AMBIENT VIBRATION TESTING AND MODAL ANALYSIS OF MULTI-STOREY CROSS-LAMINATED TIMBER BUILDINGS

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ABSTRACT: The ambient movement of three modern multi-storey timber buildings has been measured and used to determine modal properties. This information, obtained by a simple, unobtrusive series of tests, can give insights into the structural performance of these forms of building, as well as providing information for the design of future, taller timber buildings for dynamic loads. For two of the buildings, the natural frequency has been related to the lateral stiffness of the structure, and compared with that given by a simple calculation. In future tall timber buildings, a new design criterion is expected to become important: deflection and vibration serviceability under wind load. For multi-storey timber buildings there is currently no empirical basis to estimate damping for calculation of wind-induced vibration, and there is little information for stiffness under wind load. This study therefore presents a method to address those gaps in knowledge.

KEYWORDS: CLT, multi-storey, tall building, modal analysis, damping, serviceability

1 INTRODUCTION

Seven- and eight-storey timber buildings have been constructed and are well perceived in towns and cities around the world. As engineers strive to take multi-storey timber building to new heights, it is necessary to understand how these existing buildings are behaving in-service, and how their performance relates to that predicted at the design stage.

Due in part to their flexible connections between storeys, multi-storey timber buildings with shear wall structure may require a different approach to prediction of their dynamic properties than other structural forms, such as the method for predicting lateral natural frequency proposed by Leung et al. [1]. Furthermore, it is conventional to estimate damping based on measurements of buildings previously constructed in a similar form [2], and such measurements have not so far been carried out for multi-storey timber buildings, with the exception of the study on the six-storey stud-and-rail Timber Frame 2000 building by Ellis and Bougard [3].

This study provides measurements of both natural frequency and damping for modern CLT construction, by measuring some of the tallest timber buildings of the last ten years. The modal properties of each building were obtained by output-only modal testing. That is to say, the building was not artificially excited; rather its movement was measured under the dynamic loads imposed by the ambient conditions during the tests. These tests allow measurement of the as-constructed behaviour of the structure.

This paper presents a detailed description of the tests carried out on the Limnologen buildings in Växjö, Sweden, using data from a series of measurement points around the roof of the structure to estimate natural frequencies and mode shapes. Also presented are preliminary results from two further multi-storey CLT buildings which have been tested. For those buildings, the fundamental natural frequency and damping ratio are estimated based on measurements at a single point.

2 BACKGROUND

2.1 STRUCTURAL FORM OF THE BUILDINGS

2.1.1 The Limnologen Buildings

The four eight-storey residential buildings on the Limnologen block are all constructed with the first storey in in-situ cast concrete and the others with a combined

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CLT and stud-and-rail load bearing timber system. Both CLT and stud-and-rail walls contribute to the lateral load resistance of the structure.

The buildings have five apartments in each storey (storey 2-7) and two shafts with elevators and stair cases. The apartments are structurally connected only at discrete points with specially-designed connections, with the aim of reducing structure-borne sound. Lateral load introduced in the CLT flooring diaphragm can only be transferred between the apartments at these connection points, which were not designed for structural loads, and as a result, the blocks were each designed to be structurally independent. The apartment separating walls are indicated in Figure 1.

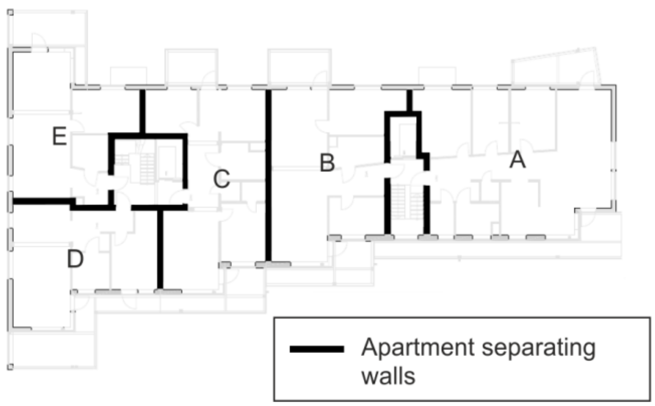

Figure 1: *Plan of a typical storey in a building on the Limnologen block. Each of the five apartments A to E is structurally connected only by specially designed connections to reduce sound transmission.*

Besides the flooring diaphragm, the stabilizing system comprises stud-and-rail shear walls with mechanically fastened fibreboard and CLT shear walls. The CLT shear walls are anchored by post-tensioned tie-down threaded rods, cast into the concrete on the first storey and continuous all the way to the top storey. The CLT walls bear directly onto one another vertically, with a partial cut to support the floors. This ensures that the CLT shear walls act as a continuous vertical cantilever throughout the height of the building, with load transferred parallel-to-grain.

2.1.2 UEA Student Residence, Norwich, UK

The UEA Student Residence building, designed by Ramboll engineers, uses platform CLT construction, with each wall panel resting on the floor panel below it and connected using angle brackets. The building is in an L-shape, with a seven-storey block and a five-storey block as indicated in Figure 2. The measurements used for the results presented here were taken at the extreme edge of the roof of the seven-storey block, as shown in Figure 2.

Since each wall bears on the floor below, the vertical load in each shear wall is transferred through the floor in perpendicular-to-grain loading. The floor panels are not reinforced perpendicular to grain.

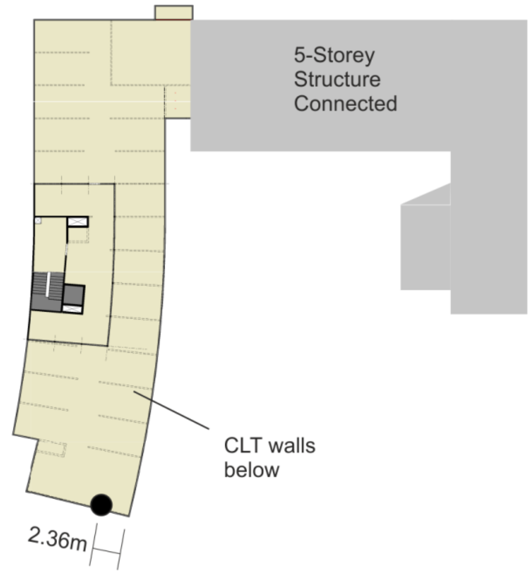

Figure 2: *Roof plan of UEA student residence, with the measurement location indicated by the black dot.*

2.1.3 Stadthaus, London, UK

The Stadthaus was completed in 2008, and has eight stories of CLT on a reinforced concrete first storey. Like the University of East Anglia building, it used platform CLT construction with angle bracket connections, but also used screw reinforcement in the perpendicular-to-grain direction in the floors to provide additional strength and stiffness [4].

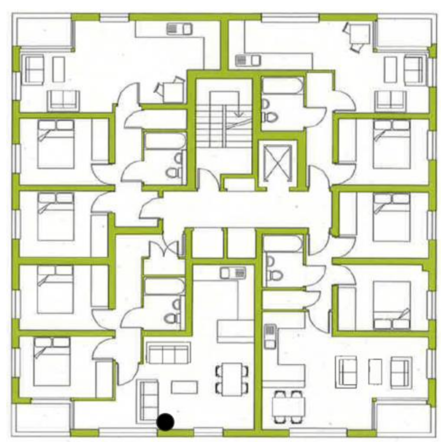

Figure 3: *Plan of the upper levels of Stadthaus, with structural CLT walls filled in [4] – the measurements were taken on the eighth floor, in the location shown by the black dot.*

3 METHOD

Three piezoelectric accelerometers were used, with a sensitivity of 10 V/g and designed to measure transient acceleration at frequencies of 0.1 Hz and above. They were mounted on aluminium blocks and placed onto the floor or roof. The mass of the accelerometers and the block was sufficient to keep them in place by gravitation, and ensure they moved with the structure, meaning that no anchorage to the structure was necessary. The accelerometers are shown in place on the Limnologen building in Figure 5.

Since no artificial excitation was required, and no fixing into the structure was necessary, the minimum of disruption was caused to the residents of the buildings or to the construction process. The buildings were either occupied and fully operational, in the case of the Limnologen and Stadthaus buildings, or under construction, in the case of the UEA building, during the tests. The unobtrusive nature of the tests was vital to obtaining permission to carry out the tests from building owners, and allowing the tests to proceed.

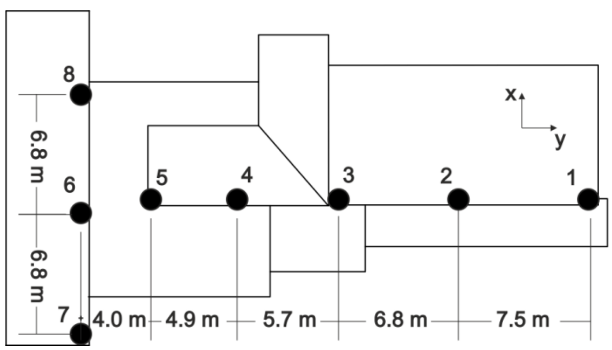

Figure 4: *Roof plan of Limnologen building showing measurement locations, numbering and axis directions.*

For the Limnologen building, measurements were taken at each location indicated with a black dot in the roof plan shown in Figure 2 for a period of 20 minutes, and the three accelerometers were moved around the roof to obtain data at 8 points, in two perpendicular directions at each point.

For each pair of readings, an accelerometer was placed at a common reference point to ensure that the measurements at locations across the structure could be transformed to a common scale. This scaling was carried out on the autocorrelation functions obtained by the random decrement technique, by scaling all the measurements so that the initial value of the random decrement signature on the reference channel was the same.

In the Stadthaus and UEA buildings, the measurements presented here are from all three accelerometers being placed at a single point on the structure, and that point is indicated by the black dots in Figure 2 and Figure 3.

The excitation force applied to the structure was assumed to be provided primarily by the turbulent wind load on the building, but also by the ambient movement of people and mechanical systems in the building. The analysis was based on the assumption that the dynamic components of these loads were stochastic, had a mean value of zero over a reasonable averaging time, and covered a sufficient range of frequency to excite the modes of vibration of interest.

These assumptions being satisfied, the ambient vibration response of the structure could be processed using the random decrement technique [5] to obtain the autocorrelation function, which could be analysed in a similar way to a free-decay response at each measurement point and in each direction. These equivalent free decays could then be analysed using conventional modal-analysis techniques, examples of which are the Ibrahim time domain method [6] and the matrix pencil algorithm [7], to find the modal properties of the structure: its natural frequencies, damping ratios and mode shapes.

Figure 5: *Accelerometers mounted to measure along three axes at a single point.*

3.1 THE RANDOM DECREMENT TECHNIQE

The random decrement technique extracts the autocorrelation function from a time-history of vibration measurement by averaging many samples, all of which start at the same initial value. It is useful for output-only analysis of structural vibration because, if the following conditions are satisfied:

- the unknown input force contains a sufficient range of frequencies,
- excites a sufficient range of points around the structure, and
- has a dynamic component with a mean of zero,

then the autocorrelation function, known as the random decrement signature, behaves similarly to the free-decay response of the structure at that point.

The random decrement signature for two of the measurement points, each in the x direction from Figure 4, is shown in Figure 6. At point 3, the vibration is dominated by a single mode, and it can be seen that the plot resembles an exponentially-decaying sinusoid. At point 1, the phenomenon of beating is observed, as the presence of two modes with close natural frequencies interfere with one another, causing the amplitude of the signal to increase and decrease. Time-domain modal analysis techniques can be applied to both these signals, or frequency-domain techniques can be applied to their Fourier transforms, to extract modal properties.

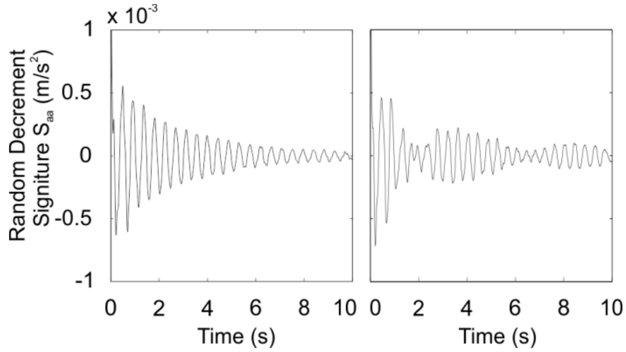

Figure 6: *Random decrement signature at point 3 (left hand plot) and point 1(right hand plot) in the y direction for the Limnologen building.*

3.2 MODAL ANALYSIS

The Matrix Pencil algorithm [7, 8] uses singular value decomposition of the time-domain signal to separate the contribution of each mode. In this way, the natural frequencies, damping ratios and residuals for each mode can be estimated from the signal from a single channel, which provides an estimate of the frequencies of the dominant modes of vibration of the structure, and the locations in which those modes have their maximum amplitude.

This single-channel analysis was applied to the channel which exhibited the largest magnitude of acceleration in the fundamental mode, as seen in the Fourier transform of the random decrement signature for each of the three channels at the chosen point.

This channel-by-channel examination of the random decrement signature also enabled the results to be inspected for the effect of harmonic excitation, which expresses itself as a non-damped virtual mode [9]. Harmonic excitation was observed, for example, in the Limnologen buildings at approximately 30 to 40Hz, which was assumed to be due to a mechanical ventilation system, which could be heard during the tests. Harmonic excitation was not observed between 0.5 and 10Hz in any of the tests, and therefore did not interfere with the vibration modes of interest.

In addition to this single-channel analysis carried out for each building, a complete multi-output analysis was carried out using the polyMAX method in LMS software. The polyMAX method is a polyreference version of the least-squares complex frequency-domain method.

This analysis was only applied to the results from the Limnologen building, using the data from all 8 measurement locations in both horizontal directions to estimate modal properties for the whole building.

4 RESULTS

Since the primary excitation of the structures was by the wind, the wind speed during the tests was recorded from nearby weather stations, in order to give an estimate of the free-field wind speed in the area. The proximity of the wind speed measurement depended on the availability of a suitable weather station. In the UK, Met Office weather stations were used, and in Sweden, a SMHI weather station was used.

The nearest weather station was as much as 20km from site in the case of the UEA Student Residence tests, so the wind speeds given are intended as an indication of the magnitude of the excitation force on the structure, rather than for use in any modelling or detailed comparison of results.

Table 1: *Wind speeds during tests*

Building under test	Wind speed	
	3-hourly mean	3-hourly peak gust
	m/s	m/s
Limnologen	3.6-4.1	-
UEA residence Test 1	6.0-7.6	8.8-11.3
UEA residence Test 2	9.4	17.0
Stadthaus	3.1-3.6	6.3-7.6

4.1 Limnologen Building

4.1.1 Single-channel analysis

The matrix-pencil curve-fitting approach enabled an assessment of the modal properties from a single channel. For the channel in the x direction at point 1 on the Limnologen building, the fitted time-domain response is shown in Figure 7.

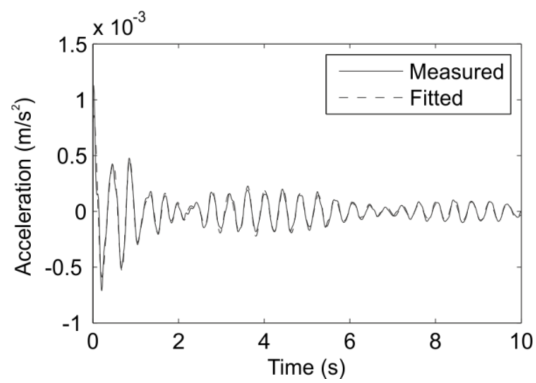

Figure 7: *Fitted time-domain response for point 1 in the y direction.*

The measured and fitted lines are barely distinguishable, and the frequency-domain representation of the same data shows that the first three modes are fitted. The modal properties of the first three modes, based on this curve fitting, are given in Table 2.

The results showed that the response was dominated by two closely-spaced modes of vibration, with natural frequencies of approximately 2.3 Hz and 2.5 Hz. The damping ratios of the first three modes are shown in Table 1.

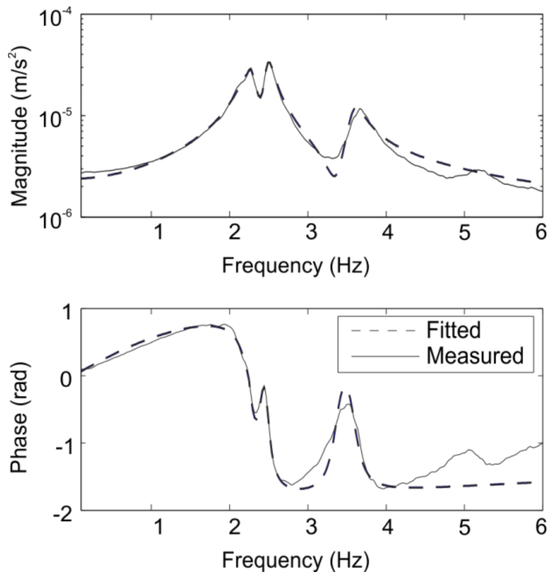

Figure 8: *Fitted spectrum for point 1 in the y direction.*

Table 2: *Natural frequencies and damping for the first three modes of the Limnologen building based on analysis of channel 1 in direction x*

Mode number	Frequency (Hz)	Damping (% of critical)
1	2.28	2.3
2	2.48	1.0
3	3.50	3.1

4.1.2 Multi-channel analysis

The multi-channel analysis carried out using the LMS polyMAX method uses data from each measurement location, and in each direction. Any nonlinearity in the response of the structure may result in a variation in natural frequency or damping with the amplitude of vibration. Since the response at different points on the structure was measured in different tests, the amplitude of excitation provided by the ambient loading would be expected to vary between points. The polyMAX method prduces a linearized set of modal parameters for the whole structure.

The results of the multi-channel analysis agree closely with the results from a single channel in their frequency estimate. The damping estimates from the multi-channel analysis differ more from the single-channel estimates, but the same trend is observed, that damping is lower in the second mode than in the first and third.

Table 3: *Natural frequencies and damping for the first three modes of the Limnologen building based on analysis of all channels*

Mode number	Frequency (Hz)	Damping (% of critical)
1	2.24	1.5
2	2.48	0.9
3	3.63	2.0

The variation in damping between the methods may be because the building exhibited different damping at the time of each test, due to a different amplitude of excitation by the wind. The records of wind speed used are not detailed enough to check this effect, however, and the results therefore highlight the uncertainty in damping.

The mode shapes for the first three modes are shown in Figure 9. It can be seen that mode one is characterized by lateral movement, with all of the apartment units moving in the same direction. The greatest movement is in apartment A, with little movement of the part of the building with apartments D and E in, which have a longer dimension in the direction of movement.

Mode two is dominated by the movement of apartment A, with very little movement in the other parts of the structure, and in Mode three, apartments A and B move in opposite directions.

It is notable that the damping is lower in the mode in which apartment A, with primarily CLT structure moves independently of the rest of the structure. It is considered that the CLT structure may exhibit lower damping than the sheathed stud-and-rail system, since in the latter, embedment of screws, friction between the studs and the sheathing and between the timber members may dissipate energy. In the CLT system, load is transferred mostly through solid timber elements and glued joints, which is expected to be a less dissipative system.

It is considered that the CLT shear walls with tensioned tie-down rods may exhibit particularly low damping, since the static friction force which must be overcome before frictional energy dissipation may contribute to damping will be higher under prestress.

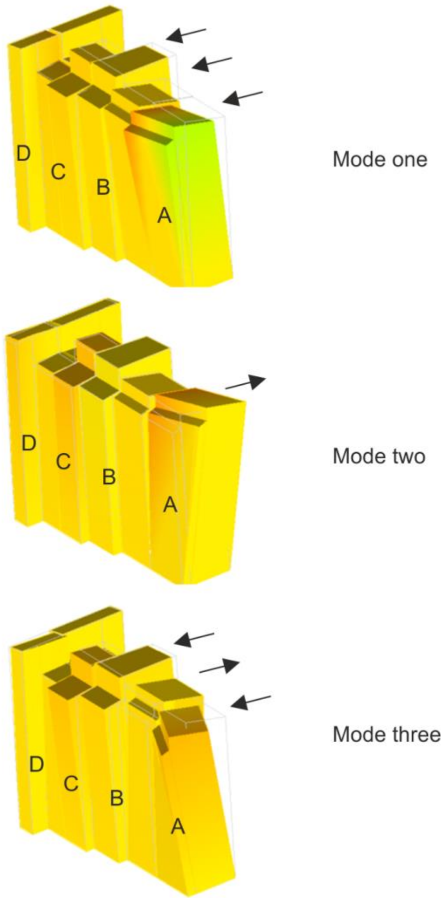

Figure 9: *Estimated mode shapes for the first three modes of vibration of the Limnologen building.*

4.2 Other Buildings

The results from the other buildings are collated in Table 4. In each case, the frequency spectrum from each of the horizontal directions was inspected, and the channel with the greatest response at the fundamental frequency was used for single channel modal identification using the matrix pencil method.

The UEA Student Residence building was tested on two occasions during its construction. The non-structural elements considered to have a potential effect on the mass, stiffness and damping were: the 50mm cement screed applied to each floor; the internal plasterboard and the external render and cladding.

The CLT structure had been completed before the first test. At the time of the first test, the screed was installed on the ground and first floors, the internal plasterboard was installed from the ground to the fourth floor, and there was no external render or cladding applied. At the time of the second test, the screed, plasterboard and external render were complete throughout the building, but construction activities were ongoing.

For the UEA tests, only one mode of vibration was clearly identifiable at the point under consideration. The effect of the additional non-structural elements added between Test 1 and Test 2 was to reduce the fundamental frequency. This is considered to be due in large part to the effect of the mass added by the floor screed, which represented approximately 30% of the total permanent load of the building.

Table 4: *Natural frequencies and damping for the first two modes of each building, based on analysis at a single point*

Building	Mode number	Frequency (Hz)	Damping (% of critical)
Limnologen	1	2.28	2.3
	2	2.48	1.0
UEA Test 1	1	2.70	3.6
	2	-	-
UEA Test 2	1	2.45	5.4
	2	-	-
Stadthaus	1	2.26	1.9
	2	2.99	2.2

The additional non-structural elements may also have had the effect of increasing the damping in the UEA building from 3.6% to 5.4%, though it should be noted that the wind speed was higher for the second set of tests, which could be partly responsible for this increased damping.

The Stadthaus was complete and occupied at the time of the tests. Its two lowest natural frequencies have similar damping ratios of around 2%, substantially lower than the UEA building. The damping ratio of both steel and reinforced concrete buildings has been observed to reduce with an increase in height [2], and so this lower damping may reflect the fact that the Stadthaus building is taller and more slender than the others tested. The Stadthaus also has screw reinforcement where there is perpendicular-to-grain loading, so if dissipative perpendicular-to-grain processes lead in part to the higher damping in the UEA building, then the screw reinforcement in Stadthaus may reduce that effect. The lower damping measured in the Stadthaus building may also be simply due to the fact that it was tested at lower wind speeds than either of the UEA building tests, as shown in Table 1.

5 COMPARISON WITH THEORETICAL PREDICTION

For the Limnologen building, an estimate of the fundamental frequency of apartment block A was carried out in order to investigate the predictability of the dynamic behaviour of the structure. This was done by approximating its behaviour as the bending of a vertical cantilever, with a distributed mass m and bending stiffness

EI. The fundamental frequency is then given by Eq (1), where h is the height of the building.

$$f = \frac{3.52}{2\pi}\sqrt{\frac{EI}{mh^4}} \quad (1)$$

m was estimated by a load run-down for the building, summarized in Table 6, and EI by calculating an equivalent stiffness for the lateral load resisting walls, indicated in Figure 10. In apartment A, there are four CLT walls in the building short direction, one external and three internal, and EI was estimated based on those four walls alone.

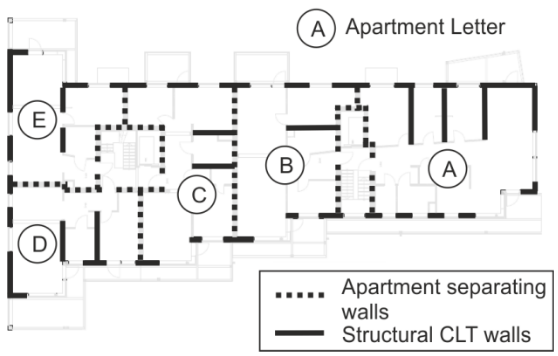

Figure 10: *Plan showing structural walls.*

The mass density inside the building envelope for the Limnologen building is estimated as 46kg/m^3, which is extremely light in comparison with conventional multi-storey buildings, which almost all have concrete floors. The CAARC standard tall building [10], for example, has a density of 160kg/m^3. This is notable, because a low mass tends to increase the accelerations caused by wind-induced vibration [11, 12].

Table 5: *Load run-down for apartment A in the Limnologen building.*

Level	Item	Quantity	Mass Density	Mass
		m^2	kg/m^2	kg
1-7	Floor/Ceiling	97	76	7338
	Walls (external)	55	63	3452
	Walls (apartment separating)	7	50	367
	Walls (internal)	29	53	1554
8	Roof	97	152	14676
			Total	103652

The natural frequency of apartment A was estimated as 1.94Hz. This is lower than the 2.48Hz measured in the mode of vibration dominated by apartment A, which suggests that the sheathed stud-and-rail apartment separating walls, the connection to the rest of the building and the contribution of non-structural elements add to the stiffness of the structure, but also that a reasonable and conservative estimate of the fundamental natural frequency can be made based on the CLT part of the structural system.

For the UEA building, an estimate of the fundamental natural frequency was obtained by assigning a plan area, and therefore a mass, to be restrained by each shear wall acting as a vertical cantilever. The natural frequency of that vertical cantilever was then assessed using (1). The mass density inside the building envelope, based entirely on the permanent load, is calculated according to Table 6, giving 150kg/m^3.

Table 6: *Load run-down for the area restrained by a single shear wall in the UEA building.*

Level	Item	Quantity	Unit mass	Mass
		m^2	kg/m^2	kg
1-7	Floor/Ceiling	15.4	255	3922
	Walls (external)	7.4	105	780
	Walls (internal)	13.0	105	1363
8	Roof	15.4	143	2196
			Total	44647

Using EI for the single CLT wall acting as a vertical cantilever, the anticipated natural frequency including the mass of the floor screed is 2.8Hz. Without the floor screed it is 3.3Hz. The measured values are lower, at2.70Hz and 2.45Hz before and after the floor screed, respectively. These results suggest that the perpendicular-to-grain loading at each floor level, and perhaps the effect of connection stiffness, neither of which are taken into account in calculating EI, may act to reduce the stiffness of the shear wall as a whole.

While these walls provide the necessary lateral stiffness for a building this height, in much taller buildings it may be necessary to use a structural system which develops a shear wall stiffness closer to the full potential EI of the continuous CLT wall.

These results therefore highlight the possible benefits of developing structural systems which avoid perpendicular-to-grain loading and increase connection stiffness.

It is notable that the UEA building does not appear to exhibit a marked increase in stiffness after addition of the non-structural cladding, as was noted by Ellis and Bougard [3] for the sheathed stud-and-rail Timber Frame 2000 building, which had brick cladding. In that study, the stiffness was observed to increase by a factor of 4 with the addition of the cladding. In the CLT building measured here, the building appears to behave as-designed, with the main structure providing the lateral resistance.

6 CONCLUSIONS

This study has shown that output-only modal testing can be used to identify modal parameters in three multi-storey CLT buildings. The tests resulted in no disruption to the building occupants, and so are suitable for a wide study of damping in this type of building in service, which is vital to inform the design of future tall timber buildings.

The results have shown a large range of damping in the buildings tested, and tests on the same building at different times during construction have shown the effect of non-structural elements and amplitude of excitation on damping. In a similar way to other forms of construction, it is considered that reliable estimates of damping can only be achieved by the development of a large set of measurements of multi-storey timber buildings, of which this study provides a part.

The magnitude of the damping covers a similar range to steel and reinforced concrete buildings according to current design guidance [13], and the lowest damping ratio measured in the Limnologen building is similar to that recommended for steel structures. This suggests that dynamic effects can be expected to affect timber structures in the same way as lightweight steel ones.

Further work is required to provide a more complete understanding of the range of damping in multi-storey timber buildings.

In this study, simple predictive calculations have been carried out to assess the stiffness of the lateral load resisting system, and estimate the natural frequency. Further study into the behaviour of connections, and the influence of perpendicular-to-grain loading under wind load would help to improve the accuracy of such calculations.

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