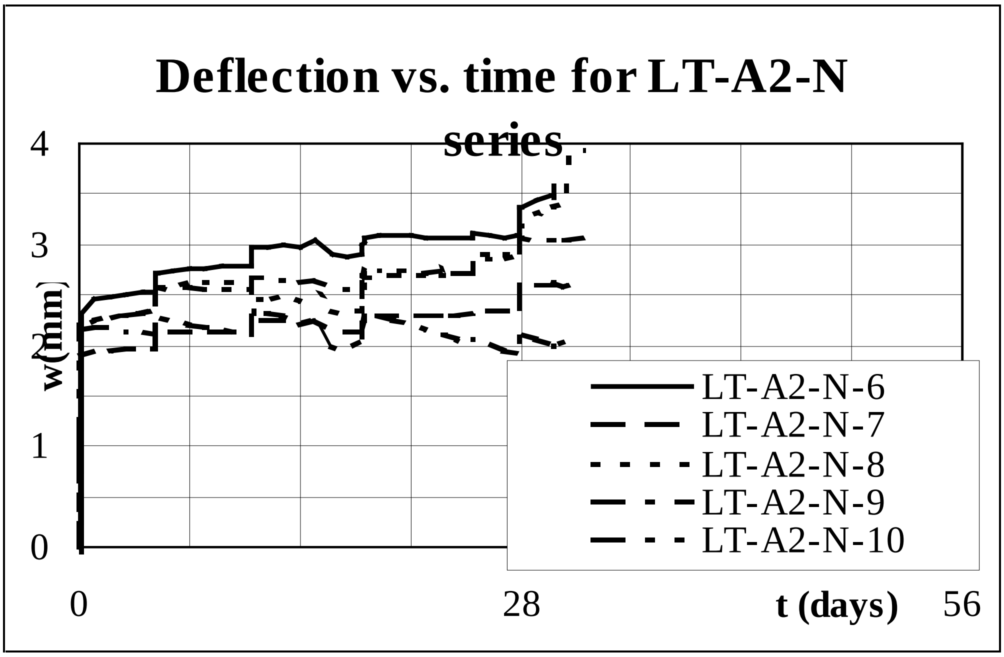


Long term creep deformation vs. time for specimens H6 to H10 in LT-A2-H series.

Deformation versus time for LT-A2-N series



Deflection versus time for specimens N1 to N5 in LT-A2-N series.

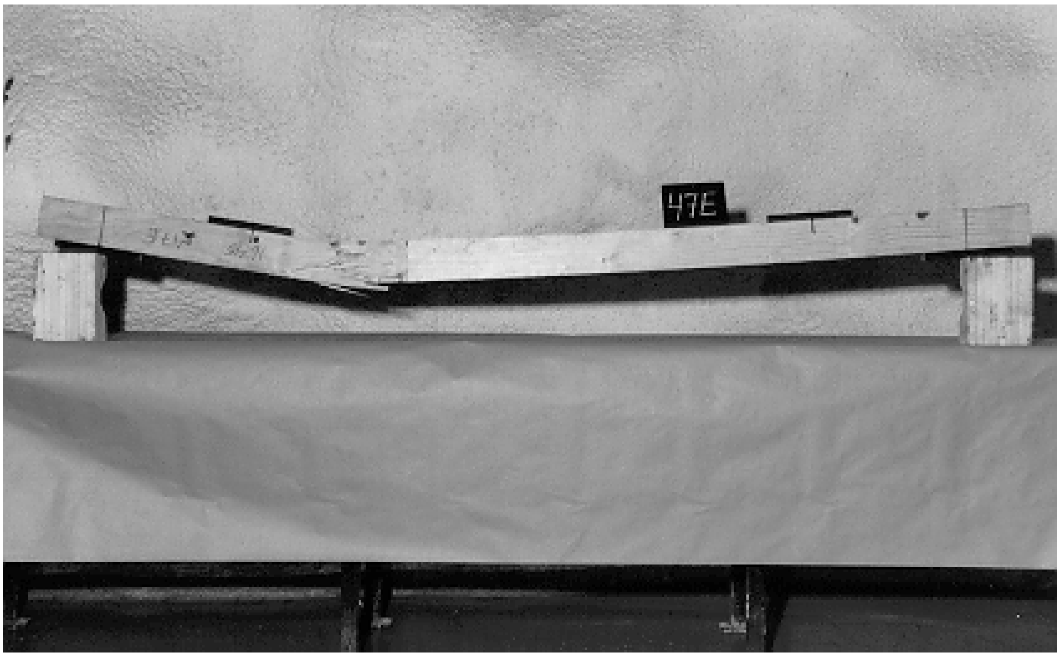


Deflection versus time for specimens N6 to N10 in LT-A2-N series.

PICTURES OF FAILED SPECIMENS Appendix E

Failure behaviour of LVL specimens: Series LT-A2-E2

(75x100x2300 mm)



Failure behaviour of specimen LT-A2-E2-5 (47 E) after 140 days.

Failure behaviour of specimen LT-A2-E2-6 (48 E) after 166 days.

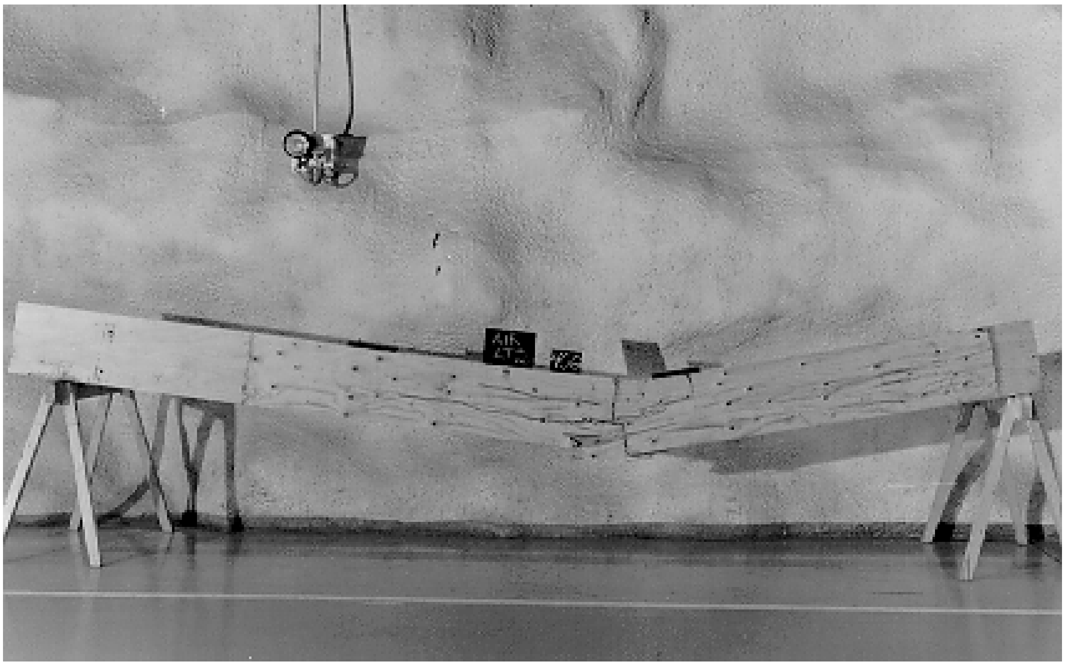
Failure behaviour of specimen LT-A2-E2-8 (49 E) after 148 days.

Failure behaviour of specimen LT-A2-E2-9 (41 E) after 159 days.

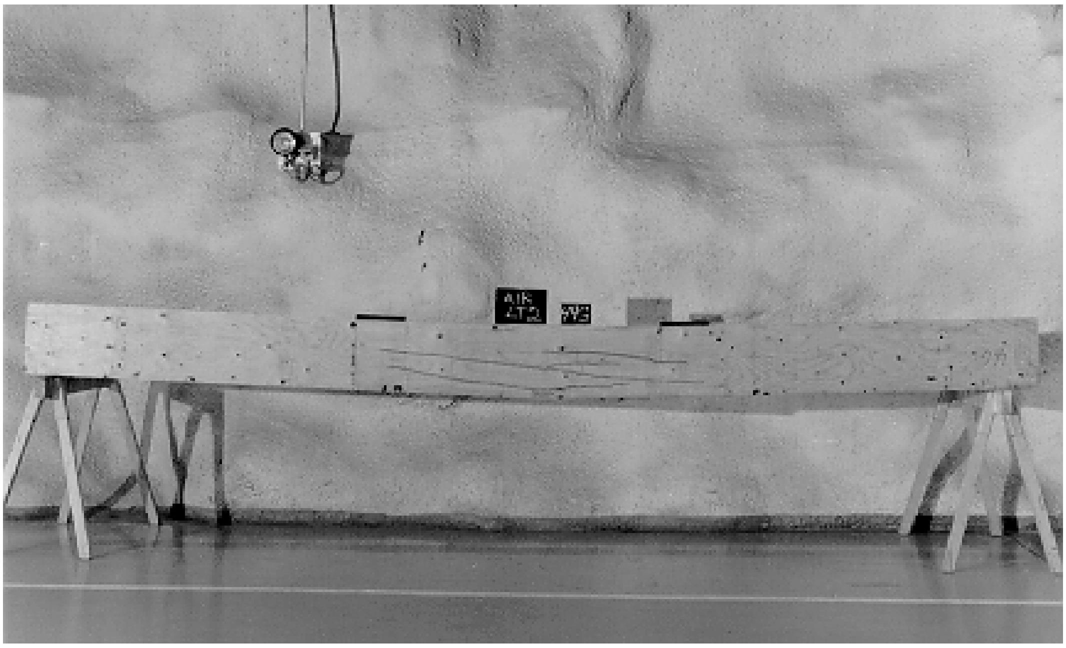
Failure behaviour of specimen LT-A2-E2-10 (42 E) after 148 days.

Failure behaviour of LVL specimens: Series LT-A2-G4

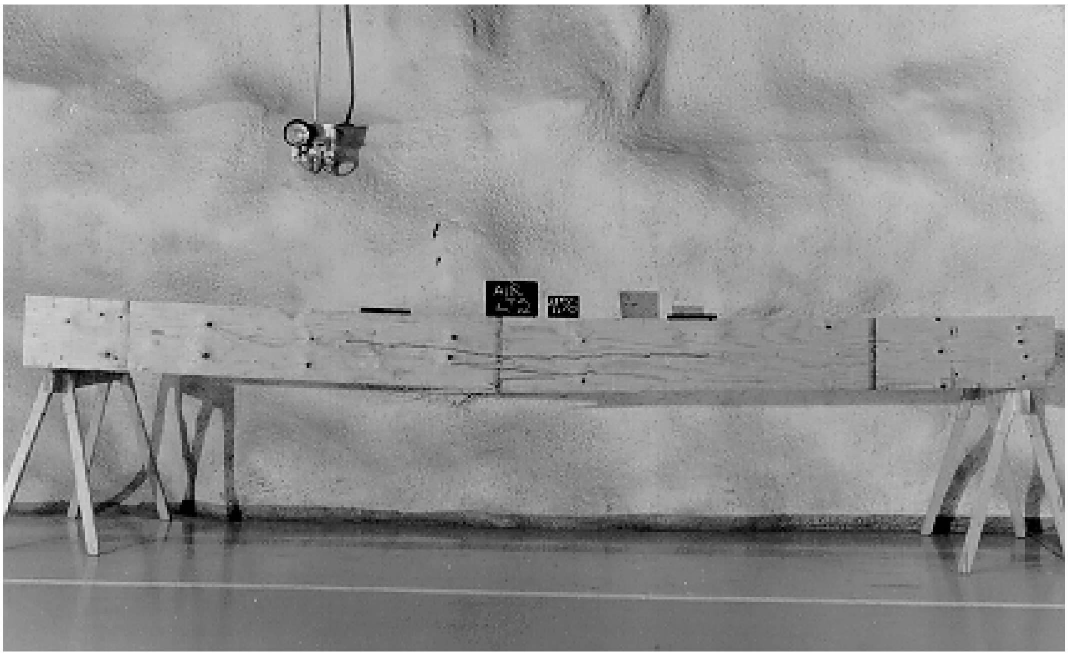
(75x300x4100 mm - only five beams failed in this series)



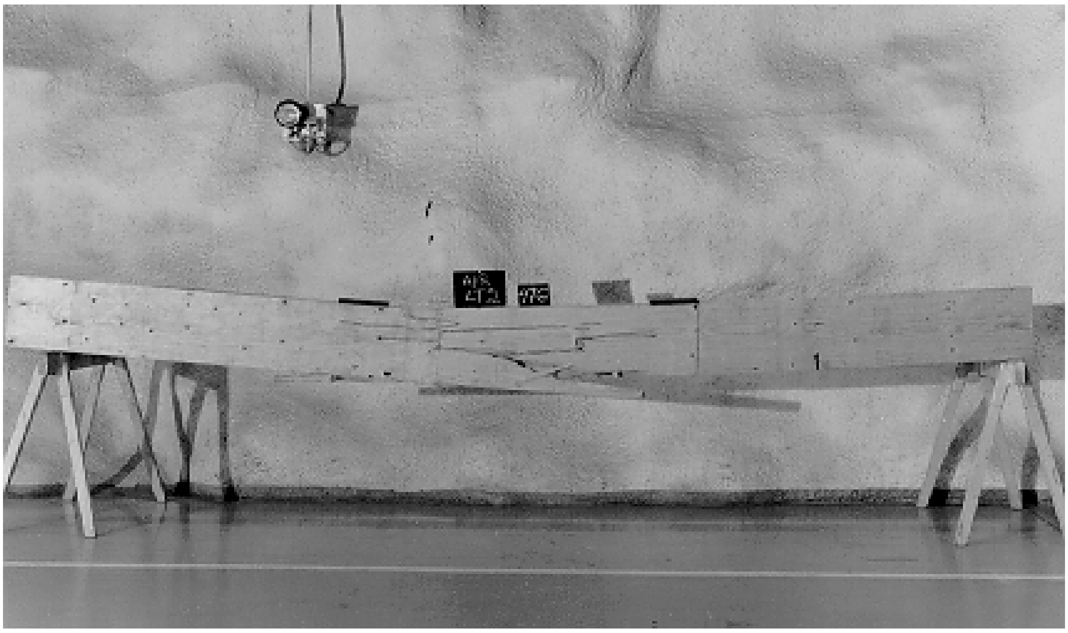
Failure behaviour of specimen (40 G) in series LT-A2-G4-6.



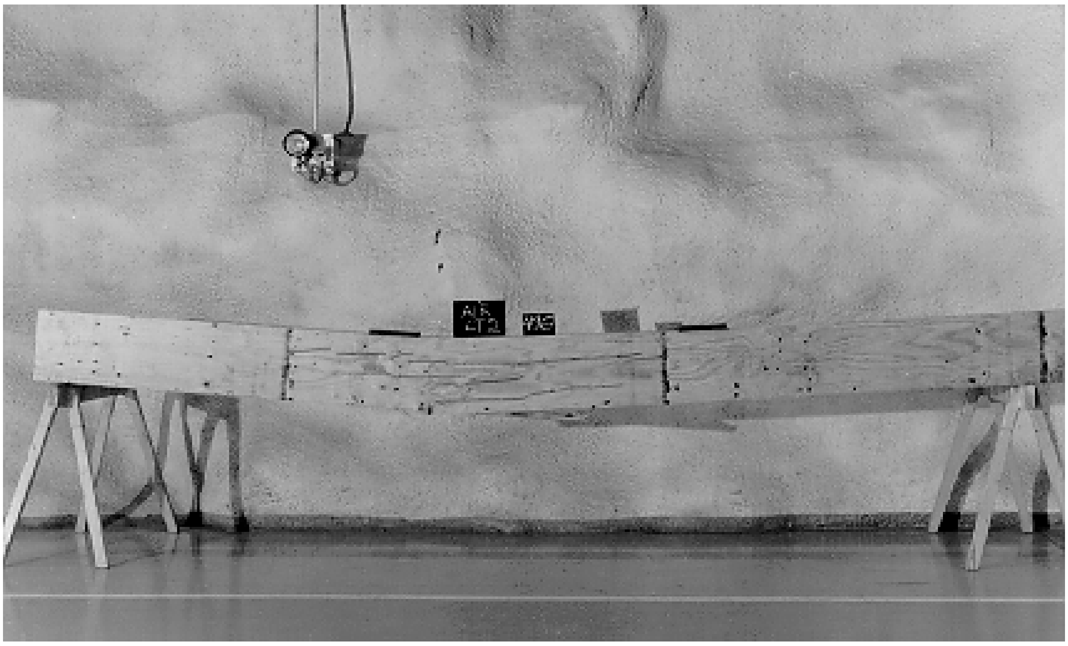
Failure behaviour of specimen (44 G) in series LT-A2-G4-2.



Failure behaviour of specimen (45 G) in series LT-A2-G4-3.



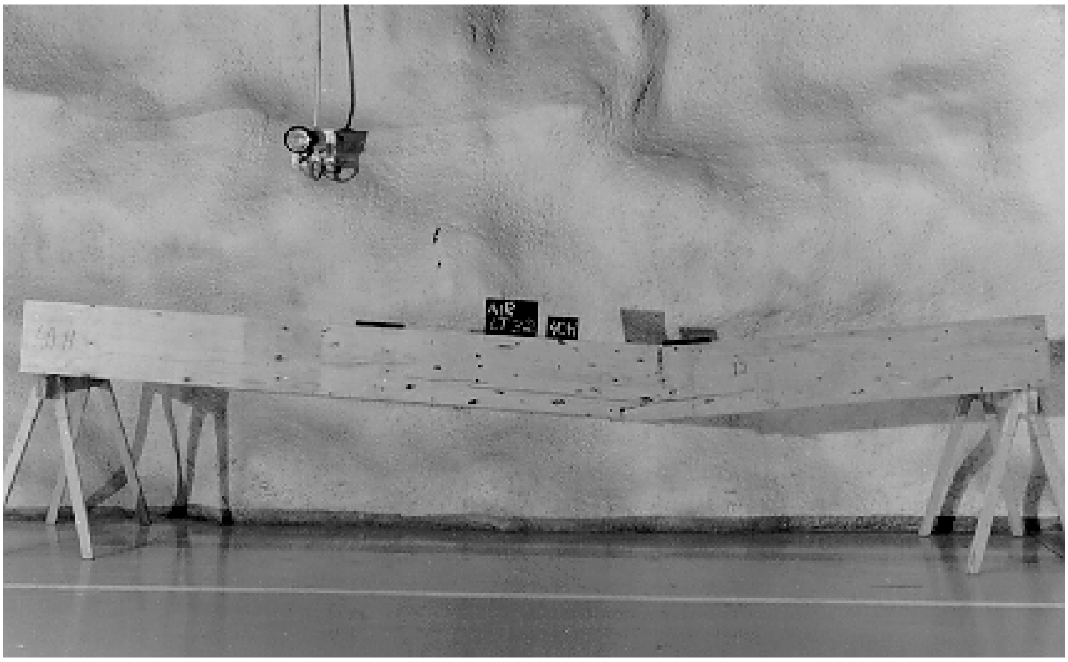
Failure behaviour of specimen (47 G) in series LT-A2-G4-10.



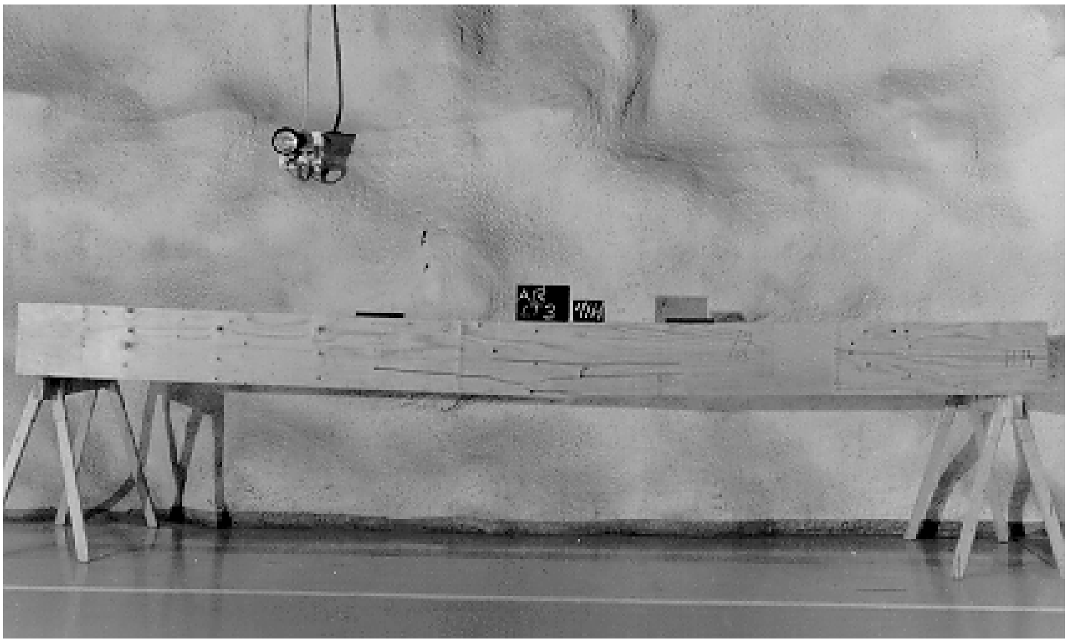
Failure behaviour of specimen (49 G) in series LT-A2-G4-9.

Failure behaviour of LVL specimens LT-A2-H5b series

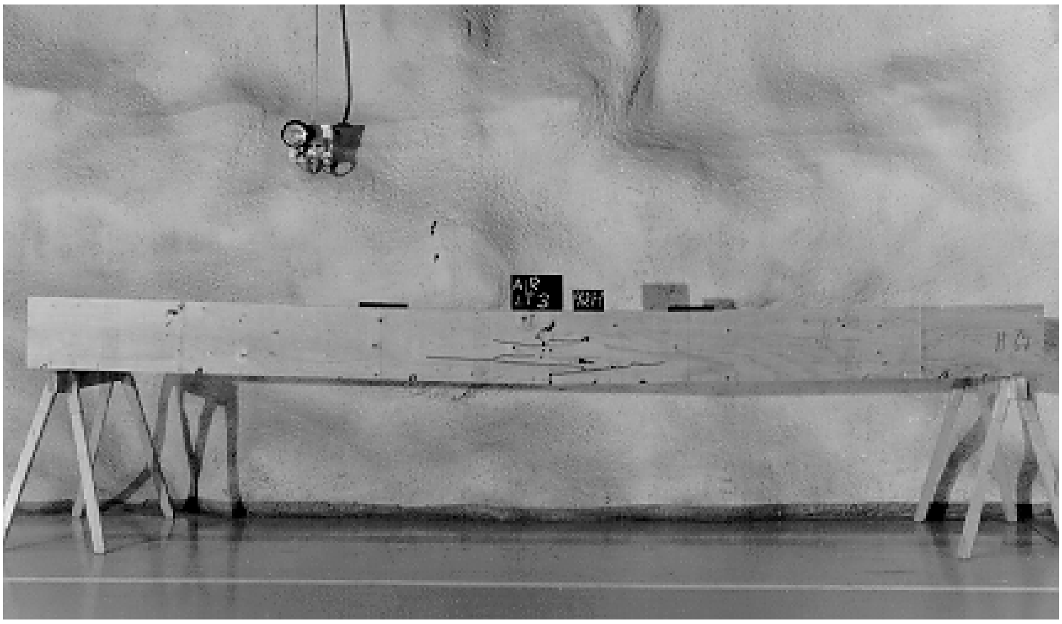
(75x300x4100 mm)



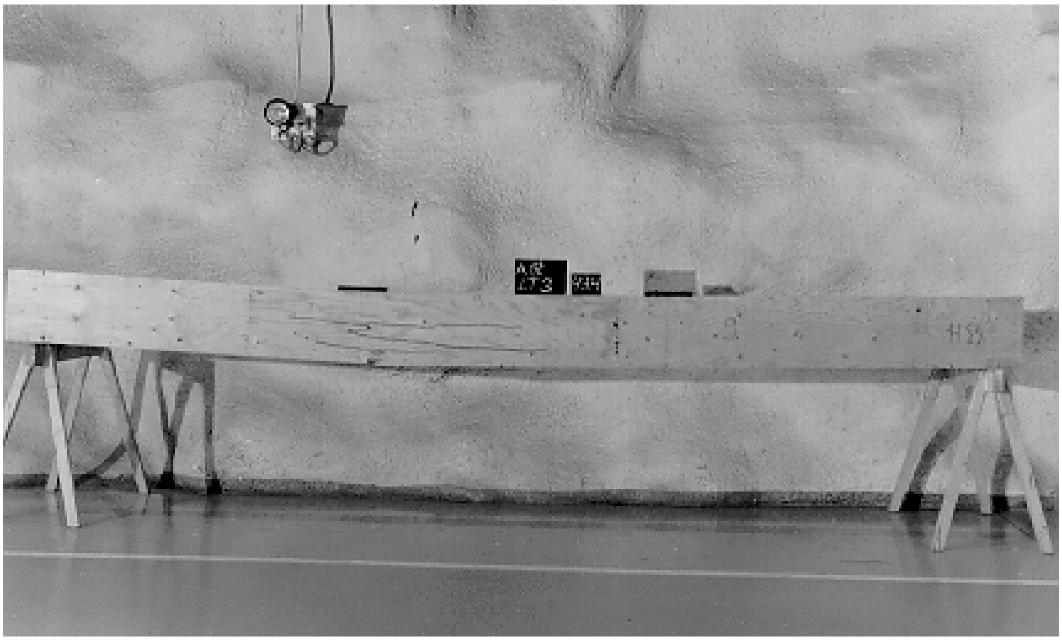
Failure behaviour of specimen (40 H) in series LT-A2-H5a-9.



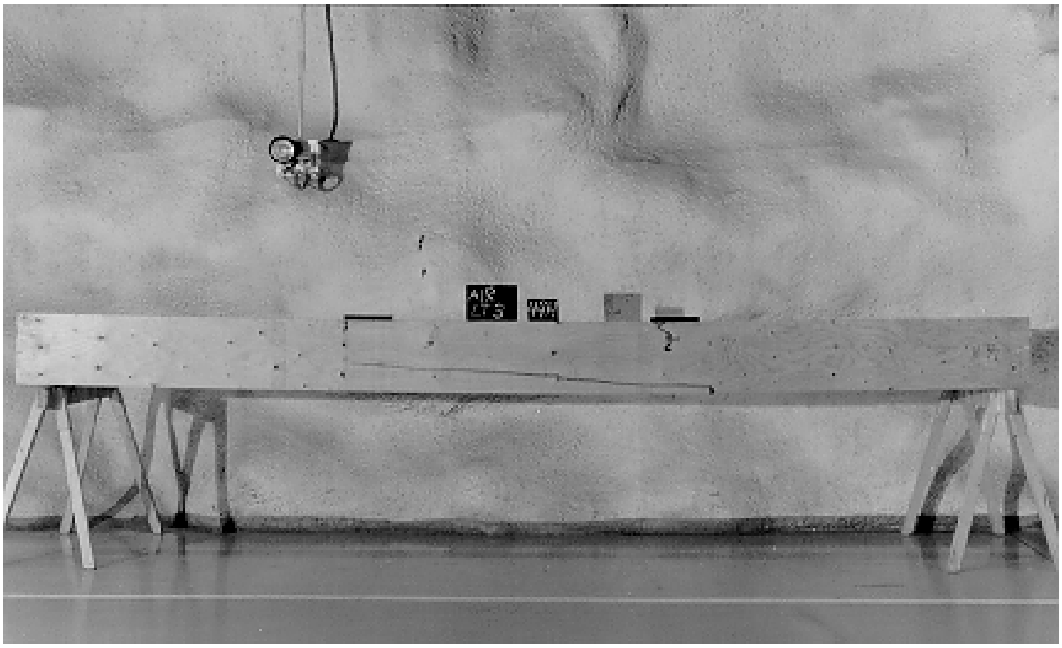
Failure behaviour of specimen (41 H) in series LT-A2-H5a-4.



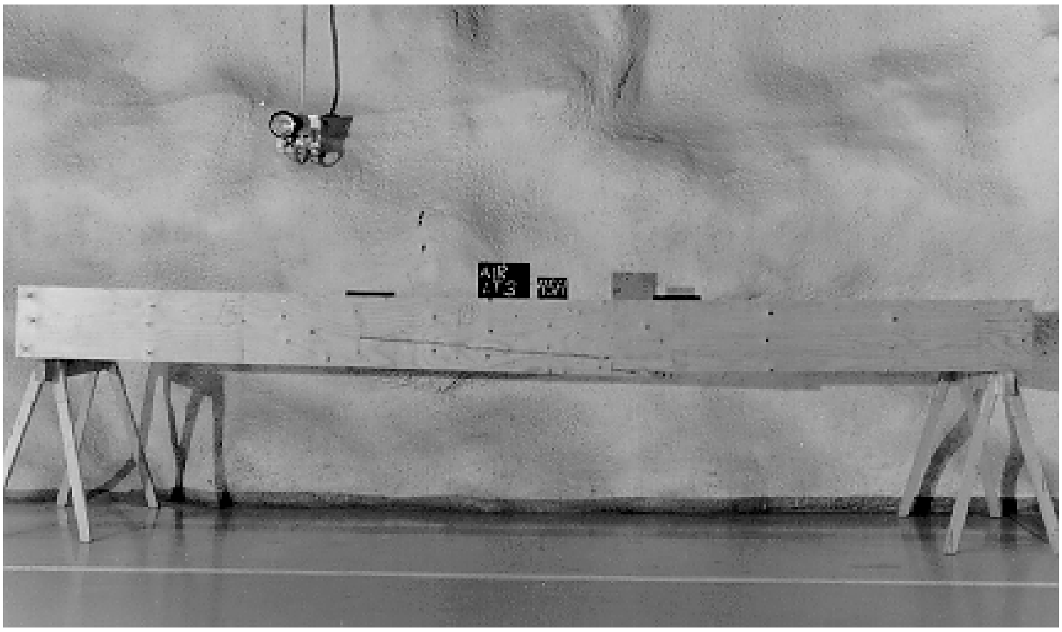
Failure behaviour of specimen (42 H) in series LT-A2-H5a-3.



Failure behaviour of specimen (43 H) in series LT-A2-H5a-1.

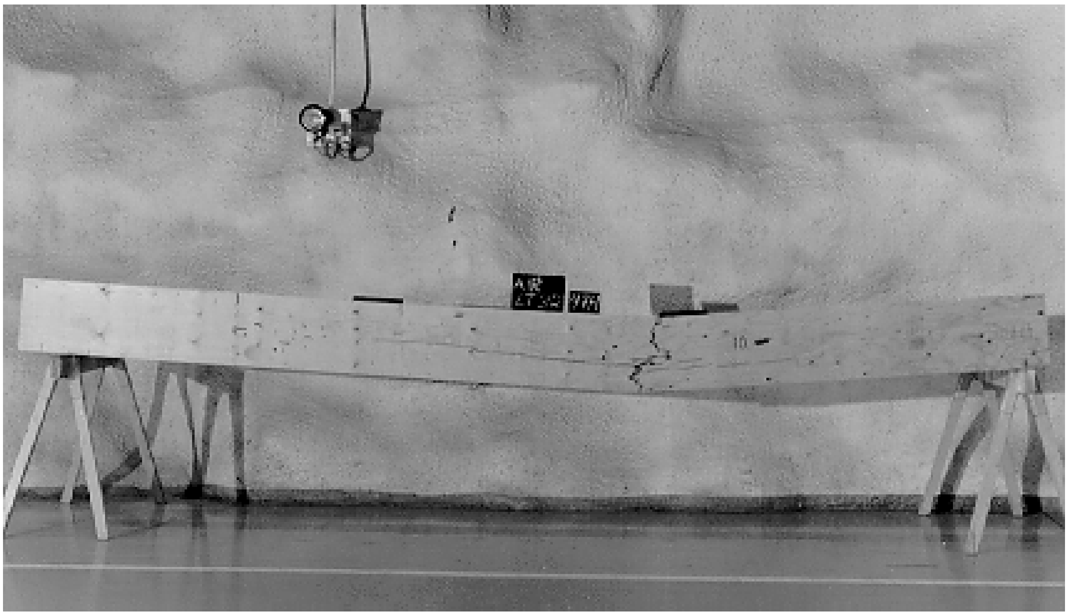


Failure behaviour of specimen (44 H) in series LT-A2-H5a-2.

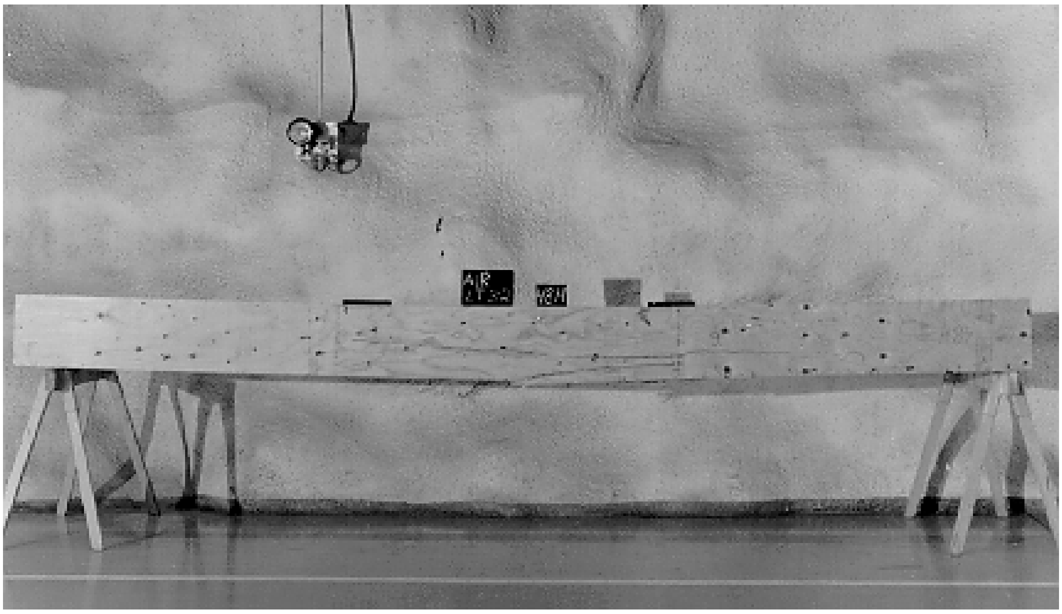


Failure behaviour of specimen (45 H) in series LT-A2-H5a-5.

Failure behaviour of specimen (46 H) in series LT-A2-H5a-8.



Failure behaviour of specimen (47 H) in series LT-A2-H5a-7.

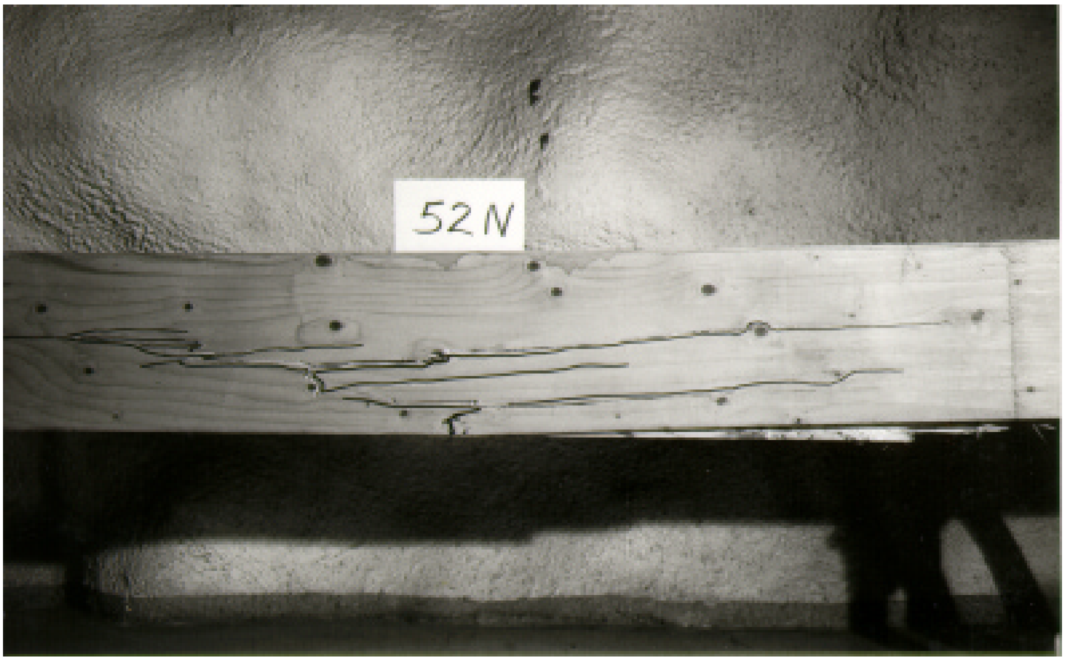


Failure behaviour of specimen (48 H) in series LT-A2-H5a-6.

Failure behaviour of specimen (49 H) in series LT-A2-H5a-10.

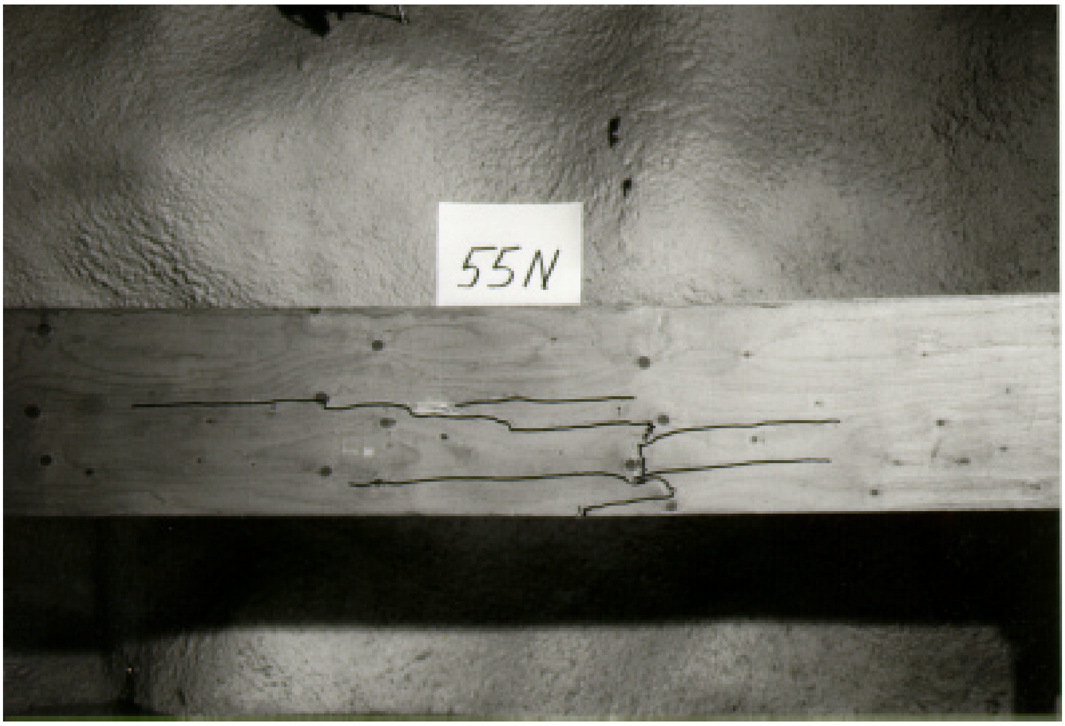
Failure behaviour of LVL specimens: Series LT-A2-N2

(75x300x4100 mm)



Failure behaviour of LVL speciman 52 N.

Failure behaviour of LVL speciman 53 N.



Failure behaviour of LVL speciman 55 N.

Failure behaviour of LVL speciman 57 N.

Failure behaviour of LVL speciman 58 N.