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SCALING STUDY ON VISCOUS DAMPING FOR GLULAM AND HYBRID GLULAM-FRP BEAMS

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ABSTRACT: Damping plays an important role in long-span, mass timber floors due to the relation it has to energy dissipation. Energy dissipation in these systems helps control how vibrations spread and whether its interaction with humans occupying the buildings causes discomfort or not. The present study focuses on the effect of scale on viscous damping in Glulam and fibre-reinforced Glulam beams. Twelve full-scale and thirteen small-scale equivalent Glulam beams (Australian Southern Pine) of two different depths were tested using the impact test method. Hybrid beams where manufactured with Fibre Reinforced Polymer (FRP) strips embedded at the interface between lamellas during manufacturing of test samples. Outcomes of this experimental study show that there is an effect of scale in viscous damping – small-scale beams experience a higher viscous damping when compared to equivalent full-scale beams, regardless of testing Glulam or Glulam-FRP beams.

KEYWORDS: Glulam, scale-effect, viscous damping, serviceability performance

1 INTRODUCTION

Timber has been a popular construction material for centuries, particularly for houses in lightweight frame structures. With the development of engineered wood products (EWPs) and adhesives, larger cross-sections, longer spans and improved structural properties have been made possible, allowing timber to compete with concrete and steel as a high-capacity building material [1]. During the last decade, mass timber buildings have rapidly gained prominence with projects all over the world, including Mjostartnet in Norway, HoHo Wien in Austria, T3 Minneapolis in the US, and Brock Commons in Canada. Australia has also contributed to the mass timber building industry with recent examples such as Daramu, International House, and 25 King St.

Timber-only floor and building systems are often limited by serviceability (static and dynamic) limitations. For taller buildings and longer spans, buildings have instead utilised hybrid-timber structural systems, such as timber concrete composites (TCC) or steel-timber composites (STC), by increasing mass and stiffness of the structural elements, as well as mechanical properties, Fibre reinforcement have also proven to be relevant in improving the timber elements properties [2].

The growing interest in studying EWPs and the surge of hybrid EWP elements to further improve their properties has led to many experimental studies to increase the knowledge of these novel systems. Most of these studies are focused on the mechanical properties of elements and structures, but for the serviceability checks required for long-span elements, variables such as natural frequencies, accelerations, damping, and stiffness are a key focus.

Many full-scale tests have been performed in long-span timber floors to study the dynamic behaviour of these systems, underlining the importance of the understanding of damping mechanisms in the context of long-span floors [3-8]. Although some standards, for example Eurocode 5 [9], indicate that vibration serviceability checks should focus on staying above the 8Hz threshold, studies indicate that increased damping can greatly improve the performance of a timber floor [4].

Testing for long-span floors and elements require large laboratory space, labour, and equipment to move and manipulate the specimens. This can be challenging when testing and can sometimes make full-scale testing difficult and cost prohibitive.

As an alternative evaluation method, down-scaled samples have been used to study and understand the equivalent full-scale performance of elements, particularly when full-scale testing is constrained by available space and budget [10]. Scaling factors are expected to make the small-scale and full-scale measurements and results related. Size effects in timber beams translate in a reduction of mechanical properties, such as strength [11]. It is known that shorter span elements present higher damping ratios [6], but no studies have been carried out to thoroughly investigate the effect of scale when determining the damping and serviceability performance of timber floors.

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This work presents non-destructive testing of unreinforced and FRP-reinforced Glulam beams and scaled versions in a 1:2.14 ratio. Experimental data was analysed to obtain natural frequencies and compare material viscous damping scale factors obtained from small and large scales.

2 MATERIALS AND METHODS

2.1 SPECIMEN CONFIGURATION

Twelve full-scale and thirteen small-scale beams were tested for vibrations with cross sections and labels shown in **Error! Reference source not found.**. The full-scale beams consisted of five (G5, HG5) and seven lamella (G7, HG7) configurations with heights of 155mm and 217mm with a width of 86mm. HG5 samples had a positive reinforcement ratio of 1% and HG7 samples had both a negative and positive reinforcement ratio of 1.5%. Scaled samples were fabricated by scaling lamellas and reinforcement (scale was determined by the commercially available CFRP strip thicknesses).

Fabrication of beams included the lamination of timber beams in both scales and in-layer reinforcement as described by Bravo Tetlak, et al. [12], with the fabrication method developed by Zaben [13]. Table 1 shows the geometric properties of the full-scale and small-scale beams.

2.2 EXPERIMENTAL SETUP

Beams were tested in a free vibration setup. A schematic figure of the configuration is shown in Figure 2. The beams were instrumented with five accelerometers (Kistler 8630B5) placed evenly on the bottom face. The accelerometers were connected to a data acquisition system where accelerations were stored to be processed using modal analysis to estimate natural frequencies and damping, according to Hearmon [14] and Casiano [15], respectively. The beams were hit with a PCB 086B02 modal hammer also connected to the data acquisition system to measure force. The sampling rate was fixed to 2500Hz, allowing to identify frequencies of up to 1250Hz without accounting for Nyquist aliasing.

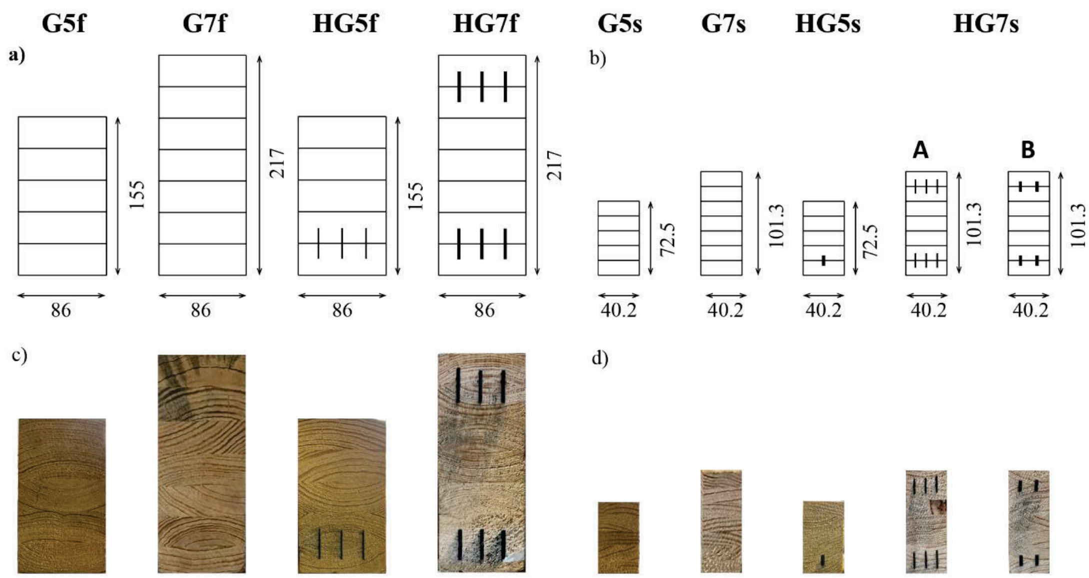

Figure 2. *Cross sections of unreinforced (G) and reinforced (HG) beams analysed. Adapted from: Bravo Tetlak, et al. [12].*

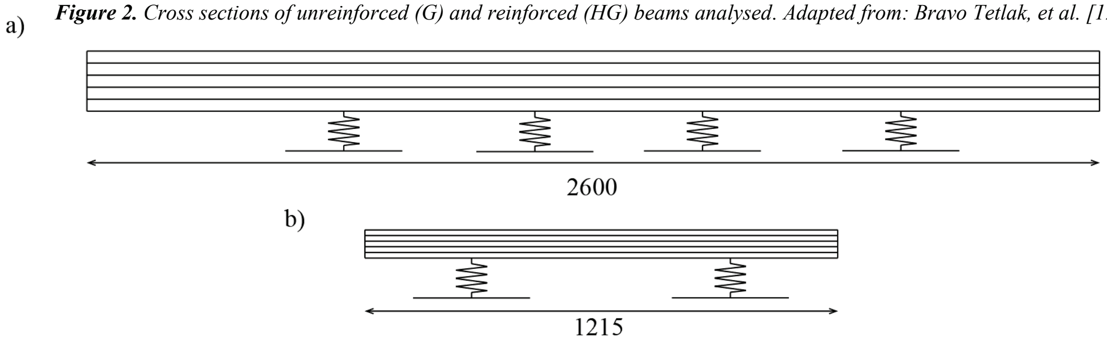

Figure 1. *Free vibration configuration and beam lengths, (top) Full-scale and (bottom) small-scale. Adapted from: Bravo Tetlak, et al. [12].*

Table 1. *Beam geometric properties.*

	Full-scale			Small-scale		
Beam ID	Width	Height	Length	Width	Height	Length
G5 # 1	85.4	155	2604	40.7	72.7	1215
G5 # 2	86.1	155	2605	40.6	72.8	1215
G5 # 3	87.0	155	2607	40.9	72.7	1215
Average G5	**86.2**	**155**	**2605**	**40.7**	**72.7**	**1215**
G7 # 1	86.1	216	2613	40.7	101.8	1215
G7 # 2	85.2	216	2603	40.4	101.3	1215
G7 # 3	85.6	216	2613	40.6	101.7	1215
Average G7	**85.6**	**216**	**2610**	**40.6**	**101.6**	**1215**
HG5 # 1	85.4	155	2607	40.6	72.7	1215
HG5 # 2	86.3	155	2620	40.4	72.5	1215
HG5 # 3	86.1	155	2620	40.3	72.5	1215
Average HG5	**85.9**	**155**	**2616**	**40.4**	**72.5**	**1215**
HG7 A # 1	86.8	216	2604	40.4	101.3	1215
HG7 A # 2	86.7	216	2601	40.3	101.2	1215
HG7 A # 3	86.7	216	2600	-	-	-
HG7 B # 1	-	-	-	40.4	101.4	1215
HG7 B # 2	-	-	-	40.4	101.3	1215
Average HG7	**86.7**	**216**	**2602**	**40.4**	**101.3**	**1215**

2.2 DAMPING COMPUTATION

According to Casiano [15] the half-power method can be used to estimate the damping values, where half of the amplitude of the power spectra at the peak (at $\frac{1}{\sqrt{2}}$ of the maximum amplitude, if using Fast-Fourier Transform FFT to obtain spectra), will yield f_u and f_l, the upper and lower frequencies at half-power. The ratio between the natural frequency of the mode, and the difference between f_u and f_l, yields the quality factor. Figure 3 shows a schematic explanation of the calculation of damping, for the case of an FFT-obtained spectrum.

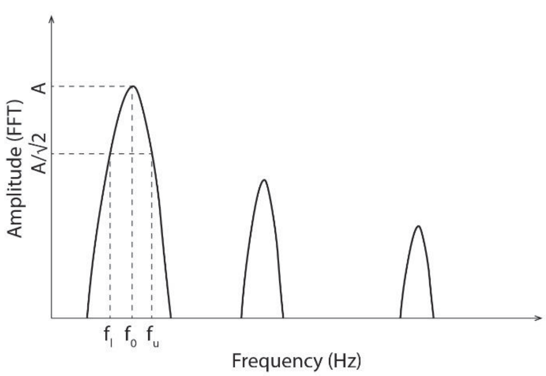

Figure 3. *Schematic representation of a frequency spectrum with the relevant parameters to estimate damping values.*

$$Q = \frac{f_0}{f_u - f_l} \quad (1)$$

If the damping values are expected to be less than 0.05 (5%), they can be estimated by [15]:

$$\xi = \frac{1}{2Q} = \frac{f_u - f_l}{2f_0} \quad (2)$$

2.3 SCALING OF SPECIMENS

According to Masaeli, et al. [16], it is assumed that, in static analysis, geometric properties and static parameters are proportional to the geometric scale. On the other hand, Carvalho [10] states that for scaled specimens, the scale factors should be derived depending on the force restoration mechanism. If the restoring forces are related to the elastic properties of the material only, scale factors should be deduced from geometric scaling and the Cauchy similitude (Equation (3)),

$$\text{Cauchy similitude: } Ca = \frac{\rho v^2}{E} \quad (3)$$

with equation parameters ρ, the specific mass, v the velocity and E, Modulus of Elasticity, as listed in Table 2.

If restoring forces are dependent on the material elastic properties and gravity loads, then the scaling factors must satisfy both the Cauchy similitude (Equation (3)) and Froud similitude (Equation (4)).

$$\text{Froude similitude: } Fr = \frac{v^2}{Lg} \quad (4)$$

with equation parameters v the velocity, L, length, and g, gravity, as listed in Table 2.

In this study, gravity loads do not play a significant role in the restoration loads, so only geometric parameters and Cauchy similitude are used to determine the theoretical scaling parameters, which are shown in Table 2.

Table 2. *Scale parameters derived from Cauchy similitude law. Adapted from [10, 17]*

Parameter	Symbol	Scale factor
Length	L	$L_p/L_m=\lambda=2.14$
Modulus of Elasticity	E	$E_p/E_m=1$
Specific Mass	ρ	$\rho_p/\rho_m=1$
Area	A	$A_p/A_m=\lambda^2=4.58$
Volume	V	$V_p/V_m=\lambda^3=9.80$
Mass	m	$m_p/m_m=\lambda^3=9.80$
Weight	W	$W_p/W_m=\lambda^3=9.80$
Frequency	f	$f_p/f_m=\lambda^{-1}=0.467$
Viscous damping	μ	$\mu_p/\mu_m=1$

3 RESULTS

3.1 GLULAM BEAMS

Natural frequencies up to the third mode are shown in Table 3 and acceleration spectra are presented in Figure 4, and were part of a broader study carried out by Bravo Tetlak, et al. [12].

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Natural frequencies presented similar values between samples, with coefficients of variation of up to 2.4%. For each natural frequency, damping values were estimated using the half-power method. Values are presented in Table 4.

Damping values in Glulam were consistently in a range between 0.43% and 0.63% in every mode, except for outlier 0.86% in Mode 1 of small-scale G5 #2. It can be observed that the variability between samples and modes is 12.9%, by discarding the outlier, CoV reduces to 8.4%, with no specific trend regarding scale.

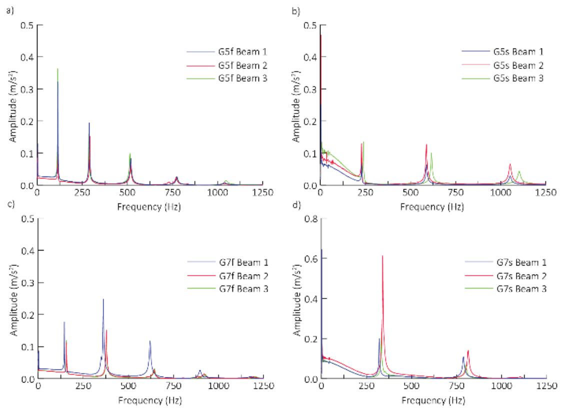

Figure 4 *Acceleration spectra for (a) G5f, (b) G5s, (c) G7f, and (d) G7s specimens. Adapted from: Bravo Tetlak, et al. [12].*

Table 3. *Natural frequencies of Glulam beams. Coefficient of variation in brackets. Source: Bravo Tetlak, et al. [12].*

	Full-scale			Small-scale		
Beam	**Mode 1**	**Mode 2**	**Mode 3**	**Mode 1**	**Mode 2**	**Mode 3**
G5 # 1	115.4	288.7	518.8	228.9	588.4	1053.0
G5 # 2	115.4	291.7	518.8	226.4	582.3	1053.0
G5 # 3	112.9	286.3	513.9	239.3	615.8	1102.0
Average G5	**114.6 (1.0%)**	**288.9 (0.8%)**	**517.2 (0.4%)**	**231.5 (2.4%)**	**595.5 (2.4%)**	**1069.3 (2.2%)**
G7 # 1	145.3	361.3	620.1	321.0	788.0	-
G7 # 2	157.5	378.4	645.1	340.6	814.2	-
G7 # 3	156.9	378.4	642.7	333.3	801.4	-
Average G7	**153.2 (3.7%)**	**372.7 (2.2%)**	**636.0 (1.8%)**	**331.6 (2.4%)**	**801.2 (1.3%)**	-

Table 4. *Damping values (in %) of unreinforced Glulam beams, G5 and G7. Coefficient of variation in brackets.*

	Full-scale			Small-scale		
Beam	**Mode 1**	**Mode 2**	**Mode 3**	**Mode 1**	**Mode 2**	**Mode 3**
G5 #1	0.54	0.51	0.63	0.54	0.54	0.53
G5 #2	0.48	0.51	0.61	0.86	0.58	0.57
G5 #3	0.54	0.50	0.60	0.48	0.51	0.57
Average G5	**0.52 (5.8%)**	**0.51 (0.5%)**	**0.61 (2.1%)**	**0.63 (26.1%)**	**0.54 (5.2%)**	**0.56 (3.2%)**
G7 #1	0.51	0.56	0.59	0.50	0.51	-
G7 #2	0.50	0.51	0.58	0.56	0.54	-
G7 #3	0.43	0.49	0.60	0.61	0.52	-
Average G7	**0.48 (6.9%)**	**0.52 (5.2%)**	**0.59 (0.8%)**	**0.56 (8.0%)**	**0.52 (2.1%)**	-

3.2 HYBRID FRP-GLULAM BEAMS

Natural frequencies up to the third mode are shown in Table 3 and acceleration spectra are presented in Figure 4, and were part of a broader study carried out by Bravo Tetlak, et al. [12].

Natural frequencies presented similar values between samples, with coefficients of variation of up to 1.6%. For each natural frequency, damping values were estimated using the half-power method. Values are presented in Table 4.

Damping values in Glulam were consistently in a range between 0.37% and 0.70% in every mode, except for outliers 0.94% in Mode 3 of small-scale HG5 #3. It can be observed that the variability between samples and modes is 18.9%, by discarding the outlier, CoV reduces to 13.8%, with no specific trend regarding scale.

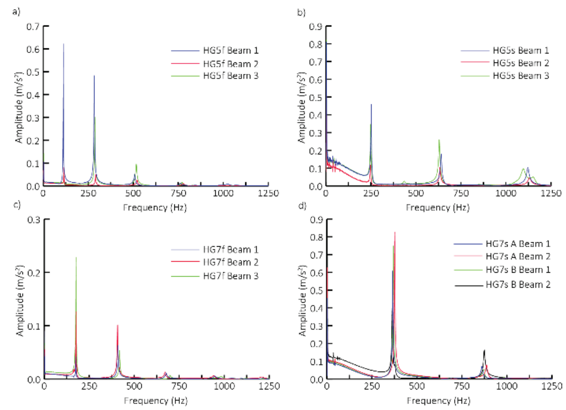

Figure 5 *Acceleration spectra for (a) HG5f, (b) HG5s, (c) HG7f, and (d) HG7s specimens, Adapted from: Bravo Tetlak, et al. [12].*

Table 5. *Natural frequencies of hybrid beams. Coefficients of variation in brackets. Coefficient of variation in brackets. Source: Bravo Tetlak, et al. [12].*

	Full-scale			Small-scale`		
Beam	**Mode 1**	**Mode 2**	**Mode 3**	**Mode 1**	**Mode 2**	**Mode 3**
HG5 # 1	111.7	283.2	507.2	252.1	640.3	1122.0
HG5 # 2	115.4	291.1	517.0	247.8	632.9	1132.0
HG5 # 3	114.1	286.9	521.2	248.4	629.9	1099.0
Average HG5	**113.7 (1.3%)**	**287.1 (1.1%)**	**515.1 (1.1%)**	**249.4 (0.8%)**	**634.4 (0.7%)**	**1117.7 (1.2%)**
HG7 A # 1	175.8	409.5	676.9	365.6	860.6	-
HG7 A # 2	176.4	407.7	672.0	376.6	887.5	-
HG7 A # 3	176.4	418.7	697.6	-	-	-
HG7 B # 1	-	-	-	369.3	871.6	-
HG7 B # 2	-	-	-	362.5	874.6	-
Average HG7	**176.2 (0.2%)**	**412.0 (1.2%)**	**682.2 (1.6%)**	**368.5 (1.4%)**	**873.6 (1.1%)**	-

Table 6. *Damping values (in %) of reinforced Glulam beams, HG5 and HG7. Coefficient of variation in brackets.*

	Full-scale			Small-scale		
Beam	**Mode 1**	**Mode 2**	**Mode 3**	**Mode 1**	**Mode 2**	**Mode 3**
HG5 #1	0.55	0.49	0.59	0.55	0.51	0.55
HG5 #2	0.57	0.52	0.56	0.59	0.51	0.56
HG5 #3	0.56	0.51	0.67	0.70	0.51	0.94
Average HG5	**0.56 (1.2%)**	**0.51 (2.4%)**	**0.61 (7.6%)**	**0.61 (10.1%)**	**0.51 (0.5%)**	**0.69 (26.2%)**
HG7 A #1	0.42	0.47	0.57	0.37	0.49	-
HG7 A #2	0.42	0.47	0.59	0.41	0.48	-

HG7 A #3	0.51	0.46	0.55	-	-	-
HG7 B #1	-	-	-	0.40	0.50	-
HG7 B #2	-	-	-	0.47	0.45	-
Average HG7	**0.45 (9.4%)**	**0.47 (1.3%)**	**0.57 (2.9%)**	**0.41 (8.7%)**	**0.48 (4.0%)**	-

4 DISCUSSION

4.1 SCALE TESTING EFFICACY IN GLULAM AND HYBRID-GLULAM BEAMS

Table 7 presents the experimental scaling factors of studied beams. While in most cases, a factor of less than 1.0 indicates small-scale samples presented a higher damping than their full-scale counterparts. HG7 for mode 1 and HG5 for mode 3 show higher average values for damping in full-scale. G7 and HG5 presented an average value of 1.0 for mode 2.

Table 7. *Average scale factors for damping of beams.*

Beam	Mode 1	Mode 2	Mode 3
G5 Average	0.83	0.93	1.09
G7 Average	0.86	1.00	-
HG5 Average	0.91	1.00	0.89
HG7 Average	1.09	0.95	-

Interestingly, if the outliers are removed from the analysis, the situation changes, as highlighted in Table 8. This indicates that more studies should be conducted to have higher statistical significance, and that there is no correlation observable between full-scale and small-scale tests that can be attributable to dynamic serviceability parameters, as consistent with that observed in Bravo Tetlak, et al. [12], and observed in Table 3 to Table 6.

Table 8. *Average scale factors for damping of beams without outliers (G5 small-scale, mode 1; HG5 small-scale, mode 3).*

Beam	Mode 1	Mode 2	Mode 3
G5 Average	1.02	0.93	1.09
G7 Average	0.86	1.00	-
HG5 Average	0.91	1.00	1.09
HG7 Average	1.09	0.95	-

4.2 GENERAL COMMENTS

Although the addition of CFRP increased the stiffness and natural frequencies of the beams, the damping parameters were not greatly affected, as observed in the studied set of beams.

The scattering of damping values for different modes in the studied beams shows no clear trend or correlation between scales, which can be a sign that scaled down elements can be studied under serviceability without accounting for size effect issues.

The ease testing of scaled down beams was greatly improved, when compared to full-scale testing, given the lighter and smaller sizes of the beams.

5 CONCLUSIONS

This work presented the damping characterisation of two sets of Glulam beams and two sets of carbon fibre reinforced hybrid-Glulam beams. Vibration tests were performed on full-scale and 1:2.14 scale beams and damping parameters were estimated from the accelerometers data acquired. The efficacy of scale testing was evaluated in the context of damping parameter calculations. The main findings can be summarised in the following:

- Downscaled versions of Glulam and hybrid-Glulam beams were significantly easier to test, compared to full-scale beams. This includes, use of laboratory space, freight, experimental set ups, and equipment demand.
- Damping of beams did not show a particular trend regarding scale, and values stayed in fairly determined boundaries, indicating no particular size effect in damping. Although more tests are required to determine if there is a statistical correlation.
- Small-scale samples presented two outlier cases in a Glulam beam, and a hybrid-Glulam beam at a higher mode. More tests should be carried out to understand if the phenomenon is common, or only a particular case in this analysis.

This study indicated that scaled down Glulam and hybrid-Glulam beams in terms of damping estimation is feasible, can yield similar results to full-scale beams and reduce the effort required for testing. In the context of long-span timber and hybrid-timber floor prototyping and testing, these results could lead to easier serviceability testing.

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