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EFFECT OF END SUPPORT CONDITIONS ON THE VIBRATIONAL PERFORMANCE OF CROSS-LAMINATED TIMBER FLOORS

Saúl A. Hernández Maldonado[1], **Ying-Hei Chui**[2]

ABSTRACT: This study focused on the vibrational behaviour of a 3-ply cross-laminated timber (CLT) plate supported on two sides with different support conditions. Three end support setups were studied; 1) top load over the two supported edges, 2) direct fastening to support using self-tapping screws, 3) ledger support. The measured response parameters were natural frequencies, damping, and static deflection under a point load. The rotational stiffness with load, screws and ledger support were characterized through static tests. In addition, the effect of the span was studied by varying the test span and repeating the vibration and deflection tests. The laboratory tests were supplemented with finite element modelling. The outcome is the development of approaches to more accurately calculate the natural frequency and static deflection under a point load, which can account for the influence of common support conditions encountered in service.

KEYWORDS: end support condition, cross-laminated timber, natural frequency, damping, static deflection

1 INTRODUCTION

The use of cross-laminated timber (CLT) in floor construction has resulted in studies that concentrated on its serviceability design to minimize disturbing vibrations. Recent floor vibration design criteria have been presented for CLT floor systems by Hu and Gagnon [4] and Hamm et al. [3]. Both criteria assume a simple end support condition and require the calculation of the fundamental natural frequency and deflection at the centre of the CLT floor under a concentrated load. Nevertheless, support conditions have been shown to be more complex as observed in a study by Jarnerö et al. [6]. These researchers reported differences in natural frequencies and damping values when comparing their test results on floors in laboratory and in-situ. This suggests that actual end support characteristics in practice should be reflected in any design calculations.

Thus, it is assumed that the end support condition in the CLT floor to wall connection is affecting the vibrational behaviour of the floor. This connection at the boundaries of the floor can be responsible for the differences between predicted and measured natural frequencies observed in previous CLT floor studies. From a mechanics standpoint, the end support condition can be characterized by the parameters of rotational stiffness and translational stiffness. These stiffness properties have been proven to be of importance in the calculation of natural frequencies of beams by several researchers, among others Huang [5], Beglinger et al. [1], Chui and Smith [2], and Leichti et al. [7].

This study focused on characterizing the stiffness properties of common support conditions and their influence on vibrational behaviour and static deflection response of CLT floor systems.

2 OBJECTIVES AND SCOPE

The objective of the study that provided the data for this paper is to investigate the influence of end support condition on natural frequencies, damping ratio and static deflection of a 3-layer CLT panel, and how the influence may be affected by span. The end support conditions studied were: application of top load, use of fasteners and resting the panel on ledger supports. These changes occur at the two supported ends of the panel. The span of the test panel was reduced progressively so as to study how the degree of the influence by support condition may be conditional upon the span. At every span the dynamic and

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[1] Saúl Antonio Hernández Maldonado, Faculty of Forestry and Environmental Management, University of New Brunswick,, Fredericton, New Brunswick, Canada. Email: sa.hm@unb.ca
[2] Ying-Hei Chui, Forestry and Environmental Management, University of New Brunswick, Fredericton, New Brunswick, Canada. Email: yhc@unb.ca

static tests were conducted to determine the first natural frequency, the damping ratio, and the deflection under a 1 kN point load at the centre. Connection tests were conducted to characterize the rotational stiffness of each type of end support condition. The final stage of the study was the modeling of the experiments with the finite element method (FEM). Once the models are validated, they will be further expanded to simulate the dynamic properties and deflection response to a static point load. These analyses will provide an indication on how common end support conditions affect natural frequency, damping and static deflection behaviour. Recommendations will be drawn on how existing floor vibration design procedures may be modified to reflect the influence of end support conditions.

3 METHODS

3.1 LABORATORY CLT FLOOR PANEL TESTS

The CLT specimen used was a 1m wide 3-ply strip with an initial span of 4.5m, Figure 1a. In all tests the strip was supported at two ends. There was an initial reference test having the panel simply supported on steel rods, Figures 1b and 2b. Three end support conditions were studied. These were the application of load over the supported end, the use of self-tapping screws to directly fasten the panel end to the CLT wall below, and the use of a ledger support which was fastened to the CLT wall below, as shown on Figure 1e and 2c. The magnitude of the applied load, number of screws used in direct fastening and number of screws on the ledger was sequentially increased during the tests.

The test setup for load application at panel ends is presented in Figures 1c and 2e. The load was applied with a hydraulic actuator, which was attached to a steel beam and a 5-layer CLT panel to distribute the load to the two ends, where there are two 3-layer CLT vertical pieces fastened to the 5-layer CLT panel. They made contact at the supported ends of the 3-layer CLT floor panel. These 3-layer CLT vertical pieces represent what would be the wall panels from the storey above in a real building. The load was sequentially increased from 10kN to 60kN with the actuator. For all tests, the total load was held constant at 10, 20, 40 and 60kN and the dynamic and static deflection tests conducted. The actual load at each of the supported ends was therefore 5, 10, 20 and 30kN respectively.

The sequence of the progressive increase in number of screws is illustrated in Figure 3a, while Figure 1d shows the test setup. For example S1 corresponds to the case with only one screw at the middle of the panel and at S5 there were a total of 13 screws connecting the floor panel to the supporting wall. The ledger support configuration is shown in Figures 1e and 2c. The ledger dimensions were 0.079 x 0.178 x 1m and it was fastened to the supporting wall panel with screws at a 45° angle. The order of increasing fasteners to the ledger-wall connection is illustrated in Figure 3b. L1 represents a total of 4 screws connecting the ledger to the wall panel. After every sequential increase of load or screws, dynamic and static tests were conducted. In the ledger configuration the length of floor panel was reduced by 15cm and fastened to the ledger with three screws, so that the clear distance between the supporting wall for all three support conditions was maintained.

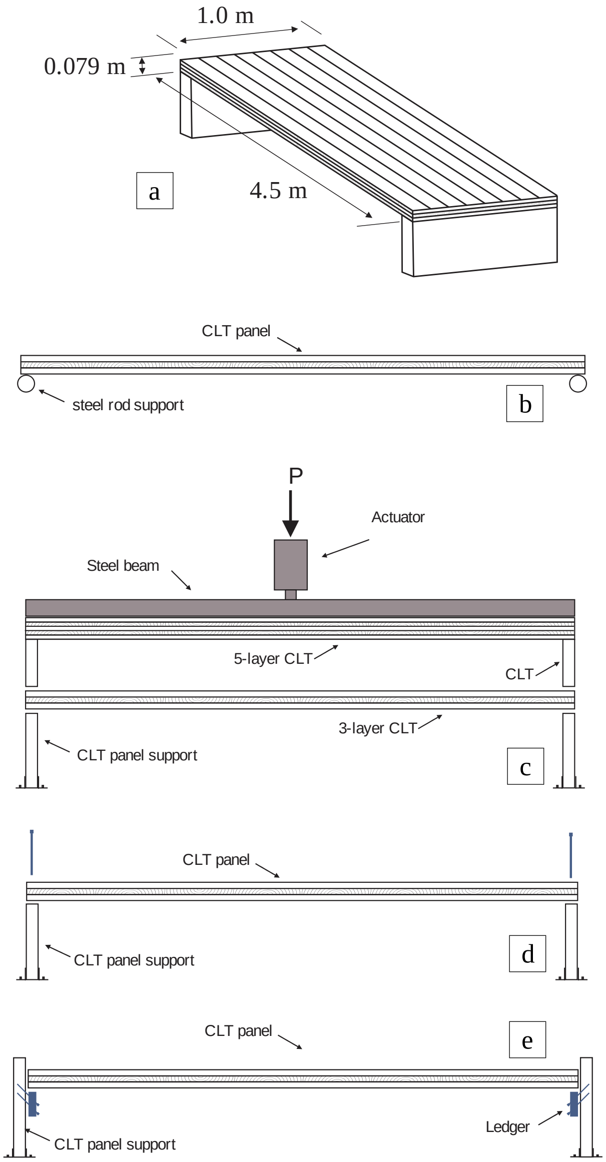

Figure 1: *CLT plate supported at two ends and laboratory test set-ups.*

The dynamic test was a modal test to measure the first natural frequency and the damping. The equipment consisting of an instrumented hammer, an accelerometer and a spectrum analyser is presented in Figure 2a. The fundamental natural frequency was extracted from the frequency spectrum which was calculated by the spectrum analyser. The damping ratio was calculated using the halfpower bandwidth method. The static test involved an application of a 1kN load at mid-span and measuring the deflection there. Additional tests included the characterization of the stiffness properties of the three end support conditions through testing of CLT floor-to-wall connections under applied load, the use of wood-screws connections and the use of a ledger respectively, Figure 4.

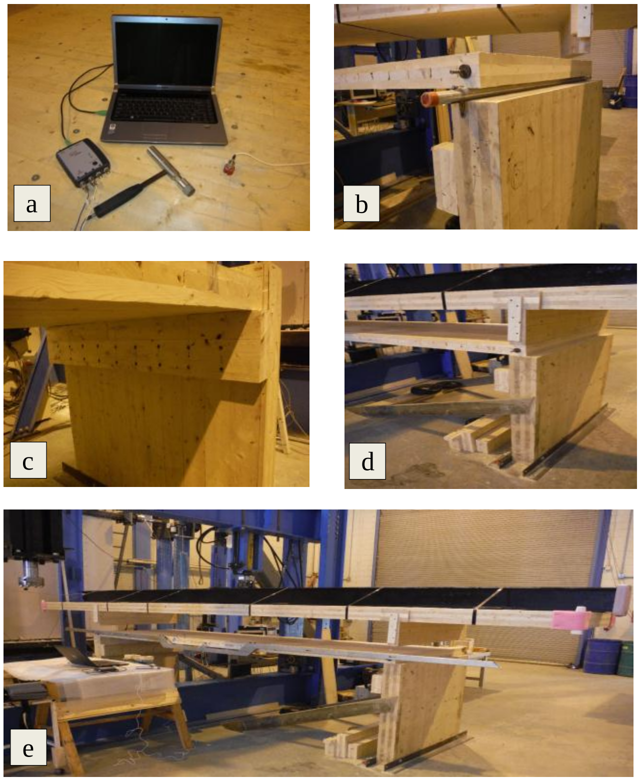

Figure 2: Vibration equipment and CLT test setup.

Since the influence of end support condition would likely be dependent on the span, the test span was sequentially reduced and the tests repeated. The panel was tested at five spans with a step decrease of 40cm, with a starting span of 4.5m and final span of 2.9m. Finite element models were developed to predict the behaviour of the test specimens incorporating the various end conditions. The measured end support stiffness properties were used as input into the FE model. Validation of the models was achieved by comparing the test results with the predicted responses.

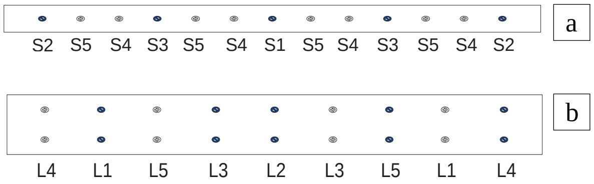

Figure 3: *Increments for number of screws in direct fastening and ledger supports.*

The laboratory test results for the first natural frequency allow for the calculation of the modulus of elasticity, E_x, employing a simplified single span equation proposed by Leissa [8], equation 1.

3.2 ROTATIONAL STIFFNESS TESTS

The rotational stiffness (K_r) of a connection is defined as the moment (kN-m) over the angle of rotation (rad). This is characterised by conducting static tests in the laboratory with the setups presented in Figure 4. The setups represent the three different end support conditions evaluated in the panel tests. The test panel dimensions were 0.079m x 0.24m x 1m. Figure 4a presents the setup for the load configuration, where a load at the support was held constant at 5, 10, 20, and 30kN, then a load was applied at the end of the cantilevered CLT panel. The deflection was measured at two different locations on the CLT panel. The characterization of the screw setup is shown in Figure 4b, in which the number of screws was increased in the order shown in Figure 3a. After each increase of number of screws a load was applied on the cantilever panel and the deflection was measured. For the ledger configuration, Figure 4c, deflections were measured for both the ledger and for the CLT panel. The angle of rotation was calculated from the measured deflections.

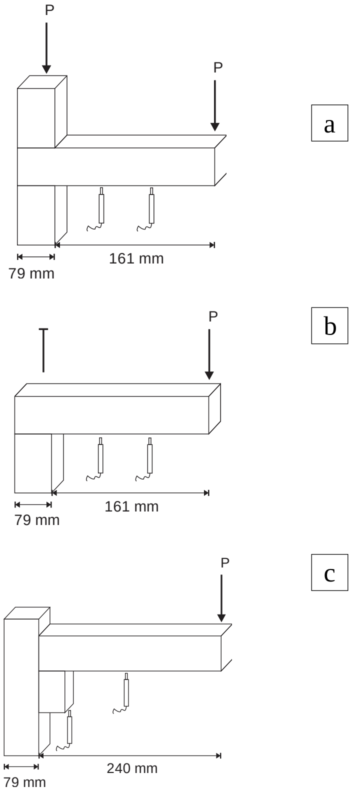

Figure 4: *Laboratory test setups to determine K_r.*

3.3 FE MODELING OF CLT FLOOR TESTS

Finite element models of the test set-ups were developed with the use of ABSQUS software, version 6.12, SIMULIA, 2012 (http://www.simulia.com).

A model was initially defined as a simply supported single span panel, with the geometry shown in Figure 1a, and elastic modulus presented in Table 1. The elastic modulus is the average of the values calculated with the use of the analytical model, Equation 1, and presented in Table 3. The initial models were used to validate the reference tests in which the panel was supported on round pipes to simulate a true simple support condition at five different spans, Figure 1b.

Connection elements were employed at the ends of the modeled panel to model the rotational stiffness, which allows for the rotational stiffness to be defined on a specific axis. The rotational stiffness values used to represent the different laboratory test conditions are given in Table 4. The deflections at centre are also modeled by adding a 1 kN load to the modeled panel.

Table 1: *CLT mechanical properties and density employed for FE models.*

Property	Symbol	Value	Units
Elastic modulus	E_x	10500	MPa
Density	ρ	484	kg/m^3
Poisson’s ratio	ν	0.30	-

The rotational stiffness tests, Figure 4, were modeled with FEM using connections elements. The purpose was to compare the laboratory measured deflections to the FEM deflection predictions. This permitted the validation of the rotational stiffness characterization and its representation with connection elements. The FE model was generated assuming that the actual rotation occurs at the inner edge of the supported portion, Figure 5. The angle of rotation for the laboratory tests is calculated at the same location.

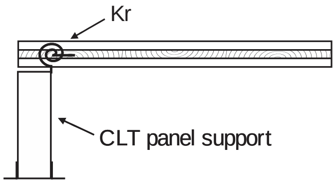

Figure 5: *Rotational stiffness at the inner edge of the supported portion.*

4 RESULTS AND DISCUSSION

4.1 MODULUS OF ELASTICITY

A model presented by Leissa [8] to predict the first natural frequency is used to calculate the modulus of elasticity. The model is simplified to represent a single span plate simply supported on two sides, equation 1. The values for the first natural frequency entered are those from the reference tests, given in Table 2. Specimens from the same CLT panel were used to determine the average density of $484\ kg/cm^3$.

$$f_1 = \frac{\pi}{2\,l^2} * \sqrt{\frac{D_x}{g}} \tag{1}$$

where:

$$D_x = \frac{E_x \cdot h^3}{12 \cdot (1 - \nu^2)} \tag{2}$$

with:
D_x = plate flexural rigidity in the x-axis
E_x = elastic modulus in the x direction
g = mass density of the plate (kg/m^2)
h = thickness of the plate
l = length of the plate
ν = Poisson’s ratio

Table 2: *Fundamental natural frequency, deflection and damping ratio for 3-layer CLT panel at five different spans of the reference set-up.*

Reference	Span (m)				
	4.5	4.1	3.7	3.3	2.9
f_1 (Hz)	8.88	10.63	13.13	15.88	19.50
Damping (%)	1.00	1.14	0.99	0.76	1.07
Deflection (mm)	3.59	2.88	2.09	1.58	1.12

The reference values for natural frequency, damping ratio and static deflection are presented in Table 2. These values are compared to measured values with the other test setups. From this reference values the effect of span on the first natural frequency and static deflection can be observed. The decrease of natural frequency as the span increases can be observed in Figure 6a. As well, the increase in static deflection as the span increases is presented in Figure 6b. Damping ratio remains around 1% and has no apparent tendency as the span changes.

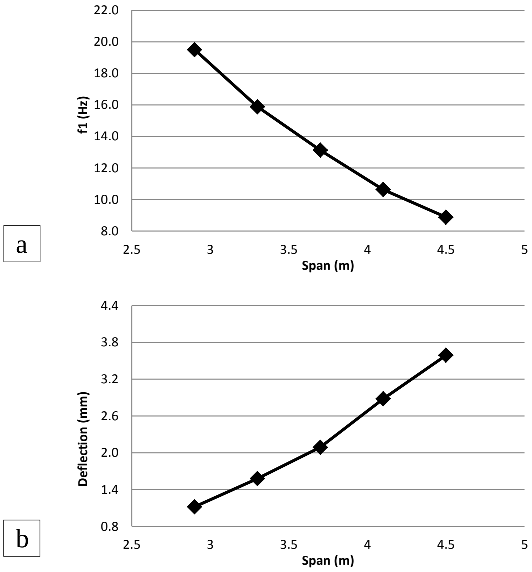

Figure 6: *Reference results for natural frequency (a) and deflection (b).*

The modulus of elasticity is calculated assuming ν = 0.3. An average value of 10,500MPa was used for the finite element models.

Table 3: *Elastic modulus calculated from known natural frequency.*

Span (m)	f1 (Hz)	$E_{x,\ \nu = 0.3}$ MPa
4.5	8.88	11086
4.1	10.63	10959
3.7	13.13	11089
3.3	15.88	10264
2.9	19.50	9231

4.2 ROTATIONAL STIFFNESS

The rotational stiffness values presented in Table 4 are a result of laboratory static tests and finite element modeling. This is to verify a more accurate value from the range of the laboratory test results. This was also necessary to eliminate any deflection reading error, since the measurements were so small and likely to have a significant margent of error. The laboratory values were entered in FEM modeling to simulate the laboratory tests and verify the deflection values measured. The process was to model with a rotational stiffness that would match the measured deflection under the specific loads. The rotational stiffness values presented are those that best corresponded to the laboratory measured data.

Table 4: *Rotational stiffness values.*

Configuration	K_r (kN-m/rad)				
Load	P10	P20	P40	P60	-
	26	40	65	78	-
Screws	S1	S2	S3	S4	S5
	5	22	30	44	50
Ledger	L1	L2	L3	L4	L5
	17	19	20	21	22

The results presented in Table 4 and in Figure 7 are the rotational stiffness values that occur at a support of the test panel. The increase of load has an important effect on the rotational stiffness as it is increased. It can be observed how the increase in rotational stiffness is consistent with the increase of load, Figure 7a, with a maximum rotational stiffness of 78kN-m/rad. The addition of screws also has a significant effect on the rotational stiffness. It is observed that the number of screws has a greater effect at the initial stages and diminishes as the number is increased, Figure 7b. The maximum rotational stiffness reached with screws is 50kN-m/rad. The ledger support is fairly stable and does not differ much from its initial rotational stiffness, having a maximum of 22kN-m/rad, Figure 7c. The rotational stiffness is mostly affected by the three screws connecting the floor panel to the ledger.

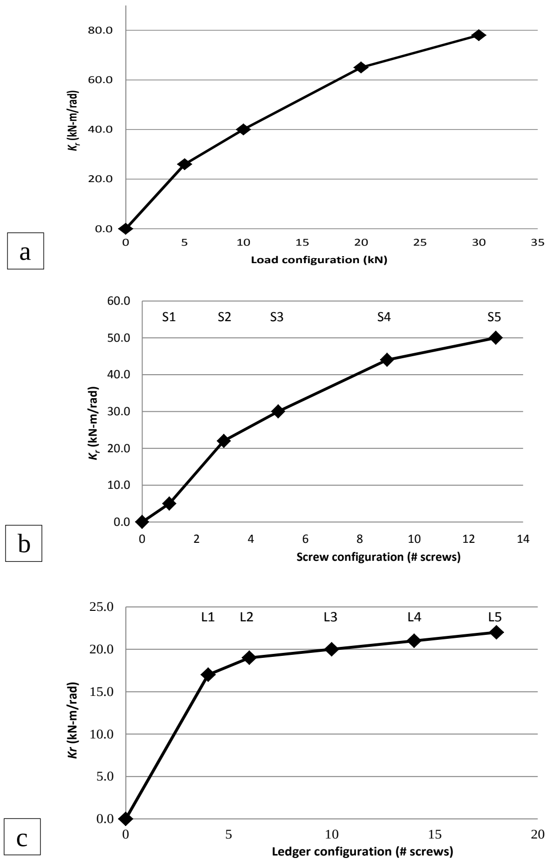

Figure 7: *Rotational stiffness results for the test setups; a) end load, b) number of screws and c) ledger support.*

4.3 INFLUENCE OF SUPPORT CONDITIONS ON NATURAL FREQUENCIES AT DIFFERENT SPANS

The influence of rotational stiffness on the first natural frequency of the CLT panel is significant. This can be observed through all the tests performed at the various spans, shown in Figure 8, for the three different support conditions; load, screws and ledger. The increase of load and number of screws has the maximum effect on the natural frequency, while for the ledger support the increase is minor. The increase of load for all spans is presented in Figure 8a. At the maximum load of 60kN a rotational stiffness of 78kN-m/rad was observed. With a rotational stiffness of 78kN-m/rad the reference natural frequency has a maximum increase of 39% at a span of 2.9m. At the same rotational stiffness a 29% increase is observed at a 3.7m span. The other spans have an effect between 39% and 29% at the maximum load. The increase of load has a consistent effect on the natural frequency.

The use of 13 screws at a spacing of 72mm leads to a maximum rotational stiffness of 50kN-m/rad, Figure 8b. The average maximum effect of the natural frequency, for all spans, is of 30%. The effect on the first natural frequency is important as the rotational stiffness increases, caused by the number of screws. Both the increments of load and screws lead to a consistent increase in rotational stiffness and have a significant effect on the first natural frequency.

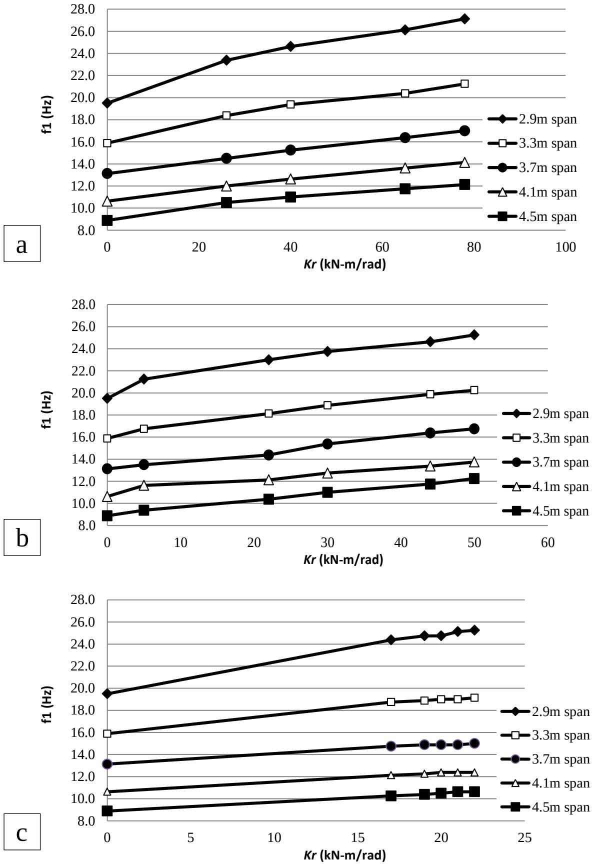

Figure 8: *Influence of support conditions on first natural frequency; a) end load, b) number of screws and c) ledger support.*

The ledger causes a maximum rotational stiffness of 22 kN-m/rad. The change in natural frequency with the ledger support is compared to the first natural frequency recorded during this test configuration. This is because the CLT panel was reduced by 15cm and is fastened to the ledger with three screws. Therefore, the first natural frequency is not equal to the reference natural frequency. Thus, only the effect of adding fasteners to the ledger-to-wall connection is evaluated. This takes into account the change in rotational stiffness from 17kN-m/rad to 22kN-m/rad. In this rotational stiffness range, the natural frequency has a maximum change of 3% and a minimum of 1%. Increasing the number of screws on the ledger-to-wall connection has a minimum influence on the first natural frequency.

4.4 INFLUENCE OF SUPPORT CONDITIONS ON DEFLECTION AT DIFFERENT SPANS

The effect of rotational stiffness on deflection can be observed on Figure 9 for the three test setups. The results are very similar to those observed for the natural frequency, except that the deflection decreases with increasing rotational stiffness. The maximum rotational stiffness with an increase of load is of 78kN-m/rad, Figure 9a. At this rotational stiffness, the maximum change in deflection from the reference deflection occurs at a span of 4.1m, being 36%. The average reduction in deflection for all spans at the same rotational stiffness is of 34%. The effect of the increase in number of screws is shown in Figure 9b. The highest rotational stiffness is of 50kN-m/rad. This causes an average maximum reduction in deflection of 32%, considering all the spans. The increase of screws on the ledger support has a minimal effect on deflection, with a maximum change of 5% and an average of 3%, at its maximum rotational stiffness, Figure 9c.

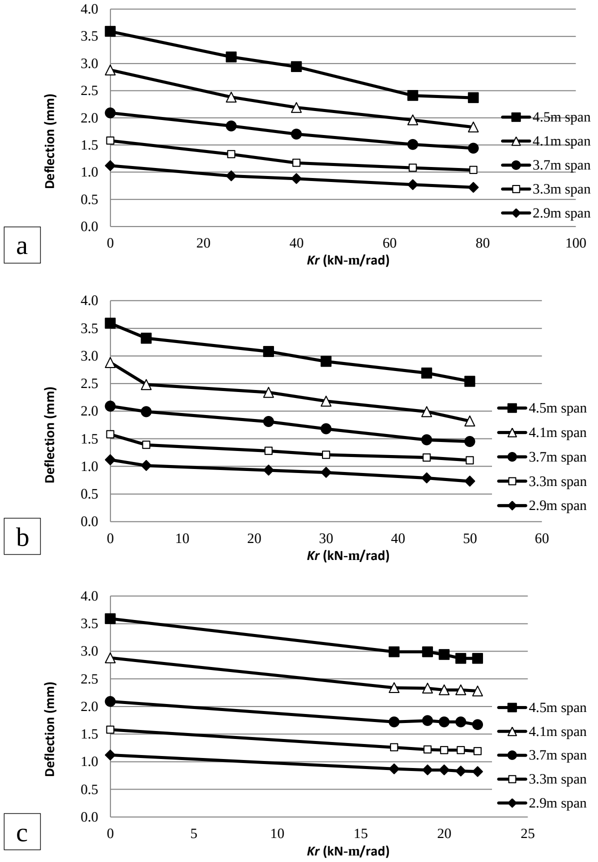

Figure 9: *Influence of end support on deflection: a) end load, b) number of screws and c) ledger support.*

4.5 INFLUENCE OF SUPPORT CONDITIONS ON DAMPING RATIO AT DIFFERENT SPANS

The effect of the rotational stiffness on the damping ratio is presented in Figure 10. It can be observed that there is no apparent tendency as the rotational stiffness increases. This is observed for all the test setups, where measurements varied from 0.4% to 2% damping ratio. It can be concluded that the damping ratio remains within this range and is close to 1%.

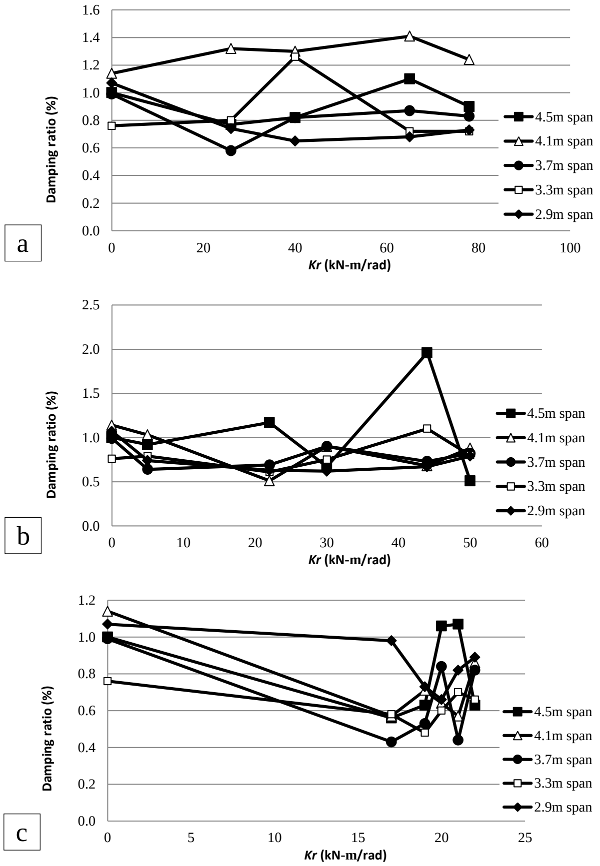

Figure 10: *Influence of end supports on damping: a) end load, b) number of screws and c) ledger support.*

4.6 COMPARISON OF MEASURED AND PREDICTED NATURAL FREQUENCIES AND STATIC DEFLECTION USING FINITE ELEMENT MODEL

The experimental and finite element model results are presented in Tables 5 to 20. Both measured and predicted results using FEM are presented for the first natural frequency and the static deflection. The tables also include the measured damping ratios for all the tests, which are shown in Figure 10.

Table 5: *Reference laboratory and FEM results for 3-layer CLT panel at five different spans.*

Reference	Span (m)				
	4.5	4.1	3.7	3.3	2.9
f_1 (Hz)	8.88	10.63	13.13	15.88	19.50
Damping (%)	1.00	1.14	0.99	0.76	1.07
Deflection(mm)	3.59	2.88	2.09	1.58	1.12
FE: f1 (Hz)	8.55	10.35	12.76	16.14	21.06
FE: Def. (mm)	4.17	3.14	2.29	1.61	1.08

Table 5 includes the values for the reference tests at the five different spans tested with the FEM values. Observing the values in Table 5, the differences in the natural frequency are between 2% and 8%. Comparing the reference static deflection with predictions there is a difference ranging from 2% to 16%. The reference test results and their FEM predictions are presented in Figure 11. The FEM predictions are close to the measured values and have the same trend.

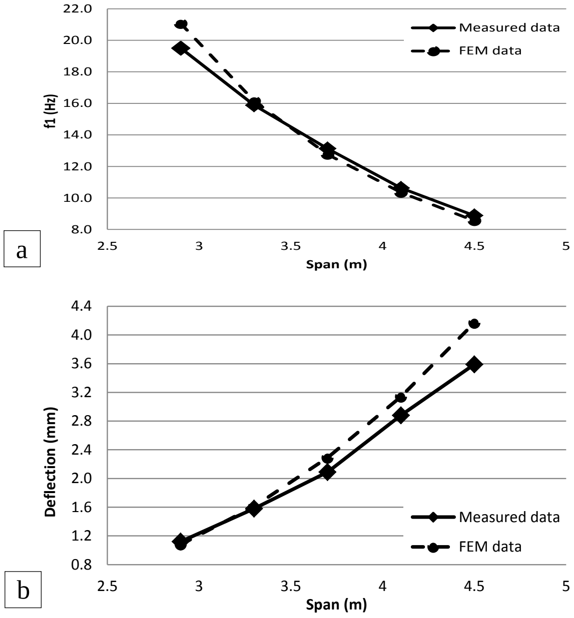

Figure 11: *Reference test and FEM results for (a) first natural frequency and (b)* deflection as span increases.

The test results for a span of 4.5m are presented in Tables 6, 7 and 8. Table 6 presents the results for the support end load tests and their FEM predictions. The differences between predicted and measured natural frequencies are minimal at about 1%. Static deflection differences range from 2% to 8%. The results for the number of screws, for a 4.5m span, are presented in Table 7. The differences are of 1% to 7% for the first natural frequency and 1% to 11% for static deflection. Ledger test results are presented in Table 8 for the span of 4.5m. The differences for the predicted and measured first natural frequencies are below to 5%. The static deflection results have a percent difference ranging from 2% to 5%. Similar results are observed for the other 4 spans tested.

The FEM predictions and measured values of the first natural frequencies and static deflections, as the rotational stiffness increases, are presented in Figure 12. The graphs include the results for all five spans tested. The continuous lines represent the values measured during the laboratory experiments for the increase of load and screws. The dashed lines represent the FEM predictions. The shorter portions of data near 20kN-m/rad are the ledger support results.

Figure 12a presents the effect of rotational stiffness on the first natural frequency for all spans. The predicted values appear very close to the measured values. The static deflections predictions and laboratory results are presented in Figure 12b. The modeled static deflections are in accordance to the laboratory results as the rotational stiffness increases. Overall, it can be observed that the laboratory and FEM values are in good agreement.

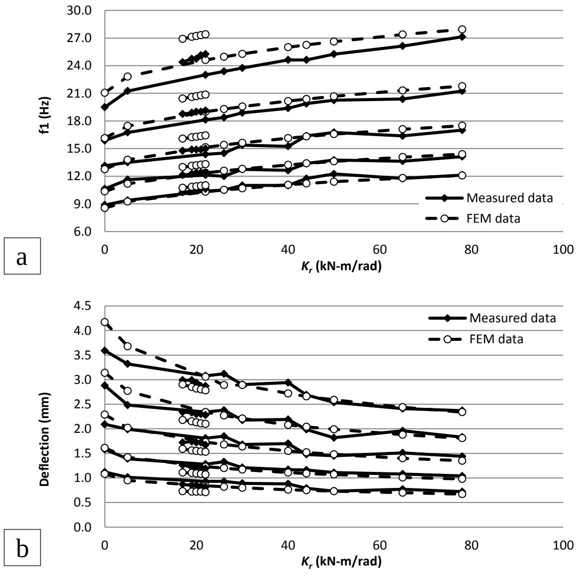

Figure 12: *Measured and predicted results for natural frequencies and static deflection at five spans.*

Table 6: *Support end load results for 4.5m span.*

Load	P10	P20	P40	P60
f1 (Hz)	10.50	11.00	11.75	12.13
Damping (%)	0.77	0.82	1.10	0.90
Deflection (mm)	3.12	2.94	2.41	2.37
FEM: f1 (Hz)	10.51	11.07	11.80	12.08
FEM: Def.(mm)	2.89	2.72	2.44	2.34

Table 7: *Direct fastening with screw results for 4.5m span.*

Screw	S1	S2	S3	S4	S5
f1 (Hz)	9.38	10.38	11.00	11.75	12.25
Damping (%)	0.92	1.17	0.67	1.96	0.51
Deflection (mm)	3.32	3.08	2.90	2.69	2.54
FEM: f1 (Hz)	9.25	10.31	10.68	11.21	11.40
FEM: Def.(mm)	3.68	3.06	2.89	2.66	2.59

Table 8: *Ledger results for 4.5m span.*

Ledger configuration	L1	L2	L3	L4	L5
f1 (Hz)	10.25	10.38	10.50	10.63	10.63
Damping (%)	0.56	0.63	1.06	1.07	0.63
Deflection (mm)	2.99	2.99	2.94	2.87	2.87
FEM: f1 (Hz)	10.74	10.85	10.91	10.96	11.02
FEM: Def.(mm)	2.90	2.85	2.82	2.80	2.78

Table 9: *Support end load results for 4.1m span.*

Load	P10	P20	P40	P60
f1 (Hz)	12.00	12.63	13.63	14.13
Damping (%)	1.32	1.30	1.41	1.24
Deflection (mm)	2.38	2.19	1.96	1.83
FEM: f1 (Hz)	12.59	13.23	14.07	14.39
FEM: Def.(mm)	2.27	2.08	1.88	1.81

Table 10: *Direct fastening with screw results for 4.1m span.*

Screw	S1	S2	S3	S4	S5
f1 (Hz)	11.63	12.13	12.75	13.38	13.75
Damping (%)	1.03	0.51	0.90	0.68	0.88
Deflection (mm)	2.48	2.34	2.18	1.99	1.82
FEM: f1 (Hz)	11.18	12.37	12.79	13.39	13.61
FEM: Def.(mm)	2.77	2.34	2.21	2.04	1.99

Table 11: *Ledger results for 4.1m span.*

Ledger	L1	L2	L3	L4	L5
f1 (Hz)	12.13	12.25	12.38	12.38	12.38
Damping (%)	0.57	0.71	0.64	0.57	0.86
Deflection (mm)	2.34	2.33	2.30	2.30	2.28
FEM: f1 (Hz)	12.99	13.12	13.18	13.25	13.31
FEM: Def.(mm)	2.18	2.15	2.13	2.11	2.10

Table 12: *Support end load results for 3.7m span.*

Load	P10	P20	P40	P60
f1 (Hz)	14.50	15.25	16.38	17.00
Damping (%)	0.58	0.82	0.87	0.83
Deflection (mm)	1.85	1.70	1.51	1.44
FEM: f1 (Hz)	15.39	16.13	17.10	17.49
FEM: Def.(mm)	1.68	1.55	1.40	1.35

Table 13: *Direct fastening with screw results for 3.7m.*

Screw	S1	S2	S3	S4	S5
f1 (Hz)	13.50	14.38	15.38	16.38	16.75
Damping (%)	0.64	0.69	0.90	0.73	0.82
Deflection (mm)	1.99	1.81	1.68	1.48	1.45
FEM: f1 (Hz)	13.79	15.14	15.62	16.31	16.57
FEM: Def.(mm)	2.02	1.73	1.64	1.52	1.48

Table 14: *Ledger results for 3.7m span.*

Ledger	L1	L2	L3	L4	L5
f1 (Hz)	14.75	14.88	14.88	14.88	15.00
Damping (%)	0.43	0.53	0.84	0.44	0.82
Deflection (mm)	1.72	1.743	1.72	1.72	1.67
FEM: f1 (Hz)	16.07	16.22	16.28	16.36	16.43
FEM: Def.(mm)	1.59	1.56	1.55	1.54	1.53

Table 15: *Support end load results for 3.3m span.*

Load	P10	P20	P40	P60
f1 (Hz)	18.38	19.38	20.38	21.25
Damping (%)	0.80	1.26	0.72	0.72
Deflection (mm)	1.33	1.17	1.08	1.04
FEM: f1 (Hz)	19.29	20.16	21.31	21.77
FEM: Def.(mm)	1.20	1.11	1.01	0.98

Table 16: *Direct fastening with screw results for 3.3m span.*

Screw	S1	S2	S3	S4	S5
f1 (Hz)	16.75	18.13	18.88	19.88	20.25
Damping (%)	0.79	0.61	0.75	1.10	0.80
Deflection (mm)	1.39	1.28	1.21	1.16	1.11
FEM: f1 (Hz)	17.45	19.00	19.56	20.37	20.67
FEM: Def.(mm)	1.42	1.23	1.17	1.09	1.07

Table 17: *Ledger results for 3.3m span.*

Ledger	L1	L2	L3	L4	L5
f1 (Hz)	18.75	18.88	19.00	19.00	19.13
Damping (%)	0.58	0.48	0.60	0.70	0.66
Deflection (mm)	1.26	1.22	1.21	1.21	1.19
FEM: f1 (Hz)	20.43	20.60	20.68	20.77	20.85
FEM: Def.(mm)	1.11	1.10	1.09	1.08	1.07

Table 18: *Support end load results for 2.9m span.*

Load	P10	P20	P40	P60
f1 (Hz)	23.38	24.63	26.13	27.13
Damping (%)	0.74	0.65	0.68	0.73
Deflection (mm)	0.93	0.88	0.77	0.72
FEM: f1 (Hz)	24.96	26.00	27.38	27.94
FEM: Def.(mm)	0.82	0.76	0.70	0.67

Table 19: *Direct fastening with screw results for 2.9m span.*

Screw	S1	S2	S3	S4	S5
f1 (Hz)	21.25	23.00	23.75	24.63	25.25
Damping (%)	0.74	0.63	0.62	0.67	0.79
Deflection (mm)	1.02	0.93	0.89	0.79	0.73
FEM: f1 (Hz)	22.82	24.62	25.28	26.25	26.61
FEM: Def.(mm)	0.95	0.84	0.80	0.75	0.73

Table 20: *Ledger results for 2.9m span.*

Ledger	L1	L2	L3	L4	L5
f1 (Hz)	24.38	24.75	24.75	25.13	25.25
Damping (%)	0.98	0.73	0.66	0.82	0.89
Deflection (mm)	0.87	0.85	0.85	0.83	0.82
FEM: f1 (Hz)	26.91	27.12	27.22	27.32	27.41
FEM: Def.(mm)	0.73	0.72	0.72	0.72	0.71

5 CONCLUSIONS

The study focused on the effect that rotational stiffness and span have on the first natural frequency, damping ratio and deflection of a 3-layer CLT plate supported at two ends.

It was found that natural frequency increases as the rotational stiffness increases and as span decreases. Damping ratio remains fairly constant though all the tests, at around 1%. The centre deflection under a 1kN load decreases as the rotational stiffness increases and decreases as span decreases.

The rotational stiffness was determined for three different support setups; end load, direct fastening with screws and ledger support. The following conclusion can be made:
- The increase of load at the supported edges significantly increases the rotational stiffness, and therefore natural frequency and static deflection.
- The increase in number of screws at the supported edges increases rotational stiffness, and it has a strong influence on natural frequency and static deflection.
- The ledger support has a minimal effect on rotational stiffness. In the ledger configuration, the three screws connecting the floor panel to the ledger have an effect on the rotational stiffness.

Finite element modelling was employed to model the influence of rotational stiffness on the first natural frequency and static deflection. The laboratory and finite element model results are in close agreement as the rotational stiffness and span are altered.

The results provide understanding on how the rotational stiffness is affecting the first natural frequency and the deflection. The rotational stiffness has an important influence in these parameters and should be considered in prediction equations.

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