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SIZE EFFECT OF LARGE SCALE TIMBER COLUMNS

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ABSTRACT: The very large glued laminated timber columns that are needed for tall timber buildings are too large to be physically tested in most facilities. To safely design these columns, it is necessary to identify and extrapolate behaviour from the physical testing of smaller specimens. Compression testing of 27 glue-laminated timber columns showed a reduction in strength with increased member size. This phenomenon is known as a size effect. The laminated timber exhibited a compressive strength much higher than the characteristic strength that it was graded it. Comparisons between columns of different lengths and widths, suggests that the homogenisation of laminated timber may mitigate the size effect. An extrapolation of the size effect from the column sizes tested, to an ultra-large column for a timber skyscraper, indicated that the magnitude of the effect could be large enough to reduce the compressive strength of the glulam to below its characteristic strength.

KEYWORDS: glued laminated timber, column, size effect, homogenisation effect, compression, tall timber

1 INTRODUCTION

Engineered timber is increasingly used as structural material for the construction of buildings. While panelised structural forms such as cross-laminated timber (CLT) platform systems have a number of advantages for low- to mid-rise construction, [1] glued-laminated (glulam) and laminated veneer lumber (LVL) systems may be more suitable for the primary structure of high-rise buildings [2]. The 14 storey Treet building in Bergen, Norway for example, the tallest timber building in the world at the time of writing, uses a structural system of partially connected glulam mega-trusses that include 405 x 605 mm glulam columns, and 495 x 495 mm glulam bracing elements [3]. Recent concept designs have indicated an architectural aspiration for buildings with timber structures into the 300 m or supertall building range. The preliminary engineering studies associated with the 300 m Oakwood Tower concept design have suggested a requirement for engineered timber mega-columns with a cross-section of 2.5 x 2.5 m [4]. Where it is not possible to directly test the largest elements that may be required in design, it is necessary to extrapolate beyond the experimental data. If such extrapolation is to take place, it is necessary to determine the extent to which size and homogenisation-effects are present within the range of the data set and whether there is a sound theoretical basis for accommodating this in any subsequent extrapolation.

The simple scaling theory implied by the stress based conception of strength, which can be traced back at least as far as Galileo in 1638 [5], holds that a nominal strength is proportional to a scaled dimension D or D^2, for one- or two-dimensional scaling respectively. Where a simple proportionality of this type does not hold, a "size effect" may be said to be present [6]. Materials that display elastic-plastic behaviour may be well described by simple scaling theory and generally do not exhibit strong size effects.

Figure 1: *Oakwood Tower proposal (Foster and Ramage, 2016) ©PLP Architecture*

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However, materials that display brittle or quasi-brittle behaviour often do exhibit strong size effects. For brittle materials, strength may be considered to be governed by the so-called weakest-link model, and the resulting Weibull stochastic size effect is well-described by a power law whose exponent is a function of the variability of the material strength [7]. For quasi-brittle materials, energetic size effects described by fracture mechanics provide better agreement with experimental results [8]. Bazant [6] summarised numerous energetic statistical scaling laws for different quasibrittle materials under different loadings conditions. However, it was acknowledged that very little work to establish such a law for timber had been done at the time.

Barrett et al. attribute the effect of size in timber to variation in strength properties within structural members [9]. These size effects in structural specimens are reported to be significantly greater those than suggested by small clear specimens [9]. Barret et al. propose a value of 0.1 as the exponent for a "width" size effect in compression. More recently it has been suggested that size effects are of 'minor importance' for timber in compression [10]. However, it has been shown that where structures exhibit post peak softening not fully explained by P-delta effects, then the softening response and the nominal strength generally exhibit a size effect [11]. Compression failure in timber columns is typically ductile and shows evidence of post peak softening due to material nonlinear stress-strain behaviour in addition to P-delta effects [10]. Notwithstanding the typically ductile compression failure in timber it has been noted that knots may induce tensile-type splitting failure [9]. Barret et al. find no evidence of significant variation in size effects across grades, species and property fractiles across a range of North American timbers [9]. A further source of potential size effect is the influence of grading methods [9].

2 METHODOLOGY

2.1 SAMPLES

To investigate size effect, two sets of glulam columns were loaded in compression, parallel to the grain until failure. The first set of 'stocky' columns all had the same aspect ratio, with a length three times the width of their square cross-section. Four columns of each of the three widths (120mm, 240mm and 360mm) were tested. The second 'slender' set had five columns, each of the same three widths above, but their lengths were twelve times their width. The same glue-laminated timber with a lamination thickness of 40mm was used for all samples. The timber was graded as having a characteristic strength in compression of 24MPa, meaning that 95% of samples should fail at a load greater than 24 MPa. The maximum capacity of the Amsler rig was 4900 kN, so the dimensions of the largest samples were chosen such that they would be expected to be able to fail in the machine.

2.2 LOADING CONDITIONS

The samples were compressed using an Amsler compression rig which is controlled by a computer to apply the load under displacement controlled conditions. The average rate of loading across all the samples was 0.008 mm/s although, this did vary slightly between samples. Displacement controlled loading allowed the behaviour of the material to be captured as it cracks and yields, whereby strain continues to increase after the maximum load has dropped.

Three separate slender columns were tested with roller connections to simulate a pin joint and allow for failure by buckling. Columns with a relative slenderness ratio greater than 0.3 could fail by buckling as per Eurocode 5 [12]. Despite having a relative slenderness of 0.78, the columns still failed in compression. Only once the timber had failed and continued to yield after the maximum load had dropped off, did the columns then deflect laterally. The remaining twenty-seven samples were tested with flat plates instead of rollers, to mimic restrained end conditions. This was easier to set up and safer to operate, because of the reduced risk of one of the larger columns deflecting suddenly. Columns were lined up on the cross hairs of the top and bottom of the plates to ensure they were placed centrally to avoid eccentric loading. As a safety measure, ties contained and supported the samples within the rig, throughout their lengths. To mitigate the risk of a splinter flying from a sample, operators stood behind a Perspex screen and the surrounding area was cleared.

Figure 2: *Amsler rig and one of the five largest 'slender' columns*

2.3 DISPLACEMENT MEASUREMENT

Displacement measurements were recorded by an Optrax camera and LED markers. LED nodes were placed on one side of the sample in three columns and at least five rows for each sample to record both vertical and horizontal displacements. The camera recorded the three-dimensional positions of each LED node, which were later processed in Microsoft Excel to determine the strain between any two LED markers.

Figure 3: *Test set up of the Optrax camera to record displacements*

3 RESULTS

3.1 COMPRESSIVE STRENGTH

The timber was graded by the supplier, Stora Enso as having a characteristic compressive strength of 24 MPa, however, testing revealed that the strength of the glulam greatly exceeded this. The average 5th percentile strength (equivalent to the Eurocode 5 definition of characteristic strength [12]) across all the sample sizes is 36.1 MPa.

The set of 'slender' columns, showed a noticeable reduction in strength with increased member size from 38.6 MPa to 35.5 MPa between 120mm width and 360mm. The 'stocky' set showed a less obvious strength reduction with size. Column strength reduced from 40.3 MPa to 39.5 MPa between the smallest and largest samples. It is notable that the smallest samples have the largest scatter of results, shown by the larger standard deviations.

Three of the four 360mm wide 'stocky' samples did not fail. Their failure has been estimated for these tests from analysing their stress strain curves.

Table 1: *Results of compression tests on 'stocky' columns*

Width (mm)	120	240	360
Length (mm)	360	720	1080
Average Force (kN)	580	2311	5114
Average Failure Stress (MPa)	40.3	40.1	39.5
Standard Deviation	5.3%	4.4%	2.1%

Table 2: *Results of compression tests on 'slender' columns*

Width (mm)	120	240	360
Length (mm)	1440	2880	4320
Average Force (kN)	556	2101	4604
Average Failure Stress (MPa)	38.6	36.5	35.5
Standard Deviation	4.0%	2.7%	3.0%

3.2 STRAIN

The vertical strain was measured by averaging the strain between the three highest and three lowest LED markers. The horizontal strains are measured by averaging the strain between the five left most and five right most LED markers. Table 3 shows the average vertical strain at failure for each sample size. There does not appear to be any obvious size effect either with the average vertical or horizontal strain at failure. The same applies to the Poisson's Ratio.

Table 3: *Average vertical strain at failure*

Width (mm)	120	240	360
'Stocky' Vertical Strain	0.45%	0.42%	0.40%
'Slender' Vertical Strain	0.36%	0.32%	0.37%

Table 4: *Average Poisson's Ratio at failure*

Width (mm)	120	240	360
'Stocky' Poisson's Ratio	34%	41%	44%
'Slender' Poisson's Ratio	44%	58%	56%

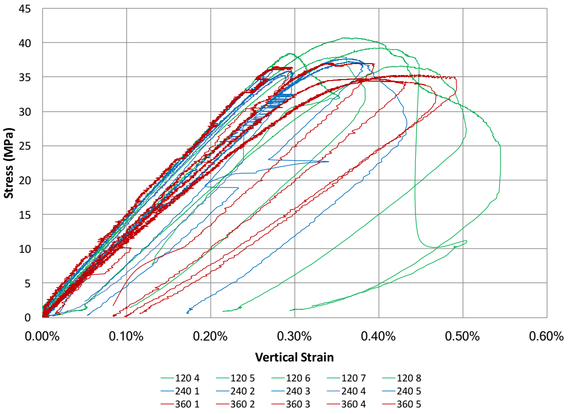

Figure 4: *Vertical strain for all 'slender' columns*

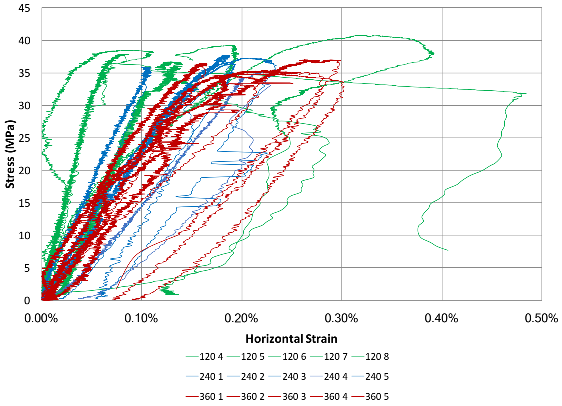

Figure 5: *Horizontal strain for all 'slender' columns*

3.3 STIFFNESS

There is also not an obvious size effect for the Young's modulus. However, Table 5 shows that there is a trend of larger sizes having less variation in stiffness.

***Table 5:** Average Young's Modulus*

Width (mm)	120	240	360
'Stocky' Stiffness (MPa)	11630	12140	11670
'Slender' Stiffness (MPa)	12504	12504	10841
'Stocky' Standard Dev.	11.9%	8.7%	8.3%
'Slender' Standard Dev.	7.2%	7.4%	4.3%

3.4 FAILURE MECHANISM

Almost every column included a kinkband failure. Figure 6 shows a selection of photographs of the failed samples. Samples that were loaded for longer after their maximum loads, tended to be more likely to have large longitudinal cracks, which would propagate further with more loading. Longitudinal cracks occurred more frequently on the sides with the lamellas, although not often directly along the glue lines. Photographs of samples that were taken before and after showed that the smaller samples were more likely to fail via kinkbands through a knot than larger samples. The larger samples, which typically had more major defects with the laminations, such as large ridges cut away between lamellas, rarely failed along these longitudinal lines, but instead more consistently failed via horizontal kinkbands, often at numerous points along the length of the sample.

***Figure 6:** Failed samples showing kinkbands failures, failures through a knot and longitudinal splitting*

For all the tests, audible cracking would occur from roughly one-third of the failure load, up until failure, generally increasing in volume until failure, as larger cracks formed. The samples failed at different positions throughout the length of the column. This is due to the statistical element of the failure mechanism of where the most significant flaw falls. This indicates that the failure mechanism cannot be a purely deterministic process; otherwise, the failure would always be expected to occur centrally.

4 ANALYSIS AND DISCUSSION

4.1 WEIBULL ANALYSIS

The results of the compression testing suggest that a size effect exists, but debate remains about the correct method to quantify a size effect. Equation (1) by Weibull [7] can be used for a set of columns with a constant aspect ratio, where τ_i is failure stress, W_i is column width and L_i is column length. When applied to the 'slender' set columns, (which exhibited a stronger size effect than the 'stocky' columns) the analysis yields an average size effect parameter S_R = 0.074.

$$\frac{\tau_1}{\tau_2} = \left(\frac{W_2}{W_1}\right)^{S_R} = \left(\frac{L_2}{L_1}\right)^{S_R} \tag{1}$$

$$S_R = S_W + S_L \tag{2}$$

$$\frac{\tau_1}{\tau_2} = \left(\frac{W_2}{W_1}\right)^{S_W} \left(\frac{L_2}{L_1}\right)^{S_L} \tag{3}$$

When compared with stocky samples, the size effect can be further broken down using equations (2) and (3) [7] to yield a lengthwise factor, S_L = 0.059 and widthwise size parameter, S_W = 0.015. These are less than the values observed by Barrett et al. who found values of S_R = 0.20 and $S_W = S_L = 0.10$ for un-laminated timber.

A similar Weibull analysis showed the strength of glulam to be proportional to the volume of timber raised to the power of -0.24 for the 'stocky' columns in compression and -0.94 for the 'slender' columns, see Figure 7 below. By comparison, studies by Astrup et al. [13] found that the strength of glulam in tension was proportional to the volume of a sample raised to the power of -0.29 and Gustafsson [14] observed a similar power law of -0.20 for loading perpendicular to the grain. The results of the 'stocky' columns tied in well with the previous data of short, stocky glulam samples. The significantly higher power law for the 'slender' columns, again demonstrates a variation in the size effect with the dimensions of samples, with longer samples exhibiting the effect most strongly. A possible explanation of this is that the width-wise lamination of timber is strengthening the samples with increased width, thereby overcoming or mitigating any width-wise size effect. The laminations do not continue to increase with length however, so the size effect is more distinct lengthwise. The variation of results between the 'stocky' and 'slender' columns suggests that a size effect for engineered timber is best not analysed on a volumetric basis.

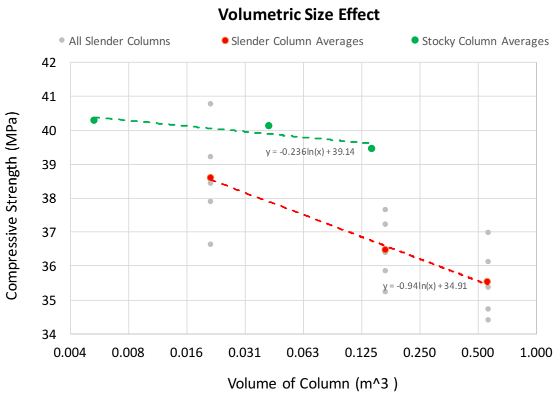

Figure 7: *Volumetric size effect plot*

With just three points for each of the ‘slender’ and ‘stocky’ columns, it not yet possible to accurately predict the strength reduction for very large samples. The length wise and width wise parameters are used to compare the two different aspect ratios on the same chart in Figure 8 by normalising the ‘stocky’ columns as if they had the same width to length ratio as the ‘slender’ columns.

One line of best fit for a Weibull scaling law, that encompasses all the samples sizes, would predict a reduction in strength from 38.6 MPa for a 120mm slender column to 32MPa for a 2.5m wide column. This is shown in green in Figure 8. The predictions are marked in black.

4.2 ENERGETIC STATISTICAL ANALYSIS

The energetic statistical size effect has been well documented by Bazant [6] for other materials, but no literature has been found to quantify it for glulam in compression. The average compressive strengths for each size have been fitted to Equation (4) [6] which is a general scaling law for quasibrittle size effect based on energetic statistical theory. Where σ_0 is the characteristic material strength, σ_N is the nominal strength of a sample, D is a dimension of the sample and D_0 is a constant that will vary depending upon the material and the chosen dimension. D_0 is dependent upon crack length and the size of the fracture process zone (FPZ). Using a characteristic strength σ_0= 42MPa and a characteristic length of D_0 = 833 mm if D is the width of the columns or D_0= 10000 mm when D is their length, produces a decent fit to the experimental data. This scaling law is plotted in blue in Figure 5.

$$\sigma_N = \sigma_0 \left(1 + \frac{D}{D_0}\right)^{-1/2} \tag{4}$$

The energetic statistical scaling law is a worst-case scenario in terms of reduction of strength. It could see the compressive strength reduced to as much as 22 MPa for the 2.5 m wide columns required for the Oakwood Tower proposal, bringing the strength of the timber below its graded value of 24MPa.

Given the small number of data points, these figures of strength reduction are rough estimations at this stage and have been calculated to understand if the magnitude of the size effect could be significant, rather than to make a firm prediction of column strength.

Overall the size effect parameters for glulam were lower than those found in the literature for un-laminated timber, which further suggests that the homogenization from laminating timber mitigates the strength reduction. Other material properties were investigated, but they did not exhibit a size effect.

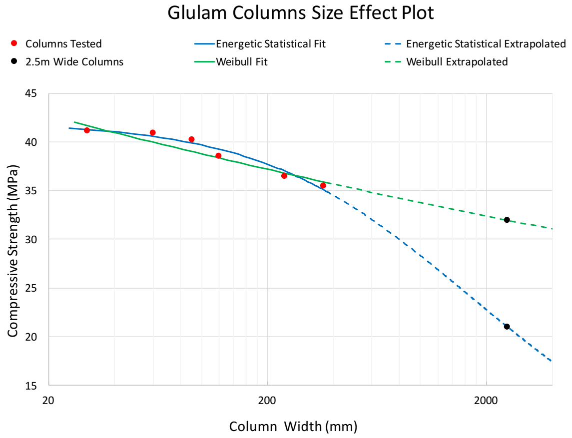

Figure 8*: Glulam columns size effect plot comparing a Weibull analysis with and energetic statistical analysis*

4.3 SOURCES OF ERROR

Different samples of wood will naturally have a slight variation in strength and stiffness due to its anisotropic structure and the presence of knots and flaws. Aside, from this, there may be a few sources of error which could have disrupted the results.

Figure 9: *The ties in contact with a 360 sample (left) and not in contact with a 120 (right)*

It was a priority to operate the experiments in a safe manner, so ties were placed along the length of the ‘slender’ columns to contain them in the event of a buckling or a sudden rupture. Due to the width of the supporting columns of the Amsler machine, these ties were in contact with the 240mm and 360mm wide columns, but not the 120mm wide ones (see Figure 9). This meant that smaller columns were less restrained which could have affected the strain or stiffness results and because it is effectively a slightly different end condition, perhaps also the compressive strength. The restraints also made it harder to align the heaviest samples precisely to the upper crosshairs. If any columns were not set perfectly vertically the load may have been applied slightly eccentrically, which would also have affected the maximum compressive stress sustained by a column.

A further measure, taken for safety, was to slightly slow the displacement rate just before failure, this was not done consistently between the different sample sizes. Overall there was also some variation in the displacement rates.

It does not affect the compressive strength and size effect analysis, but because the range of Optrax camera could not cover the entire length of the medium and large samples, some error in the strains and stiffness may have been introduced here.

5 CONCLUSIONS

Tests on twenty-seven glulam columns (of six different sizes) showed a reduction in compressive strength, parallel to the grain, with increased member size. This indicates the presence of a size effect over the range of samples tested. Initial estimations to quantify the effect indicate that, although small across the samples tested so far, the strength reduction could be large enough to cause a significant strength reduction for very large scale columns.

Analysis of the results showed numerous indications that the homogeneity of timber, due to the laminated layers of wood, was mitigating the strength reduction. Firstly, the characteristic strength of the laminated timber was approximately 36 MPa, fifty percent higher than the 24 MPa that the timber was graded as. Secondly, the size effect was much greater lengthwise than width-wise (where the number of laminations would also increase with column size). Finally, quantifying the results to a Weibull analysis gave lower values for the size effect than for test on un-laminated timber found in the literature.

The experimental results demonstrated a size effect over a limited range of column sizes. Although the number of samples for each dimension was small, the low standard deviations of the strengths give a reasonable level of significance to the experimental results.

5.1 FURTHER WORK

Further sample sizes will be required to determine an energetic statistical scaling law that could be used to confidently predict the strength of large-scale glulam columns. To achieve this, it will be necessary to strategically select an array of samples that will be able to isolate the effect of homogenisation from the size effect. This may involve a more scalable way of laminating the columns. To increase the range of columns sizes that have been tested, it would be beneficial to test a set of smaller or intermediate samples. Unfortunately, it would not be possible to test, and successfully crush, columns with a larger cross section in the Cambridge University Engineering Department due to capacity of the machine having been reached. It would be particularly beneficial to test a larger range of lengths for a given cross section, to more accurately isolate a lengthwise size effect, given that this appears to be dominant over a width-wise effect. An accurate quantification of the size effect and impact that laminations have, could be used to design the most suitable engineered timber for very large scale construction.

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