THE MATERIAL BEHAVIOUR OF RADIATA PINE UNDER COMPRESSION*

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ABSTRACT

To investigate connection details under compression stress using FE methods, one needs to know not only the compression strength but also the complete stress-strain behaviour including the hardening of the wood for all directions. Up to now, this data is unavailable for New Zealand Radiata Pine. To gather the missing information, comprehensive compression tests were carried out according to different testing standards including different loading configurations and using different evaluation methods. Furthermore, these include different load-to-grain angles as well as different load-to-annual ring directions. Both, the stress-strain behaviour including softening and hardening parts and the material properties are analysed and described. The results are presented and provided in this paper.

INTRODUCTION

There are many situations in a structure where loads have to be transferred from one member to another. In many cases and details, this will be performed much better in compression than in tension and leads often to more ductility in the failure behaviour. The Finite Element (FE) methods and simulations are very helpful methods for the development, investigation and improvement of new or existing complex construction details. But for reliable modelling results, it is necessary to implement the complete and real stress-strain behaviour for all directions and stress situations. Thus researchers need to know the complete stress-strain behaviour including the failure behaviour of wood.

Many research studies outside of New Zealand and Australia have been carried out to determine the compression strength and compression behaviour under various load-to-grain directions. For example, Baumann [1], Keenan [2], Poulsen [3], Reiterer & Stanzl-Tschegg [4] and lately Franke [5] have carried out different tests to investigate, amongst others, the compression behaviour and the compression strength including more or less different load-to-grain angles, annual ring directions or combined stress situations for different species of wood. However, insufficient information on the compression strength values and the compression behaviour for Radiata Pine lumber and laminated veneer lumber (LVL) from New Zealand is available in the literature. To correct this situation, compression tests were carried out to gather the missing information.

The significant elastic-plastic strength behaviour of timber under compression, the deformation and the loading conditions make it difficult to determine a defined strength value caused by failure. Furthermore, the current testing standards around the world use different tests and evaluation methods which result in non consistent strength values and there is still an active discussion about the tests and design methods, e.g. Larsen et al. [6] and Blaß & Görlacher [7].

TEST SERIES AND METHODS

TEST STANDARDS

The AS/NZS 4063:1992 [8], draft AS/NZS 4063.1:2009 [9], EN 408:2003 [10], ASTM D143-94 (2007) [11], ISO 3132:1975 [12] and DIN 52192:1979 [13] are different test standards used to determine the compression strength of wood. Each standard uses different test configurations and/or different evaluation methods, which shows the difficulty to determine a consistent strength value and to compare the values. Many researchers distinguish between 6 different loading configurations, as shown in Figure 1, and discuss the comparability of their compression strength values. There is furthermore an influence of the specimen length and the length of the support on the stress-strain behaviour and therefore, on the strength value as well, as shown in Figure 2. All configurations are loaded over the complete depth. Therefore, configuration A is fully loaded and called "pure block test". All other configurations are partly loaded and called "rail tests".

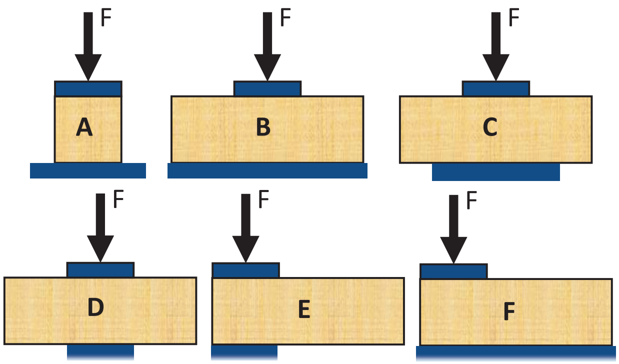

Figure 1. Loading configurations for determining compression perpendicular to grain, cf. Larsen et al. [6]

Each testing standard uses one of the configurations A, B or D. A description, summary and comparison of the specific procedures of the test standards are given in Franke and Quenneville [15].

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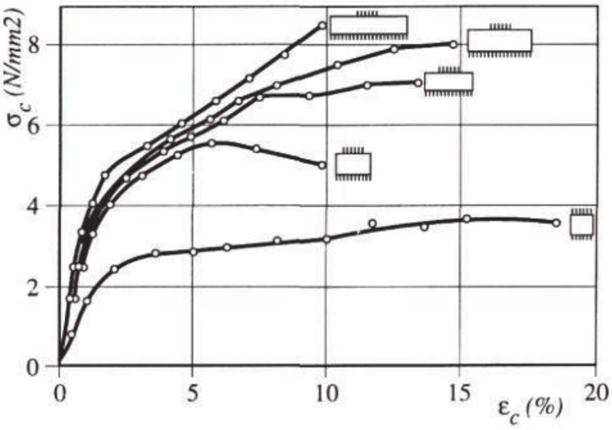


Figure 2. Different stress-strain behaviours under compression perp. to grain, cf. Suenson [14]

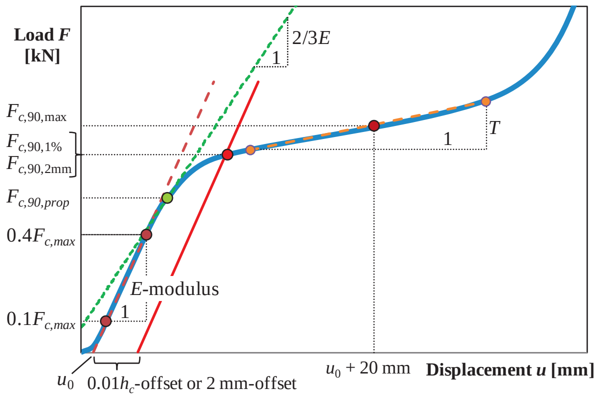


Figure 3. Evaluating methods for the compression strength

EVALUATION METHODS

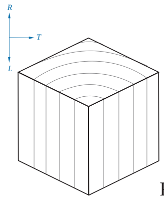
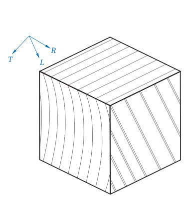
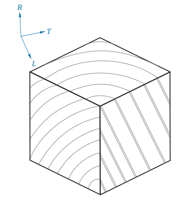
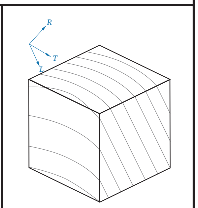
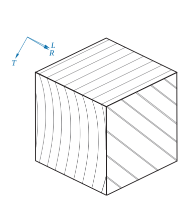
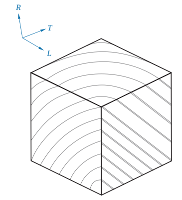
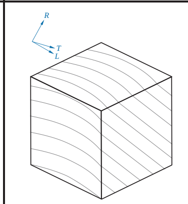
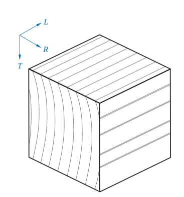
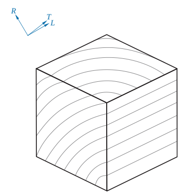
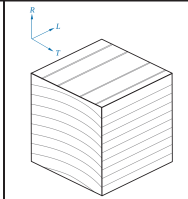
According to the different testing standards used, different evaluation methods were adopted. For determining the material properties, on one side the basic yield loads $F_{c,90,1\%}$ or $F_{c,90,2mm}$ were evaluated for each test. On the other side and additional to that, the MOE, the tangent-modulus as the slope of the curve after yielding and the extended proportional limit load $F_{c,90,prop}$ needs to be determined to describe the complete material behaviour, as shown in Figure 3. The MOE, the proportional limit point or the yield strength and the tangent-modulus are important parameters to describe the material behaviour in a FE simulation using a bilinear material behaviour for example. This can be extended using a multi-linear or non-linear material behaviour formulation.

The MOE was calculated as the slope of the line between approximately 10 % and 40 % of the maximum load. The extended proportional limit load is defined as the contact point of the test data and a line with a slope of 2/3·MOE according to DIN 52192:1979. The 1 %-offset method (EN 408:2003) and the 2 mm-offset method (AS/NZS 4063.1 draft), were adopted to evaluate the yield load. In this paper the yield compression strengths $f_{c,90,1\%}$ or $f_{c,90,2mm}$, and the maximum compression strength $f_{c,90,max}$, calculated using the corresponding compression load divided by the compression area, are reported. All displacements shown in the paper are corrected with the initial slip u_0.

TEST SERIES AND SPECIMENS

The compression test series with Radiata Pine lumber and LVL includes a total of 250 pure block tests (configuration A), which covers both different load-to-grain directions from 0° to 90° and different load-to-annual ring direction from tangential to radial as shown in Table 1.

Table 1. Configurations of the compression tests

	β = 0° - tangential	β = 45° - not oriented	β = 90° - radial
α = 0°	 RP/LVL-C-NOL0		
α = 22.5°	 RP/LVL-C-TL22.5	 RP-C-NOL22.5	 RP-C-RL22.5
α = 45°	 RP/LVL-C-TL45	 RP-C-NOL45	 RP-C-RL45
α = 90°	 RP/LVL-C-TL90	 RP-C-NOL90	 RP/LVL-C-RL90

Each group of one load-to-grain angle is divided into specimens predominantly for a tangential TL (β = 0°), radial RL (β = 90°) and not-oriented NOL ($\beta \approx$ 45°) load-to-annual ring direction. For LVL only the five relevant configurations NOL0, TL22.5, TL45 TL90 and RL90 were tested, cf. Table 1. To investigate the influence of different support configurations under compression perpendicular to grain, 170 additional rail tests (configurations B and D) were done. Each of these test groups includes a variation of the load-to-annual ring direction β, as well.

The labelling of the specimens, e.g. RP-C-TL90-2, include at first the type of wood product (RP = Radiata Pine), followed by the testing (C = compression), the predominant load-to-annual ring direction or plane in load direction (T = tangential, R = radial, L = longitudinal, NO = not oriented) together with the load-to-grain angle α (90 = 90°) and finally the number of the specimen. The specimens of Radiata Pine of the configurations B and D are all labelled with NO for the load direction, because each configuration includes all

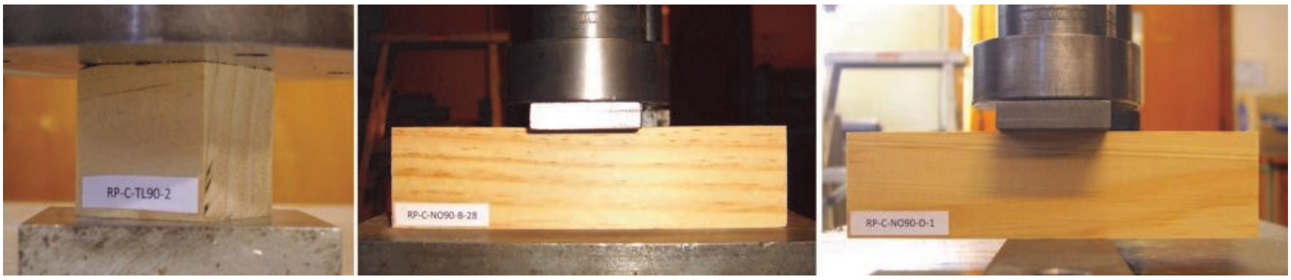


Figure 4. Test photos of the configurations A, B and D for Radiata Pine

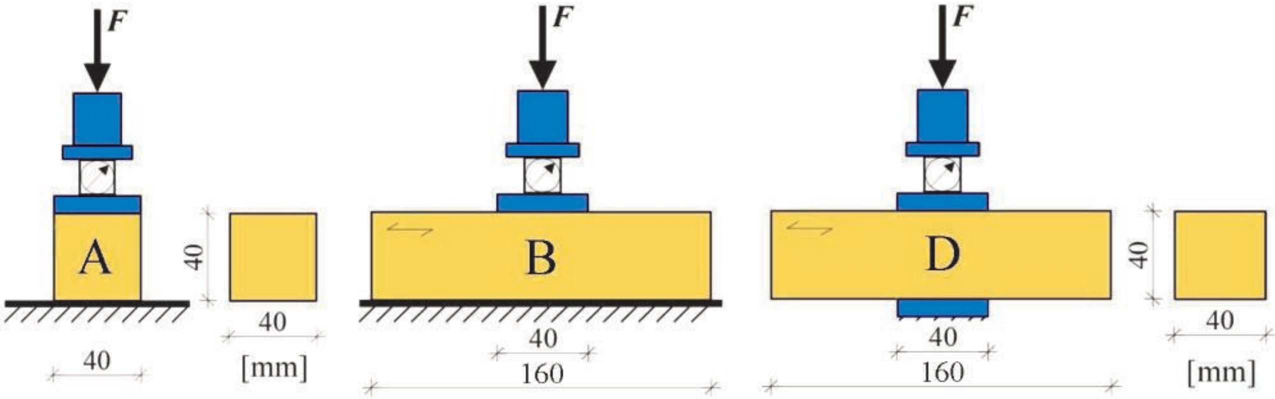


Figure 5. Test setup of the configurations A, B and D

Table 2. Parameters of the compression tests with New Zealand Radiata Pine

Group name	No. of speci-men	Width/Height/ Thickness w / h / t [mm]	Mean Density ρ [kg/m^3]
RP-C-NOL0	30	40 / 40 / 40	469.6
RP-C-TL22.5	10	40 / 40 / 40	486.1
RP-C-NOL22.5	10	40 / 40 / 40	440.8
RP-C-RL22.5	10	40 / 40 / 40	438.9
RP-C-TL45	10	40 / 40 / 40	489.8
RP-C-NOL45	10	40 / 40 / 40	451.1
RP-C-RL45	10	40 / 40 / 40	438.0
RP-C-TL90	30	40 / 40 / 40	472.1
RP-C-NOL90	30	40 / 40 / 40	489.9
RP-C-RL90	30	40 / 40 / 40	481.3
RP-C-NOL90-B	30	160 / 40 / 40	478.1
RP-C-NOL90-D	30	160 / 40 / 40	496.4

load-to-annual ring directions $(0 \leq \beta \leq 90^\circ)$, but they have the additional letter B or D according to the configuration.

A small quantity of tests with European spruce was carried out before by Franke [5]. These tests are characterised using the same sizes and test procedures, so that they are an excellent basis for comparison.

Prior to the tests, the specimens were conditioned to 20 °C and 65 % relative humidity until mass consistency was reached. Configuration A is carried out according to the European standard EN 408:2003, configuration B according to the ASTM D143-09 and the AS/NZS 4063.1:2009 and configuration D according to the procedures in the appendix of AS/NZS 4063.1 draft standard. Figure 4 and Figure 5 show a test photo and the test setup for each configuration. The tests were loaded at uniform rate of about 3.5 mm/min until approximately 37.5 % and 50 % strains were reached, which amounts to 15 mm and 20 mm respectively. The test duration was about 5 min. Due to the good accuracy of the preparation of the parallel opposite test sides of the specimens, the tests were done without using universal joints. The load was measured in the axis of loading and the deformation between the loaded steel plates. The moisture content of all specimens was measured to 11.9 % and 12 % in average for Radiata Pine and LVL respectively.

Table 3. Parameters of the compression tests with LVL

Group name	No. of speci-men	Width/Height/ Thickness w / h / t [mm]	Mean Density ρ [kg/m^3]
LVL-C-NOL0	20	40 / 40 / 40	574.5
LVL-C-TL22.5	5	40 / 40 / 40	599.7
LVL-C-TL45	5	40 / 40 / 40	615.8
LVL-C-TL90	20	40 / 40 / 40	617.2
LVL-C-RL90	20	40 / 40 / 40	579.5
LVL-C-TL90-B	20	160 / 40 / 40	561.4
LVL-C-RL90-B	20	160 / 40 / 40	554.6
LVL-C-TL90-D	20	160 / 40 / 40	563.0
LVL-C-RL90-D	20	160 / 40 / 40	550.7

The strength related results for the tests perpendicular to grain and a comparison between the cases A, B and D for $\alpha = 90^\circ$ have been already published for Radiata Pine in more detail and can be found in Franke and

Quenneville [15]. This paper focuses on the description of the complete stress-strain behaviour and their characteristic parameters to provide information for simulation modelling.

RESULTS

COMPRESSION BEHAVIOUR

The failure behaviour under compression can be classified in general in a ductile manner and classified into different sections: the elastic section, the nonlinear section with the yielding, a possible softening or load drop, a plateau with some hardening and the strong hardening after big compressive strains. In relation to the orthotropic cellular structure of the wood, the behaviour is strongly dependent on the load-to-grain direction, as one can see in Figure 6 and Figure 7.

The long and narrow cells are oriented in longitudinal direction and act like columns which results in a high stiffness as well as in a high strength, compared to the ones in perpendicular to grain direction. Hence, the failure behaviour under compression parallel to grain is formed by buckling of the cell walls and thus a collapse of the cell which can be characterised as a stability failure and leads to the loss of the load capacity of the cell. A clearly visible kink or crushing band will evolve throughout the specimen and the load capacity of the specimen drops down or decreases slightly as you can see from the curve of NOL0 in Figure 6. After about 55 % compressive strains, a hardening or a splitting could be observed. In comparison, the failure behaviour of Radiata Pine in longitudinal direction is slightly different to the one of European spruce which has shown a more severe load drop and a distinctive plateau, as described by Franke [5]. Also, LVL shows a more severe load drop and lead to more splitting, cf. Figure 7.

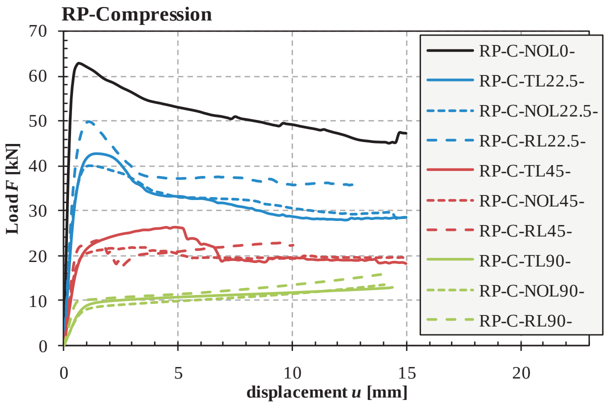


Figure 6. Load-displacement behaviour for Radiata Pine for all configurations A

For a load-to-grain direction perpendicular to grain, $\alpha = 90°$, the cells are loaded in bending which results in a lower stiffness and lower strength. As a matter of principle, the behaviours are very similar independent on the annual ring direction although of different failure mechanism in the microstructure. After the linear elastic part and yielding, some hardening occurs, which always changes into a strong hardening between 40 % and 45 % compressive strain for Radiata Pine, cf. Figure 6. This behaviour can be observed throughout all investigated species. Only the tangentially loaded LVL specimens show a more constant load level whereas the radial ones show a severe increase, cf. Figure 7.

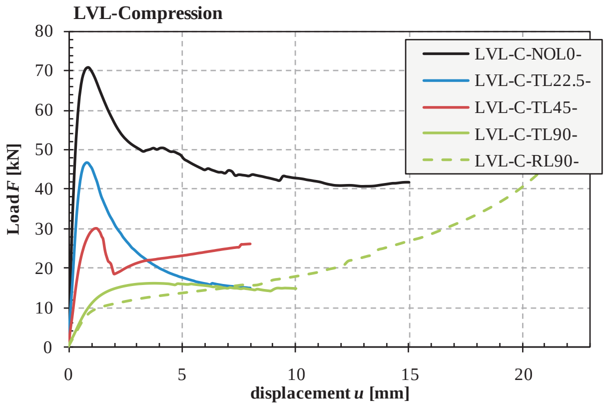


Figure 7. Load-displacement behaviour for LVL for all configurations A

From the transverse to the longitudinal load direction, the shear stress will influence the failure behaviour more significantly. For Radiata Pine in Figure 6, some ductile behaviour with some hardening could be observed before the development of the shear planes and the loss of load capacity. The load couldn't drop down completely because of the constraint of the split and sliding parts to the lower and upper steel plates loaded. A more distinctive strength degradation and nearly no ductile behaviour were observed with the LVL specimens. In comparison, the behaviour of European spruce is more alike the behaviour of the LVL, see Franke [5].

COMPRESSION PARAMETERS

As already mentioned for the material behaviour, the strength values are strongly dependent on the load-to-grain direction. The mean values of the modulus of elasticity *E*, tangent-modulus *T*, the proportional limit strength $f_{c,\alpha,prop}$ and the yield strength $f_{c,\alpha,1\%}$ using the 1 %-offset method are summarized in Table 4 for Radiata Pine lumber and in Table 5 for LVL. In comparison, LVL has in average a 23 % higher value for the 1 %-offset yield strength than the Radiata Pine ones. The proportional limit strength is in average 78.2 % of the yield strength for Radiata Pine and 76 % for LVL.

In spite of the higher density of the LVL specimen compared to the Radiata Pine specimen, they show a lower stiffness in longitudinal and radial direction as well as for the partial loaded rail tests. The value of the MOE can also be used to describe the slope of the strong hardening phase after more than 50 % compressive strains.

The positive tangent moduli T can be used to define the slope of the hardening phase after yielding explicitly, whereas the negative values only indicate a softening or a failure, since most material laws allow a positive value only. The value itself does not really represents the slope of the softening, it depends more on the test setup and the constraints of the split and sliding parts, induced by the shear failure, to the steel plates.

SUMMARY AND CONCLUSIONS

Table 4. Results of the compression tests with New Zealand Radiata Pine (mean values)

Group name	E [MPa]	T [MPa]	$f_{c,\alpha,prop}$ [MPa]	$f_{c,\alpha,1\%}$ [MPa]
RP-C-NOL0	5429.2	-32.2	29.8	39.1
RP-C-TL22.5	1852.7	-16.2	18.4	26.0
RP-C-NOL22.5	2053.3	-22.3	17.8	25.0
RP-C-RL22.5	2371.6	-8.2	21.2	30.5
RP-C-TL45	795.9	-3.6	9.9	13.3
RP-C-NOL45	963.4	-6.5	9.8	12.6
RP-C-RL45	1124.2	10.8	11.8	13.7
RP-C-TL90	288.2	5.8	4.4	5.7
RP-C-NOL90	280.0	9.3	4.1	5.1
RP-C-RL90	514.8	12.0	5.5	6.2
RP-C-NOL90-B	548.5	21.6	7.5	9.3
RP-C-NOL90-D	514.5	14.9	6.8	8.5

Insufficient information on the compression strength values and the compression behaviour for Radiata Pine lumber and laminated veneer lumber (LVL) from New Zealand is available in the literature. To correct this situation, compression tests were carried out to gather the missing information.

The compression test series with Radiata Pine lumber and LVL covers both different load-to-grain directions from 0° to 90° and different load-to-annual ring directions from tangential to radial. Using different standards and to provide parameters, which allow the description of the compression behaviour in FE simulations, the MOE, the tangent modulus, the proportional limit strength as well as the yield strength were evaluated.

The compression behaviour is strongly dependent on the load-to-grain direction and show many similarities between Radiata Pine lumber, LVL from Radiata Pine and European spruce. The behaviours perpendicular to grain are also independent on the annual ring direction although of different failure mechanism in the microstructure. In general, the behaviour can be divided into different sections for which the parameters are provided. Unfortunately, only user defined material laws in the FE program ANSYS allow defining all these sections to simulate the complete behaviour.

Table 5. Results of the compression tests with LVL (mean values)

Group name	E [MPa]	T [MPa]	$f_{c,\alpha,prop}$ [MPa]	$f_{c,\alpha,1\%}$ [MPa]
LVL-C-NOL0	4799	-180	34.2	45.2
LVL-C-TL22.5	2353	-249	22.6	28.7
LVL-C-TL45	1125	-185	12.6	18.1
LVL-C-TL90	297	-19	6.2	8.3
LVL-C-RL90	271	19	5.2	6.4
LVL-C-TL90-B	507	29	9.9	13.3
LVL-C-RL90-B	462	36	8.0	10.3
LVL-C-TL90-D	441	25	8.6	11.8
LVL-C-RL90-D	399	28	7.3	9.3

The presented results provide an accurate basis for the compression parameters and the compression behaviour for further use in many research fields.

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