Long-Term Behaviour of Laminated Veneer Lumber Members Prestressed with Unbonded Tendons**

Matthew Davies[1] & Massimo Fragiacomo[2]

[1]Design Engineer, Dunning Thornton Consultants, Wellington, New Zealand
[2]Associate Professor of Structural Design, University of Sassari, Alghero, Italy

Summary

This paper briefly presents and discusses the results of experimental tests undertaken to resolve an issue regarding the viability of multi-storey prestressed timber structures, specifically the reduction in prestress load over time. The test programme included full-scale specimens, reduced scale specimens and small blocks of laminated veneer lumber (LVL). Based on the experimental data, the creep functions of LVL in bending and compression parallel and perpendicular to the grain were evaluated. The creep perpendicular to the grain was found to be significantly larger (about four times) than the creep parallel to the grain. The prestress losses were found to be relatively low (around 10%) when timber is loaded parallel to grain only, such as a beam. However, the losses markedly increased and reached a 34% value when 11% of the frame's length was loaded perpendicular to grain. An attempt has been made to separate the contributions made to prestress losses by key factors, namely creep and mechano-sorption parallel and perpendicular to the grain of the LVL. Lastly, an analytical solution is proposed, developed and compared with the experimental values.

1 Introduction

With recent developments towards damage-avoidance design and the importance of constructing sustainable buildings, unbonded post-tensioned LVL frames and walls are being tested as part of a major experimental programme at the University of Canterbury, New Zealand [1-3]. As timber is typically regarded as soft material, there is some scepticism regarding the viability of these post-tensioned structural systems, particularly concerning long-term losses of prestress. There is considerable uncertainty surrounding this issue because there is very little information available on the creep properties of LVL and, more specifically, Radiata Pine LVL, which is extensively used in Australasia. At present, only one set of significant test results have been published [4] and these used LVL manufactured from a different species. Also, these tests did not consider creep perpendicular to the grain, which is critical in a frame, where the prestressing acts perpendicular to the grain in the columns.

The purpose of the paper is to present the results of an extensive experimental programme undertaken at the University of Canterbury intended to measure the losses of prestress in LVL members prestressed with unbonded tendons. Creep and relaxation functions of LVL, parallel and perpendicular to grain, and steel tendons in different environments were derived and used to validate a closed form solution for the prediction of the losses at a structural level. The values monitored over one-year of testing were extended to the end of the service life using approximating functions and then compared with analytical values to demonstrate the accuracy of the formula proposed.

2 Experimental Programme

The experimental tests were set up and conducted over a period of approximately two years and included specimens of many different shapes, sizes and purposes. There were two sets of tests that ran parallel in different environments. The first environment was controlled, heated and indoors; and, the second was uncontrolled, heated and indoors. The controlled environment (a climate chamber) was kept constant for approximately 220 days, and after this the relative humidity was deliberately cycled. The initial, controlled period was nine months in length, during which the temperature was kept constant at 20°C and the relative humidity was kept constant at 50%.

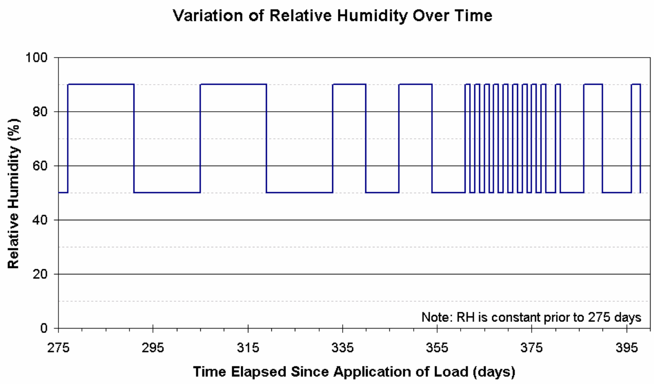

Fig. 1 Variation of relative humidity over time in the controlled environment

** *Presented at World Conference on Timber Engineering (WCTE) 2008, Japan.*

Following this, the test specimens were subject to cyclic conditions. The relative humidity was cycled between 50% and 90% while the temperature remained constant at 20°C. The length of these cycles was initially 14 days. This then decreased to seven days and, eventually, one day. After these cycles, the cycling was more or less random for approximately 20 days. This is illustrated in Figure 1. The relative humidity and temperature histories of the second (uncontrolled) environment are plotted in Figure 2.

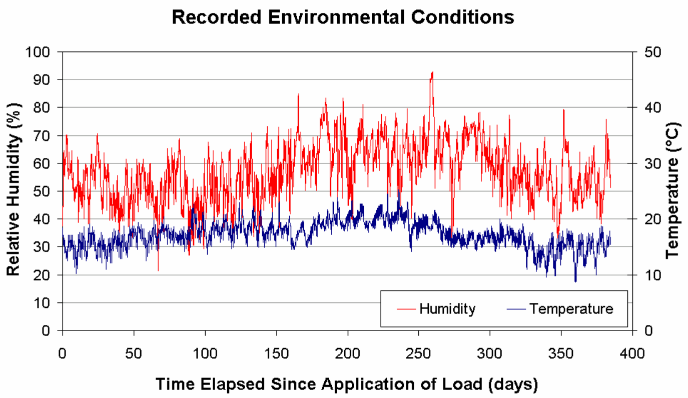

Fig. 2 Variation of relative humidity and temperature over time in the uncontrolled environment

In each of these environments there were two lever apparatuses that placed a stack of 45×45×45 mm LVL blocks under constant compressive stress (see Figure 3). This allowed for the measurement of the pure creep and mechano-sorptive creep properties of the material. As some of the blocks were placed with the veneers parallel to the load and others had the veneers perpendicular to the load direction, both parallel and perpendicular to the grain properties were considered. Similarly, a heavy steel circular hollow section (CHS) was prestressed as a relaxation test to determine the relaxation properties of the prestressing strand.

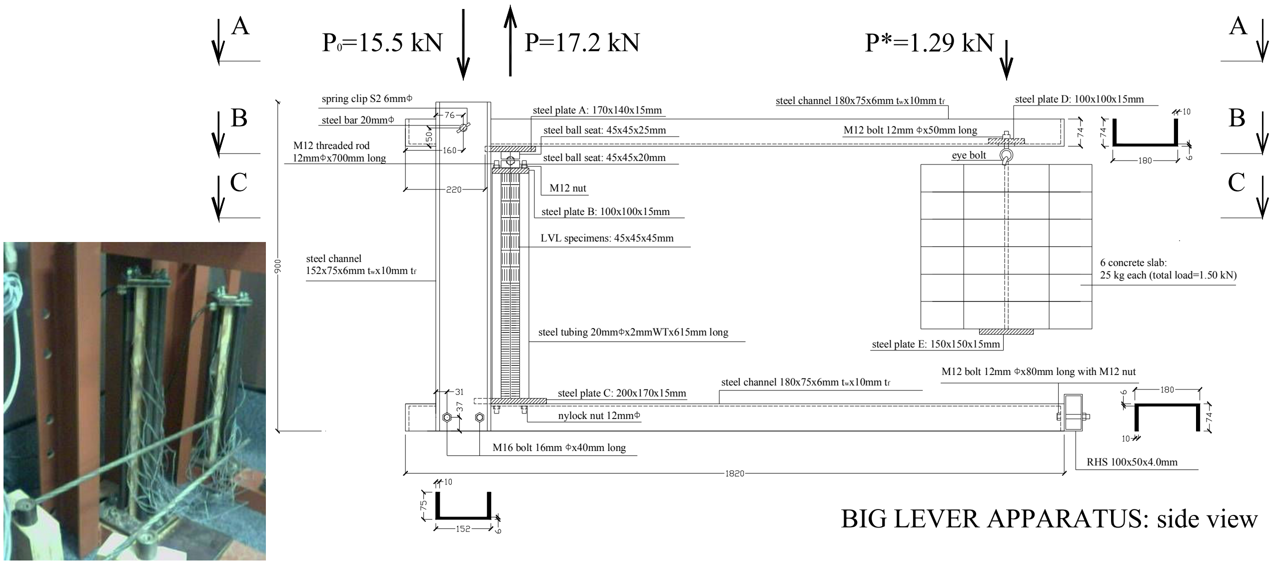

Fig. 3 Small LVL specimens loaded in compression in lever apparatus

These tests provided data regarding the long-term behaviour of the individual materials but additional tests were necessary to provide data on the long-term behaviour of the structural system. For this, several frame and beam specimens were tested in each environment. Four frame specimens were in each environment and they were each loaded by different methods. One method was to apply the prestress once then leave the specimen; the second method was to apply the prestress then reapply the prestress about ten days later; and, the third method used disc springs to try to maintain a constant load over time and simulate a sort of creep test. The fourth specimen was left without prestressing (dummy specimen). A fifth specimen was a beam with no column at the ends prestressed only once at the beginning. The prestressing load was 107 kN, which corresponded to 70% of the strand strength and 6% of the compressive strength of LVL parallel to the grain.

Due to space limitations there was a difference in size between the specimens in the two different environments; however, their proportions along the length and cross-sectional areas (Figure 4) were still the same. To investigate if the length of the specimen influences prestress losses a smaller specimen was also tested in the uncontrolled environment. The frame specimens in the controlled environment are displayed in Figure 5, while Figure 6 displays a photo of the frame and beam specimens in the uncontrolled environment. The former were 1.40 m long, whilst the latter were 5.63 m long.

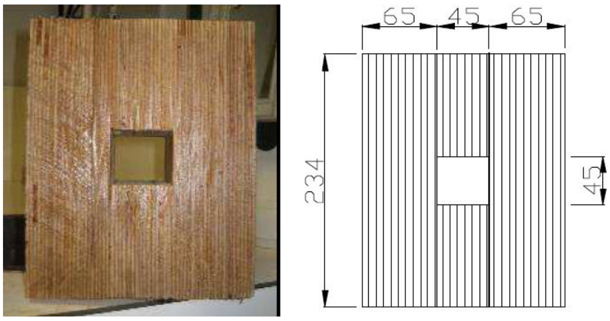

Fig. 4 Cross-section of the beam specimens (dimensions in mm)

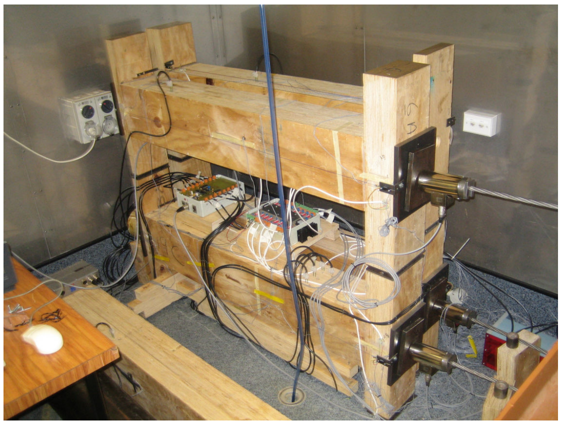

Fig. 5 Frame specimens in controlled environment

Fig. 6 Frame (on left and on the floor) and beam (on top of the second frame specimen, from left) specimens in the uncontrolled environment. On right: beam specimen loaded in bending

Fig. 7 Beam specimens in the uncontrolled environment tested in bending (in the foreground: prestressed specimen)

Two additional beam specimens with the same length as the frame specimens were tested in the uncontrolled environment (Figure 7). One was prestressed and loaded in bending, and the other was loaded in bending only.

3 Results

3.1 Material Results

Figures 8, 9 and 10 show the results (total strain) for the small block specimens subject to constant compressive stress perpendicular to the grain and laminations (54% of ultimate stress), parallel to the grain under 8% of ultimate stress, and parallel to the grain under 22% of ultimate stress, respectively. All these specimens were in the controlled environment.

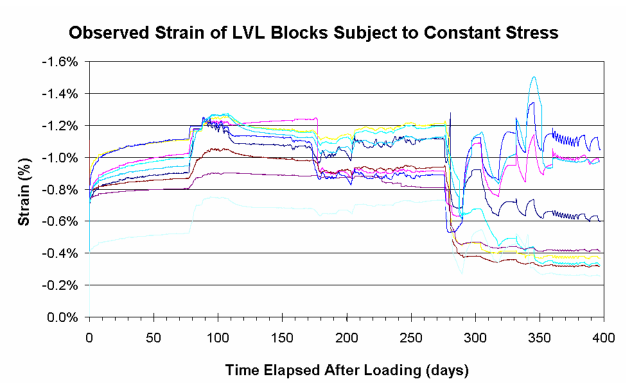

Fig. 8 Observed strains of LVL blocks subject to constant stress ($0.54\sigma_u$) perpendicular to the grain and laminations in a controlled environment

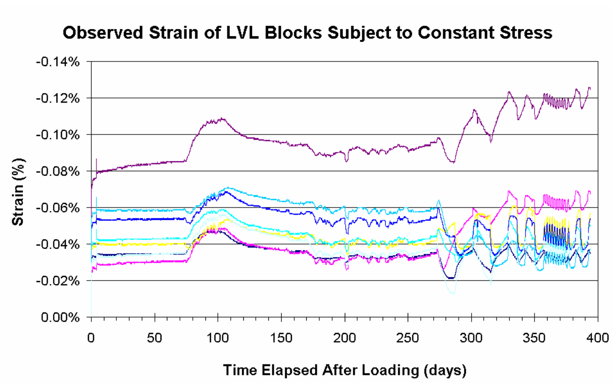

Fig. 9 Observed strains of LVL blocks subject to constant stress ($0.08\sigma_u$) parallel to the grain in a controlled environment

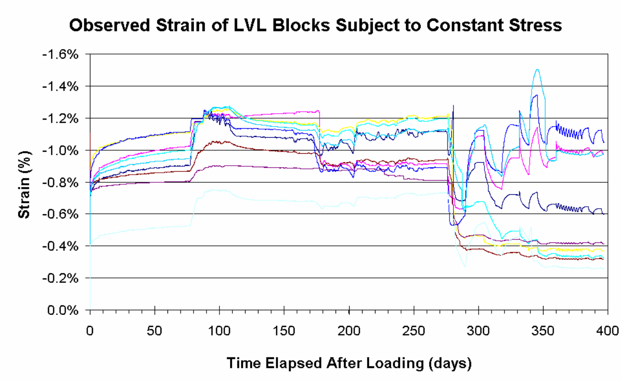

Fig. 10 Observed strains of LVL blocks subject to constant stress ($0.22\sigma_u$) parallel to the grain in a controlled environment

The variation between 80 and 200 days after loading is due to an unexpected variation in relative humidity. It can be seen that the deliberate cycling of the relative humidity began approximately 275 days after the initial load was applied.

The observed total strains were used to determine creep coefficients for the LVL in its different forms of loading in the controlled and uncontrolled environment. The creep coefficients found for the test duration were extrapolated out to the end of a predicted service life of 50 years. An example is depicted in Figure 11, which reports the creep coefficient of LVL beams loaded in bending. The final mean creep coefficient was found to be 1.0. This value is in good agreement with the New Zealand Standard NZS3603 [5], which suggests a value of one for timber and LVL members loaded in bending or in compression parallel to the grain. Figure 12 reports the extrapolation of the experimental results monitored on LVL blocks loaded perpendicular to grain in the uncontrolled environment. The mean value of the creep coefficient at the end of the service life was 4.0, whilst the value of 0.9 was obtained for block specimens loaded parallel to the grain.

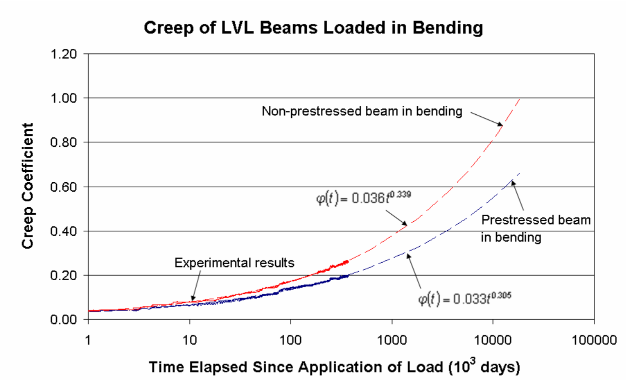

Fig. 11 Creep coefficient of LVL beams in bending in an uncontrolled, heated, indoor environment (extrapolated to 50 years)

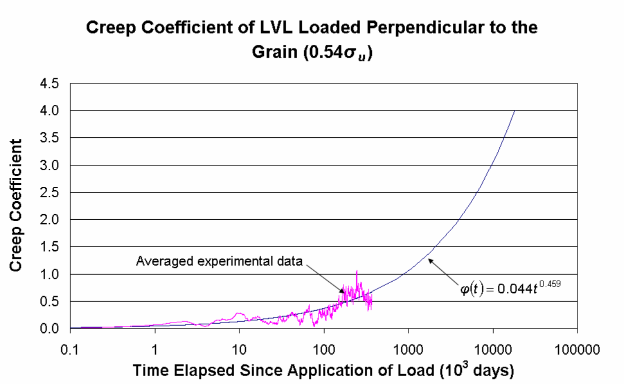

Fig. 12 Creep coefficient of LVL blocks in compression perpendicular grain in an uncontrolled, heated, indoor environment (extrapolated to 50 years)

Relaxation tests performed on the steel strands showed a 1 % reduction in load after one year of testing. Extrapolation to the end of a 50 year service life implies a 3.5 % reduction in load.

3.2 Frame Results

All the frame specimens are characterized by prestress losses significantly larger than the beam specimen (Figure 13). This is consistent with the larger creep coefficient found for LVL loaded perpendicular to grain, contributing to an additional shortening of the frame in the column regionsjoint where LVL is stressed perpendicular to grain.

When comparing the results of the frame specimens loaded using different loading methods (Figure 13), the specimen with springs in the anchorage (method three) had lesser losses than the specimen without springs. Re-stressing the specimen (method two) ten days after construction appears to generate greater long-term losses than stressing the specimen just once (method one).

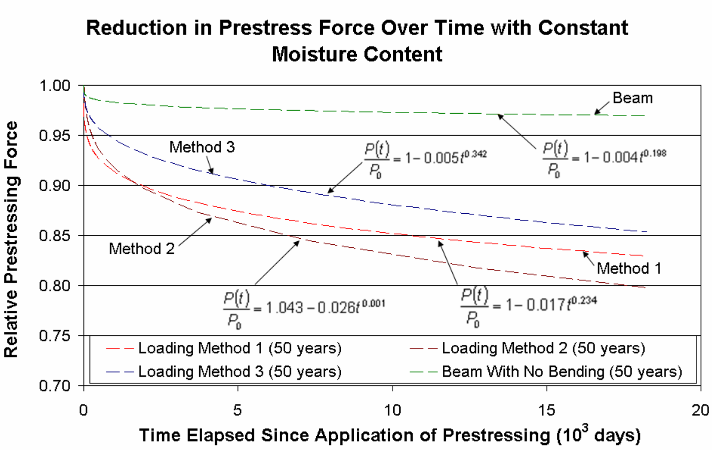

Fig. 13 Reduction in prestress force over time for specimens with a constant moisture content (extrapolated to 50 years)

Therefore, this method of construction, used sometimes to reduce the prestress losses in precast concrete structures, does not seem to provide any benefit in timber structures.

Through the addition and subtraction of results obtained from the different environments and specimen types it was possible to evaluate the fraction of the losses due to a specific contributing phenomenon, such as pure creep, mechano-sorptive creep and so forth. Table 1 summarises the different contributions to the global losses of prestressing load at the end of the test period (one year) and at the end of the projected service life (50 years).

Table 1 Summary of the prestress losses caused by the different phenomena

Phenomenon	Beam			Column			TOTAL
	Creep	MS*	Total	Creep	MS*	Total	
One year	1.4%	1.5%	2.9%	5.3%	0.2%	5.5%	8.4%
50 years	4.3%	3.7%	8.0%	15.5%	10%	25.5%	33.5%

*MS=Mechano-sorption

The contribution made by inelastic strains is not included because their influence is cyclical and should be equal at the end of each year. The percentages shown represent the reduction in prestressing load attributed to the associated phenomenon. The influence of relaxation of the prestressing steel is inherent in all values as it is unable to be removed from the experimental results.

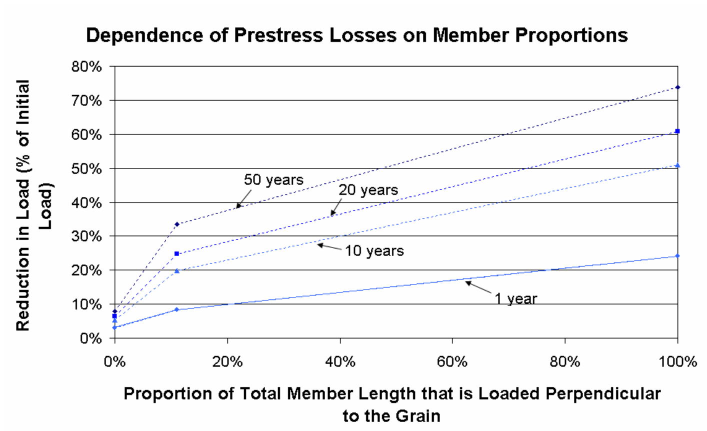

Fig. 14 The influence of the member's proportions on the losses of prestressing load at different times

When considering the effect of the frame proportions on the extent of losses, it can be seen (Figure 14) that the proportion of the frame's length that is perpendicular to the grain has a notable influence. In Figure 14 the data point representing a member that is composed of perpendicular to the grain LVL only (100% point) was found using the Eurocode 2 [6] equation (Eq. 1) for prestressed concrete in combination with experimental results for the materials' properties.

$$\Delta N = A_p \frac{\varepsilon_{cs} E_p + 0.8\Delta\sigma_{ps} + \frac{E_p}{E_{cm}}\varphi(t,t_0)\sigma_c}{1 + \frac{E_p}{E_{cm}}\frac{A_p}{A_c}\left[1 + 0.8\varphi(t,t_0)\right]} \qquad (1)$$

Where:

$\Delta\sigma_{ps}$	is the absolute value of the variation of stress in the tendons at time t, due to the relaxation of the prestressing steel
ΔN	is the change in prestress load
ε_{cs}	is the estimated shrinkage strain of the concrete (assumed zero for timber)
σ_c	is the mean stress in the concrete member
$\varphi(t,t_0)$	is the creep coefficient at a time, t, with the load being applied at time t_0
A_c	is the cross sectional area of the concrete member
A_p	is the cross sectional area of the prestressing steel
E_{cm}	is the modulus of elasticity of the concrete member
E_p	is the modulus of elasticity of the prestressing steel

4 Discussion

There are many possible explanations for the greater long-term losses that occur when the specimen is re-stressed. Firstly, the accuracy of the extrapolation cannot be guaranteed and only one specimen was tested in such conditions using each of the methods of interest. However, this may not be the only explanation as some authors [7] have stated that viscoelastic strain rate is dependent on, amongst other factors, the stress history of the timber. Therefore, it is plausible that when the timber was re-stressed it deformed at a greater rate than the specimen that had no previous stress applied. Furthermore, the same authors also stated that the strain rate is also dependent on the level of applied stress. Hence, re-loading the specimen is likely to increase the rate of creep relative to a specimen that has already lost some of its load. Last but not least, the relaxation of the steel strand was found to be low (1% after one year of testing) when compared with the creep phenomenon in timber. Therefore, re-stressing the tendon to cancel out the prestress loss due to pure relaxation of steel is almost unnecessary. Furthermore, it increases the load in the timber and, therefore, the prestress losses due to creep deformation of timber. However, further investigation is needed to clarify this issue.

In conjunction with the experimental programme an analytical solution was developed to facilitate the prediction of losses. This analytical solution is similar in form to the Eurocode 2 equation, in that it applies the age-adjusted effective modulus method. However, the solution has additional complexity due to the anisotropy of LVL. The analytical solution is presented as Equation 2.

$$\Delta N(t)=\frac{-N(t_0)\left(\frac{l_{ll}\varphi_{ll}(t)}{A_{ll}E_{ll}}+\frac{l_{\perp}\varphi_{\perp}(t)}{A_{\perp}E_{\perp}}+\frac{l_{tot}\Gamma_p(t)}{A_pE_p\left(1-\chi_p\Gamma_p(t)\right)}\right)+\Delta\varepsilon_{ll,in}l_{ll}+\Delta\varepsilon_{\perp,in}l_{\perp}-\Delta\varepsilon_{p,in}l_{tot}}{\frac{l_{ll}}{\left(\frac{A_{ll}E_{ll}}{1+\chi_{ll}\varphi_{ll}(t)}\right)}+\frac{l_{\perp}}{\left(\frac{A_{\perp}E_{\perp}}{1+\chi_{\perp}\varphi_{\perp}(t)}\right)}+\frac{l_{tot}}{A_pE_p\left(1-\chi_p\Gamma_p(t)\right)}} \qquad (2)$$

Where the subscripts *ll*, ⊥ and *p* denote parallel to the grain, perpendicular to the grain and prestressing steel, respectively. Furthermore:

$\Gamma(t)$	is the relaxation function
ε_{in}	is the inelastic strain of the element under consideration
$\varphi(t)$	is the creep coefficient at time t
χ	is the aging coefficient of the element under consideration
A	is the cross sectional area of the element under consideration
E	is the modulus of elasticity of the element under consideration
l	is the length of the element under consideration
N	is the prestressing force, applied at time t_0
ΔN	is the loss of prestressing force at time t

To improve the applicability of the analytical solution it was important to make use of the experimental results and determine appropriate values for the aging coefficients (χ_{ll}, $\chi_{\perp}$ and χ_p). It is also important to assess whether or not the analytical solution exhibits the same trends as the experimental results and can be accurately used for predicting the losses.

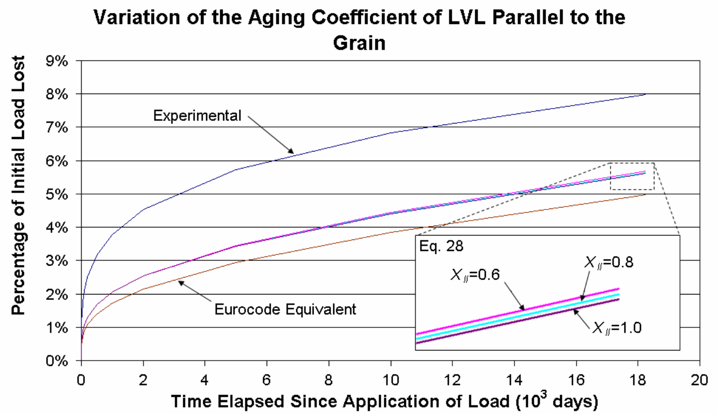

Fig. 15 Comparison between experimental results and analytical solutions for a beam specimen (no perpendicular to the grain LVL)

Manipulation of the aging coefficients (χ_{ll}, $\chi_{\perp}$ and χ_p) revealed that the refinement of any prediction by using aging coefficients in the range of physical meaning for them (from 0 to 1) would be impossible. By changing the aging coefficient for LVL parallel to the grain (χ_{ll}) from 0.6 to 1.0 (Figure 15), the difference in results is seen to be negligible. Therefore, it is proposed that the aging coefficients be set to unity for the purpose of simplifying the calculation of losses. Further comparison with experimental results and neglecting relatively small terms allows for further simplification of the analytical solution. The final, simplified solution is presented as Equation 3.

$$\Delta N(t)=\frac{-N(t_0)\left(\frac{l_{II}\varphi_{II}(t)}{A_{II}E_{II}}+\frac{l_{\perp}\varphi_{\perp}(t)}{A_{\perp}E_{\perp}}\right)}{\frac{l_{II}}{\left(\frac{A_{II}E_{II}}{1+\varphi_{II}(t)}\right)}+\frac{l_{\perp}}{\left(\frac{A_{\perp}E_{\perp}}{1+\varphi_{\perp}(t)}\right)}+\frac{l_{tot}}{A_pE_p}} \tag{3}$$

The seemingly poor comparison between the analytical solution and the experimental results can be attributed to the variability of the material. Although LVL is less variable than traditional sawn timber, it is still a variable material. As such it is likely that the specimens tested had different properties than those assumed for use in the analytical solution. If, for example, the test specimen was to have a below average stiffness and/or above average creep coefficient the experimental results would show greater losses than the analytical solution which assumes average values. In Figure 16 the upper bound applies the smallest Young's moduli and largest creep coefficient values, whereas the lower bound applies the largest Young's moduli and smallest creep coefficient values. This figure clearly shows the scatter of results using the different values of the material properties as measured in the experimental tests performed on the small LVL blocks.

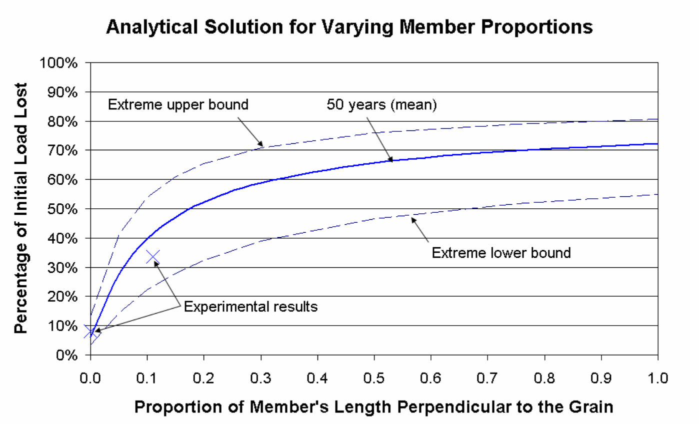

Fig. 16 The proposed analytical solution evaluated using the "worst case", mean and "best case" material properties

5 Conclusions

From the results and analytical model it is clearly demonstrated that the most influential variable is the proportion of the member that is perpendicular to the grain. That is, once the less desirable properties of LVL perpendicular to the grain are introduced into the system, the magnitude of the losses increases. The 10% losses predicted at the end of the service life for an LVL member loaded parallel to grain would increase to 34% if 11% of the length was loaded perpendicular to the grain, such as for a prestressed LVL frame. In addition, the rate at which losses occur decreases over time.

The use of disc springs in the anchorage reduced losses, but their size limits their practicality as a solution for reducing losses and the reduction achieved is not significant. It is difficult to conclude whether or not re-stressing the member is beneficial. There are too many unknown variables. However, it does not seem to dramatically improve the behaviour and, generally speaking, would not offer a significant enough advantage to be applied in practice.

At the material level, the creep coefficient of LVL perpendicular to grain was found to be almost four times the value parallel to grain, which was in close agreement with the value of one provided by the New Zealand Standard. The relaxation of the steel strand was found to be 3.5% after 50 years.

An analytical formula similar to that recommended by the Eurocode 2 for precast concrete structures prestressed with unbonded tendons was derived. Even if some differences between experimental and analytical results exist, mostly due to the scatter of experimental results, this simple formula can be used in the design of timber structures prestressed with unbonded tendons to predict losses over the service life.

6 Acknowledgements

Thanks to those who have provided technical and financial support; Hank Bier (Wairiki Institute of Technology); Warwick Banks (Carter Holt Harvey); Colin Palmer (Adhesive Technologies Ltd.); Rob McGregor (New Zealand Moisture Meters); John Maley, and the staff of the University of Canterbury's Department of Civil Engineering laboratory.

7 References

[1] Buchanan A., Deam B., Fragiacomo M., Pampanin S., and Palermo A., “Multi-storey prestressed timber buildings in New Zealand.” *Structural Engineering International, IABSE, Special Edition on Tall Timber Buildings*, in print, 2008.

[2] Palermo A., Pampanin S., Fragiacomo M., Buchanan A.H., and Deam B.L., “Innovative seismic solutions for multi-storey LVL timber buildings.” *Proc., 9th World Conference on Timber Engineering WCTE 2006*, Portland (U.S.A.), 2006, 8 pp., CD.

[3] Davies M. E., *Long Term Behaviour of Laminated Veneer Lumber Members Prestressed with Unbonded Tendons*, University of Canterbury, Christchurch, New Zealand, 2007.

[4] Toratti T., *The Creep Properties of Kerto-Laminated-Veneer-Lumber*, Helsinki University of Technology, Espoo, Finland, 1988.

[5] *New Zealand Standard 3603: Code of Practice for Timber Design*, Standards New Zealand, Wellington, 1993.

[6] *Eurocode 2: Design of Concrete Structures – Part 1-1: General Rules and Rules for Buildings*, European Committee for Standardization, Brussels, 1992.

[7] Hanhijarvi A., and Hunt D., “Experimental indication of interaction between viscoelastic and mechano-sorptive creep”, *Wood Science and Technology*, Vol. 32, 1998, pp. 57-70.