RESEARCH OF ′DURATION OF LOAD′ EFFECTS IN TIMBER ELEMENTS IN BENDING

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Abstract
The Duration of Load (DOL) effect is the combined influence of the mechanical loading history and climatic history on the strength of materials. DOL effect is one of the most important characteristics of wood and wood-based materials. The material degradation or damage induces strength reductions. Creep is one of the most important effects of DOL. Creep is a phenomenon that negatively affects functional compliance, behavior and strength of timber structures in extended years of exploitation. The creep phenomenon is affected by surrounding temperature, relative humidity, timber moisture content and other factors. The study aimed to establish a correct factor system for accurate prediction of long-term deformations of timber structures that is corresponding to environmental conditions and timber properties in the region of Latvia. The experimental research was made in Jelgava, Latvia, and represents timber beam four-point long-term loading in bending with variable cross section height-span length ratio under uncontrolled climatic conditions. There were 12 timber beams with two different span lengths – 1.32 m and 1.50 m used. The timber beam cross section dimensions: height – 60 mm, width – 30 mm. The timber beams were not dried and the moisture content at the start of the experiment varied from 19% to 33%. The applied load values – 0.40 kN and 0.31 kN. Moisture content fluctuations and negative air temperature accelerated creep development and intensity. Prediction of final long-term deformations should rate not only the type of timber material and service class but the strength class, too.
Key words: Duration of Load, creep phenomenon, long-term loading, height-span length ratio.

Introduction

Molecular structure of wood is a very complex system with uneven distribution of molecules. J. Bodig and B.A. Jayne (1982) found that wood has very manifold physical and mechanical properties because of its anisotropy and fibrous structure which needs to be taken into consideration when using wood in construction. Wood structure is the reason why mechanical and physical properties of wood are significantly affected by the surrounding environment. Wood adapts to the environment in which it is located. This process is called hygroscopicity – material ability to absorb moisture from the surrounding environment. During this process, the water molecules penetrate into the wooden molecules that physically alter the material. Heterogeneous structure of wood with a high level of hygroscopicity causes swelling and cracking of the material. Climatic variability and, in particular, a large amount of moisture content changes has a very negative impact on the wooden constructions in long-term loading.

Increasing of moisture and durability of the load combination effect in time leads to reduction of the strength of a timber. This effect known as DOL (Duration of Load) effect is one of the most important characteristics of wood and wood-based materials.

For the first time the idea of different short-term and long-term timber loading behavior was expressed by the French naval architect George Louis Le Buffon (1740). He observed the behavior of structural oak beams under long-term bending load and concluded that the maximum long-term load in bending should not exceed 50% of the short-term strength.

When loading timber structures with long-term constant load, deflection increases over time. This process is called ′creep′. Creep is deformation increase at constant load (Schniewind, 1968).

S. Thelandersson (1995) and D.G. Hunt (1999) proved that work in linearly elastic phase and creep phenomena are the most basic wood mechanical properties. Serviceability (deflection) requirements are often the main to determine the size of the beam cross section dimensions, if they are subject to long-term and permanent load.

Over time, as a result of creep development, wooden structures do not longer fulfill the serviceability requirements, deflections become unacceptably large and, in the worst case, the construction even loses its load-bearing capacity and collapses. Creep is a ′time-dependent′ deformation. Under long-term load, at low stress levels and under normal moisture and temperature conditions, wood behaves in linear manner. L.R.J. Whale (1988) and P. Morlier (1994) stated that at a higher level of stress and/or under changing environmental conditions, wood shows non-linear correlation between stresses and deformations.

The goal of this study is to establish a correct factor system for accurate prediction of long-term deformations of timber structures that is corresponding to environmental conditions and timber properties in the region of Latvia.

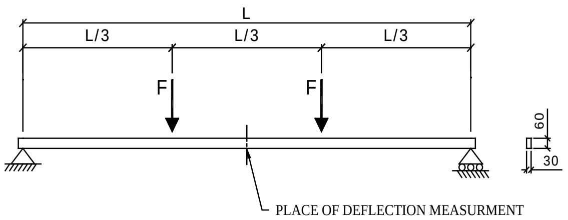

Figure 1. Test model of experiment.

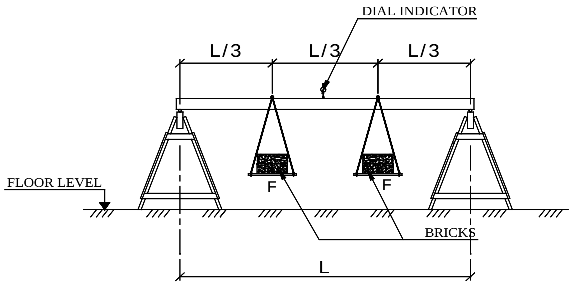

Figure 2. Timber beam loading.

Materials and Methods

The experimental creep test was started in December 2011 in Jelgava, Latvia, and was carried out in a newly constructed house which is not currently populated at this moment. This house was not heated in the winter period; therefore, the climatic conditions were not controlled in any way that allowed checking the timber beam creep operation and development in variable climatic conditions of ambient humidity and temperature.

The experimental creep test at this moment represents long-term loading of twelve (free of knots) pinewood (*Pinus sylvestris* L.) beam in four-point bending. The loading scheme is given in Figure 1. The timber beam cross section nominal dimensions (height and width) – 60 mm and 30 mm. During the whole test it is planned to load timber beams with four different span lengths – a) 1.08 m, b) 1.20 m, c) 1.32 m and d) 1.50 m, but at this moment only two types of span length c) 1.32 m (group of beams KS-3) and d) 1.50 m (group of beams KS-4) are loaded with long-term load.

Concentrated forces were represented by clay and silicate bricks which were suspended on timber beams (Figure 2). The deflection measurements were made with dial indicators. Measuring precision of indicators – 0.01 mm. Measuring diapason of indicators – 50 mm. The dial indicators were placed in the middle of the span on the compressed side of the beam. The environmental climatic condition parameters were recorded once in the day. Temperature (T, °C) in the room and outdoors was fixed with mercury-in-glass (Hg) type thermometers.

The timber beams were loaded in four-point bending with two concentrated forces that each force was calculated so as instantaneous deflection u_{inst} at the middle of the span does not exceed 1/150 part of the timber beam span length u_{inst} < L/150, where L – timber beam span (cm). The timber beam theoretical calculation of four different span lengths is given in Table 1. Four different timber beam span lengths were chosen to examine how the span to depth ratio (18, 20, 22, and 25) influences creep development. For lumber and glued laminated beams, the European static standard ratio is 18:1 (Morlier, 1994).

Parallel to environmental climatic condition parameter recording, timber beam moisture content (MC, %) and relative humidity (RH, %) recordings were made daily.

In order to judge about the timber beam strength properties, theoretical Modulus of Elasticity (MOE) was calculated after registering instantaneous elastic deflection (u_{inst}) immediately (1 minute) after loading. Theoretical MOE (E_{app}) of rectangular cross-section elements, which are loaded in bending with two

Table 1

Timber beam theorethical calculation

Marking	Load (F), kN	Span length (L), m	Design moment (M_d), kNm	Span-heigth ratio Lh^{-1}	Cross section width (b), cm	Cross section heigth (h), cm	Second moment of area about the strong axis (I_y), cm^4	Bending stress σ<1.4 kN cm^{-2}	Inst. defl. u<L/150 (u_{inst}), cm	Permissible inst. defl. L/150 (u_{perm}), cm
KS-1	0.60	1.08	0.216	18	3	6	54.00	1.200	0.71	0.72
KS-2	0.49	1.20	0.196	20	3	6	54.00	1.089	0.80	0.80
KS-3	0.40	1.32	0.176	22	3	6	54.00	0.978	0.86	0.88
KS-4	0.31	1.50	0.155	25	3	6	54.00	0.861	0.98	1.00

symmetrical concentrated forces, was calculated using equation (1):

$$E_{app} = \frac{F \cdot a}{4 \cdot b \cdot h^3 \cdot u_{inst}}(3 \cdot L^2 - 4 \cdot a^2) \ , \tag{1}$$

where: F – sum of two concentrated forces, kN;
a – distance from support to concentrated force, cm;
L – timber beam span, cm;
b – width of cross section, cm;
h – height of cross section, cm;
u_{inst} – instantaneous deflection, cm.

The creep coefficient c_r in this study is expressed in terms of the initial elastic deflection (u_0):

$$c_r = \frac{u_t - u_0}{u_0} \ , \tag{2}$$

where u_t is the deflection at time (t) in step with the moisture content of wood (MC) and temperature of air (T).

Coefficient of variation (COV) was calculated for mean values of environmental climatic parameters – moisture content, temperature, relative humidity, and relative deflection.

Regression analysis was made for relationship between relative creep c_r and time, and coefficient of determination R^2 was calculated, too.

Results and Discussion

The value of moisture for the twelve loaded beams at the start of the test was variable from 19% to 33% with the mean value of moisture 25.25% with a coefficient of variation (COV) of 19%.

After 64 days of test, the moisture content exhibited a mean value of 12.17% with a COV of 11%.

The monthly average for outdoor temperature were 3.5 °C (December), -1.1 °C (January), and -10.2 °C (first 17 days of February). The monthly average for indoor temperature ranged from 3.9 °C to - 4.9 °C with a mean value of 0.2 °C.

Monthly average for indoor relative humidity ranged from 55.8% to 76.4% with a mean value of 68.2%.

The sizes of the beam cross-section presented mean values of 30.68 mm in width and 58.36 mm in height. Span to depth ratio for the loaded beams was 22 for the group KS-3, and 25 for the group KS-4. Table 2 represents cross-section dimensions of the loaded timber beams.

Table 3 summarizes the main results for the instantaneous deflections (u_{inst}) and creep deflections (u_{creep}) after 64 days of test. In addition, relative creep deflections after 7 and 64 days of test are given. Values of instantaneous and creep deflections are divided in 3 groups which correspond to accurate loading duration and span length of timber beams. According to Eurocode 5, one week is the limit between short-term and medium-term load duration classes, six months is the limit between medium-term and long-term load duration classes, and 10 years is the limit between long-term and permanent load duration classes.

Relative deflection values after 64 days of test showed that loaded beam behavior under long-term load is very different. A detailed analysis shows that four beams – KS-3.1, KS-3.3, KS-3.10, and KS-4.7 – exhibited a very high value of 1.91, 1.96, 1.84 and

Table 2

Cross-section dimensions of timber beams

Marking	Height (mm)			h_{vid}, mm	Width (mm)			b_{vid}, mm
	h_1	h_2	h_3		b_1	b_2	b_3	
KS-4.10	58.30	57.00	57.80	57.70	30.80	30.40	30.50	30.57
KS-4.9	58.50	60.30	58.40	59.07	31.90	32.30	32.80	32.33
KS-4.8	58.20	58.60	58.50	58.43	30.00	30.80	30.70	30.50
KS-4.7	58.30	58.00	57.70	58.00	30.80	30.20	29.80	30.27
KS-3.10	58.70	58.80	58.50	58.67	31.50	31.40	31.70	31.53
KS-3.9	58.60	58.40	58.70	58.57	30.40	30.50	30.30	30.40
KS-3.8	58.60	58.20	58.50	58.43	32.50	32.10	32.30	32.30
KS-3.7	58.30	58.10	58.10	58.17	29.30	28.10	27.50	28.30
KS-3.5	58.10	58.80	58,50	58.47	32.00	31.80	31.90	31.90
KS-3.3	57.50	58.30	57.90	57.90	27.10	30.00	28.40	28.50
KS-3.2	58.30	58.60	58.40	58.43	30.80	32.00	31.40	31.40
KS-3.1	58.40	58.50	58.40	58.43	31.10	30.20	30.80	30.70

Table 3

Results of instantaneous and creep deflections

Marking	Instantaneous deflection (U_{inst}), mm	Creep deflection ($U_{creep,64}$), mm	Relative deflection after 64 days U_{64}/U_{inst}	Relative deflection after 7 days U_7/U_{inst}	Mean value of inst. deflection ($U_{inst,mean}$), mm	Mean value of creep deflection ($U_{creep,64,mean}$), mm
KS-4.10	8.00	4.28	1.54	1.03	9.50	5.04
KS-4.9	13.00	6.71	1.52	1.05		
KS-4.8	12.00	4.22	1.35	1.11		
KS-4.7	5.00	4.94	1.99	1.14		
KS-3.10	6.00	5.03	1.84	1.16	8.50	5.09
KS-3.9	7.00	4.08	1.58	1.06		
KS-3.8	12.00	5.89	1.49	1.08		
KS-3.7	9.00	5.36	1.60	1.13		
KS-3.3	7.90	7.60	1.96	1.18	6.30	4.24
KS-3.5	7.70	3.01	1.39	1.06		
KS-3.2	4.80	1.95	1.44	0.98		
KS-3.1	4.80	4.40	1.91	1.06		

1.99 for relative deflection u/u_{inst} with a mean value of 1.93. Creep deflection for these four timber beams presented 4.40 mm, 7.60 mm, 5.03, mm and 4.94 mm respectively. The remaining 8 specimens presented relative creep values ranging between 1.35 and 1.60. The relative deflection mean value for all timber beams after 64 days of test presented the value of 1.63 with COV of 14%.

The established relative creep ratio values after 7 days of test ranged between 0.98 (KS-3.2) and 1.18 (KS-3.3) with a mean value of 1.09 with a COV of 5%. The value of the coefficient of variation (COV=5%) testifies that dispersion of the results is small and they are credible.

Relative creep relationships versus time during 64 days are analyzed in Figure 3. The curves of timber beams summarize the relative creep histories for the test beams under long-standing (64 days) load. This diagram shows that the test period of 64 days can be divided in two periods: period A) from the start of the test to the forty second day (1.-42.); period B) from the forty second day to the sixty fourth day (42.-64.). These two periods – A and B – are marked in Figure 3. Creep development speeds of 10 specimens in the period A were very similar, with an exception of two timber beams – KS-4.9 and KS-3.3. Creep developments for these two beams were 0.11 mm day^{-1} and 0.17 mm day^{-1} correspondingly. Nine specimens presented creep development speed values from 0.03 mm day^{-1} to 0.07 mm day^{-1}. The timber beam KS-3.2 showed negative (-0.02 mm day^{-1}) creep development during the period A, which means that, deflection of this beam after loading decreased. The mean value of creep development speed during the period A showed a value of 0.057 mm day^{-1}.

Start of the period B, when rise in creep development speed was registered, represents perfect compatibility with rapid decrease in surrounding air temperature. Fast decrease in indoor relative humidity in this cold period caused a subsequent fall in the moisture content of timber beams.

Creep development speed values of all timber beams during the period B were much higher than in the period A. Two timber beams – KS-3.1 and KS-3.3 – represented creep development speed values of 0.17 and 0.23 mm day^{-1}, other 10 specimens recorded speed values ranged between 0.08 mm day^{-1} and 0.14 mm day^{-1} with a mean value of 0.115 mm day^{-1}.

In this case we can conclude that the registered decrease in air temperature (starting on the 42nd day of test) initiated faster creep development which continued till the 64th day of test. Relative humidity and moisture content depleted together with air temperature, which is demonstrated in Figure 4. Creep development was accelerated because air temperature rapidly decreased to minus 10 °C and water froze in the cells of wood. The period of negative indoor air temperature continued for 23 days (starting from the 43rd day of test). Apparently water in the cells of wood was frozen in this period.

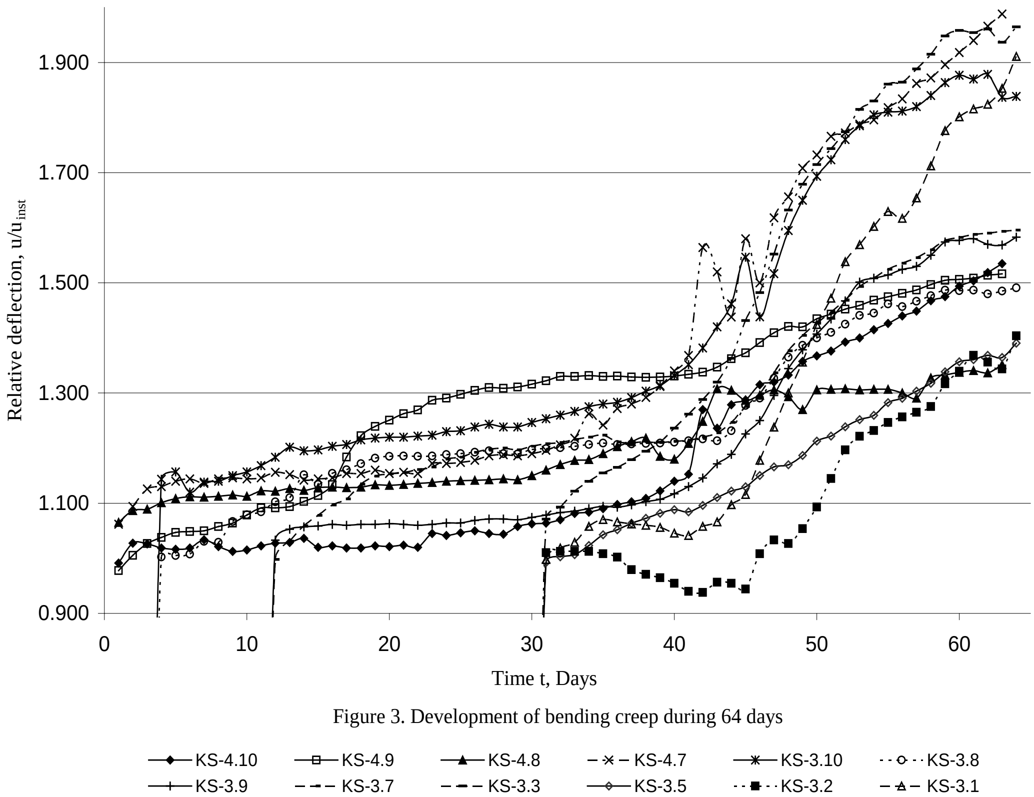

Figure 3. Development of bending creep during 64 days

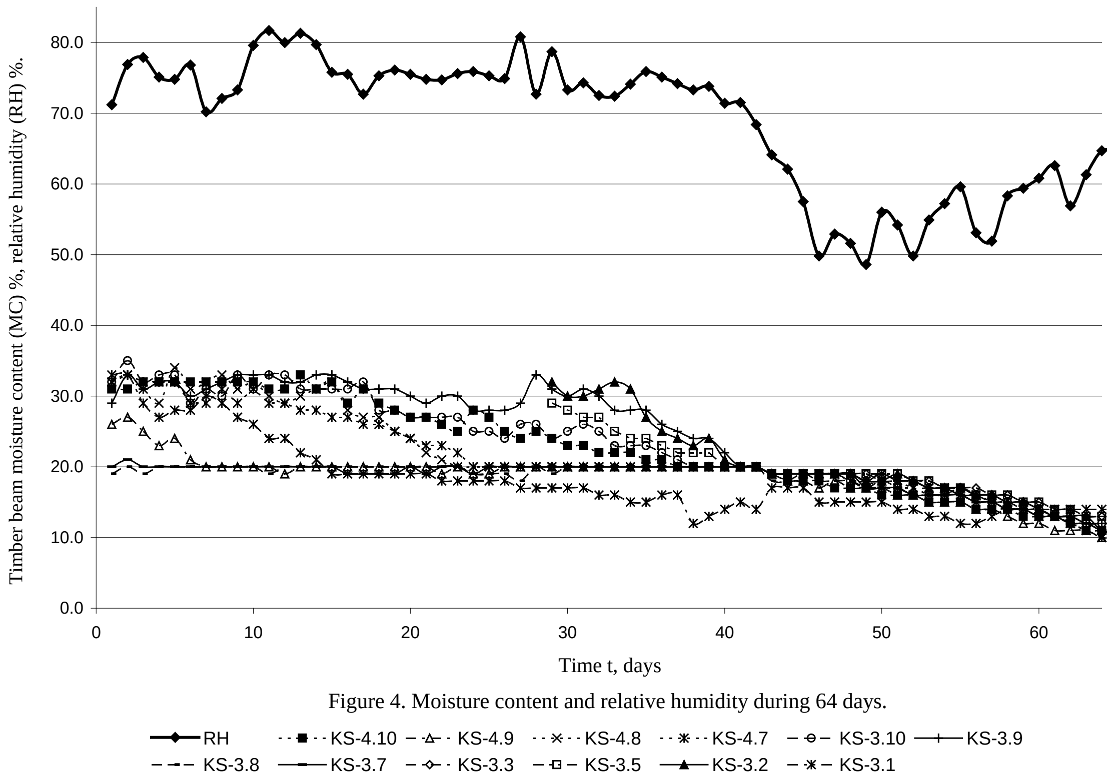

Figure 4. Moisture content and relative humidity during 64 days.

Figure 4 represents hygroscopic behavior of wood – the moisture content of timber beams during air temperature decrease experienced faster drying than it was before this mentioned cycle. Decrease in the moisture content continued even when the rise in air temperature started. The timber beam moisture content at the start of test ranged from 19% to 33% with a mean value of 28%. The mean value of the moisture content of all beams after 64 days was 12.17%.

Table 4

Relative creep c_r of timber beams

Period	Timber beam											
	KS-4.10	KS-4.9	KS-4.8	KS-4.7	KS-3.10	KS-3.9	KS-3.8	KS-3.7	KS-3.3	KS-3.5	KS-3.2	KS-3.1
A	0.12	0.33	0.19	0.31	0.33	0.12	0.21	0.21	0.24	0.09	-0.05	0.05
A+B	0.54	0.52	0.35	0.99	0.84	0.58	0.49	0.60	0.96	0.39	0.40	0.91

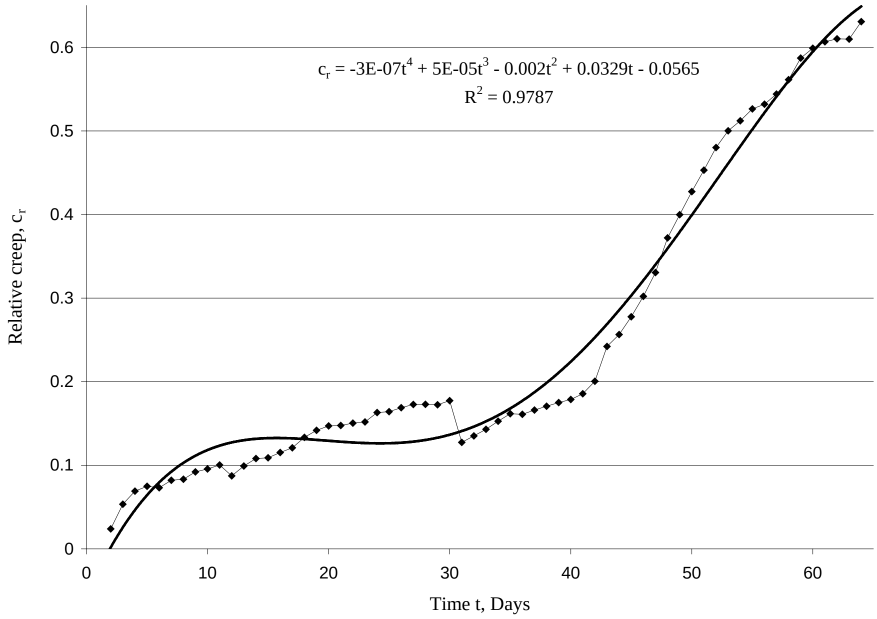

Figure 5 a. Polynomial approximation of average relative creep values versus time under load.

Summary of creep coefficients of all timber beams during the periods A and B is given in Table 4. The analysis of the creep coefficients shows that the period A represents values ranging from -0.05 to 0.33 with a mean value of 0.18.

The creep coefficient values during 64 days of test varied from 0.35 to 0.99. Four timber beams (KS-4.7, KS-3.10, KS-3.3, and KS-3.1) represent creep coefficient values from 0.84 to 0.99, other 8 specimens show values from 0.35 to 0.60. The mean value of creep coefficient c_r during 64 days of test – 0.63.

Different mathematical models were examined to describe the creep relationships according to the

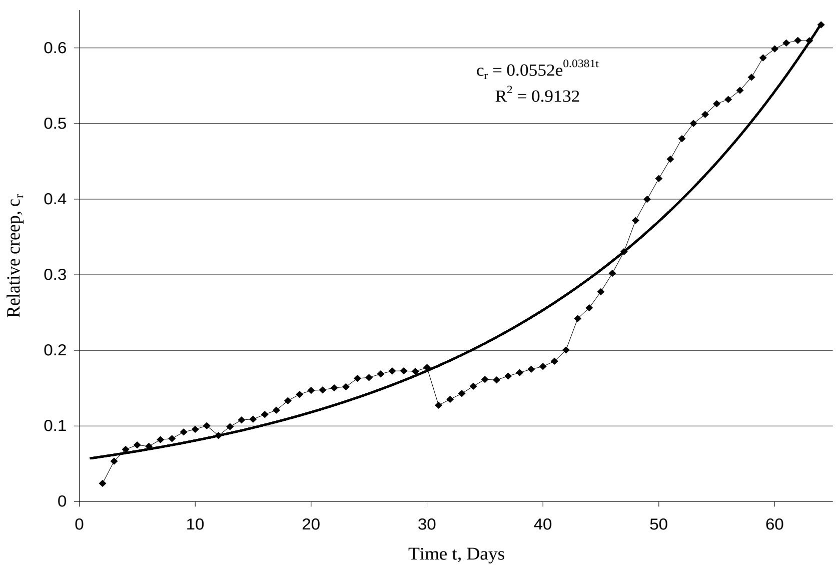

Figure 5 b. Exponential approximation of average relative creep values versus time under load.

test data. Best fitting between the test curve and regression model may be obtained by exponential and polynomial curves. In this study the exponential and polynomial relationships were found as sufficiently good approximations testified by the coefficient of determination R^2 values close to unity (Figure 5a and 5b).

Conclusions

This provisional study provides a background for future experiments in order to establish an accurate factor system for prediction of final deformations in timber structures.

Creep of wood is dependent on season – moisture variation causes fluctuation in creep curves. Relative humidity fluctuations and frozen water in wood cells, which were initiated by radical decrease in air temperature (indoor temperature receded to minus 10 °C), accelerated creep development speed that continued even when constant increase in air temperature was observed. Small cross-section beams are especially influenced by humidity cycling. Small sample size and variability in MOE make it difficult to make more detailed conclusions at this stage of test.

The estimated creep coefficient c_r during 64 days of test presented the mean value of 0.63.

Further studies on wood structure and creep behavior under variable climatic conditions are necessary to adequately judge about all influencing factors. These studies are necessary to accurately predict the final deformations in timber structures corresponding to climatic conditions, type of timber material, service class, and timber strength.

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