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Ambient vibration tests of a cross-laminated timber building

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Cross-laminated timber has, in the last 6 years, been used for the first time to form shear walls and cores in multi-storey buildings of seven storeys or more. Such buildings can have low mass in comparison to conventional structural forms. This low mass means that, as cross-laminated timber is used for taller buildings still, their dynamic movement under wind load is likely to be a key design parameter. An understanding of dynamic lateral stiffness and damping, which has so far been insufficiently researched, will be vital to the effective design for wind-induced vibration. In this study, an ambient vibration method is used to identify the dynamic properties of a seven-storey cross-laminated timber building in situ. The random decrement method is used, along with the Ibrahim time domain method, to extract the modal properties of the structure from the acceleration measured under ambient conditions. The results show that this output-only modal analysis method can be used to extract modal information from such a building, and that information is compared with a simple structural model. Measurements on two occasions during construction show the effect of non-structural elements on the modal properties of the structure.

Notation

E	elastic modulus of section
E_n	elastic modulus of component n
E_T	equivalent elastic modulus of complete shear wall
e_T	total deformation
f	natural frequency of vertical cantilever
h_n	Height of component n
h_T	vertical cantilever height
I	second moment of area of complete wall cross-section
m	mass
ε_m	mean strain
σ	total applied stress

1. Introduction

Timber buildings of seven storeys or more have now been constructed in towns and cities around the world, using cross-laminated timber (CLT) as the primary structural material. This represents an increase in height beyond the existing six-storey platform timber frame buildings, the robustness and fire resistance of which were validated in studies such as Timber Frame 2000 by the Building Research Establishment (BRE) (Ellis and Bougard, 2001).

In taller, more slender and flexible timber buildings, serviceability considerations associated with lateral movement assume increased importance compared with low-rise buildings, where strength is usually the governing design criterion. That is to say, the forces imposed by wind, for example, on a tall and slender building, while they may not damage any structural element, may cause deformation or vibration in the building, which could cause discomfort to occupants, damage non-structural elements, or otherwise prevent the normal operation of the building. Such issues have been recorded in reinforced concrete buildings of just six storeys (Thor Snaebjörnsson and Reed, 1992), but have been more commonly observed and investigated in much taller buildings (Kwok *et al.*, 2009).

The strength-to-weight and stiffness-to-weight ratios for timber compare favourably with steel and reinforced concrete, suggesting that it has the potential to form the structural material for high-rise buildings. For this to happen, however, systems must be developed to overcome issues such as the relative weakness and flexibility of connections, combustibility and unfavourable material properties in the perpendicular-to-grain directions. As engineers strive to take multi-storey timber building to new heights, it is necessary to understand how existing buildings, and current construction systems, are behaving in-service, and how their performance relates to that predicted at the design stage.

The potential for extensive prefabrication and rapid construction in CLT has made it competitive with conventional structural materials for buildings in congested urban locations. The ability of the structural material to store carbon for the life of the building means that these substantial structures have the potential to contribute to mitigation of climate change. However, as a new form of construction, and to understand the feasibility of building taller still, there is a need for research into the in situ performance of multi-storey CLT buildings.

Such buildings can have low mass in comparison to conventional structural forms. This provides the benefits of reduced foundation requirements and loads for transportation. Low mass means that, as CLT is used for taller buildings, their movement under wind load is likely to be a key design parameter. This movement will be determined by both the lateral stiffness of the building, and the damping which represents the dissipation of energy in the structure as it vibrates. Both have so far been insufficiently researched. A structure's mass and stiffness determine its natural frequency, and natural frequency and damping are modal properties of a particular mode of vibration of a structure.

An ambient vibration method is used in this study to begin to address that gap in knowledge by investigating the modal properties, and the variation of modal properties with amplitude, in a seven-storey CLT building: The University of East Anglia (UEA) student residence in Norwich, UK. Figure 1 shows the seven-storey block of the building after completion, and its CLT structure.

2. Background

Owing to their relatively rigid panels, and relatively flexible connections between storeys, multi-storey CLT buildings with a shear wall structure may require a different approach to prediction of their dynamic properties than other structural forms. Methods have been proposed for predicting lateral natural frequency of timber frame structures (Casagrande *et al.*, 2012; Leung *et al.*, 2010), but the solid timber construction of CLT exhibits different deformation mechanisms, and requires a different approach. Tests have been carried out on CLT structures and systems under high-amplitude vibration representative of seismic action (Ceccotti *et al.*, 2013; Gavric 2013; Vessby *et al.*, 2009). Under such loads, lateral stiffness is dominated by connection behaviour, and perhaps as a result, the in-plane stiffness of the panels themselves has been studied less. Under lower-amplitude movement, friction and direct contact are expected to be responsible for the majority of load transfer between panels. Connections may not, therefore, contribute to stiffness, and the elastic properties of the panels themselves may assume increased importance. Such properties have been measured by various research studies, although the appropriate shear modulus for the panels is a subject of ongoing research (Flaig and Meyer, 2014; Gsell *et al.*, 2007).

Figure 1. University of East Anglia student residence building

As well as stiffness, there is a need for further research into damping in this new form of multi-storey building construction. It is conventional to estimate damping based on measurements of buildings previously constructed in a similar form (Smith *et al.*, 2010), and such measurements have not, so far, been carried out for multi-storey timber buildings of seven storeys or more, although there are some examples of such work on multi-storey timber buildings, such as the six-storey stud-and-rail Timber Frame 2000 building by Ellis and Bougard at the BRE (Ellis and Bougard, 2001), and the range of buildings up to six storeys studied by Hu *et al.* (2014). CLT buildings of seven storeys or more therefore represent a class of buildings for which no experimental data exist regarding their dynamic properties. The present work begins to address that gap in knowledge.

This study provides measurements and analysis of both natural frequency and damping under wind-induced vibration in a seven-storey CLT building, through ambient vibration testing. That is to say, the building was not artificially excited, but its movement was measured under the dynamic loads imposed by the ambient conditions during the tests. Such tests have been widely used to extract modal properties from structures (Ceravolo and Abbiati, 2012; Beskhyroun *et al.*, 2013; Farrar and James III, 1997; Magalhães *et al.*, 2010; Snæbjörnsson and Ingolfsson, 2013). Jeary (1992, 1996) showed that output-only techniques can be used not only to assess the modal properties of such structures, but also how those properties vary with amplitude of vibration, and his work led to studies to quantify that variation for tall buildings as wind speed varies (Li *et al.*, 2002, 2003; Tamura and Suganuma, 1996).

In this study, the building was tested at two stages during construction, which allowed analysis of the influence of the non-structural elements added between the two tests on the measured modal properties. Alhough the structural form of the building was not regular overall, the part of the building which was tested could be approximated as a vertically cantilevering shear wall system, whose stiffness was provided by shear walls at regular intervals. This allowed a simple analytical calculation of the fundamental natural frequency.

This work extends the field by presenting measured modal properties of a relatively new form of construction. It provides a basis of prediction of the natural frequency of such structures under wind load, given the different deformation mechanisms that dominate the behaviour, compared with those under the more widely studied seismic loading. Finally, analysis illustrates the variation of these properties with amplitude of vibration, which must be considered in future measurements, since design according to modal properties measured at one amplitude of vibration may be unconservative at another.

3. Method

3.1 Structural form of the building

The UEA student residence building is located in Norwich, UK. It uses conventional platform CLT construction, with each wall panel resting on the floor panel below it and connected using angle brackets. The angle brackets for the upper five floors are Simpson Strongtie ABR-105 brackets, at 400 mm spacing on either side of each vertical panel, and above each floor panel. At the bottom two levels, ABR-100 angle brackets are used, and are connected above and below each floor panel. At each floor level, 240 mm long, 8 mm outer dia. part-threaded screws are installed vertically to connect the floor panel to the wall panel below. These screws are spaced at 400 mm centre to centre for the bottom two floors, and 300 mm or 200 mm for the upper five floors, depending on the predicted load. At the base, AKR-95 hold-downs connect to a reinforced concrete slab. The vertical load in each shear wall is transferred through the floor in perpendicular-to-grain loading, and there is no designed reinforcement of the floor panels perpendicular to grain, although some reinforcement may be provided by the vertical screws connecting each floor to the wall below.

The floor-to-ceiling height is formed by a single 2·6 m high panel. Internal walls in the area of the building tested are 4·6 m long, and connected to the external wall by ABR-105 brackets at 400 mm spacing vertically on either side of the panel.

The building has a C-shape in plan, with a seven-storey block forming one side, and a five-storey block on the other two sides, as shown in Figure 2. In this study, measurements were taken along the roof level of the seven-storey block, as shown in Figure 2, in order to record the lateral movement, and calculate the modal properties, at the most flexible part of the structure.

3.2 Test procedure

Three piezoelectric accelerometers were used, with a nominal sensitivity of 10 V/g, and a lower frequency limit of 0·1 Hz. They were mounted on aluminium blocks and placed onto the surface of the 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.

Acceleration was measured at three points along the roof, as shown in Figure 2, and at each of the three points, the acceleration was measured in two perpendicular horizontal directions, giving a total of six measurement channels. For each pair of readings, an accelerometer was placed at a common reference point, so that the measurements at each location could be transformed to a common scale and phase, as shown in Table 1.

These tests were carried out on 2 days: 15 January 2014, which will be referred to as day 1, and 20 March 2014, which will be referred to as day 2. On day 1, the CLT structure was complete, a 55 mm cement screed was installed on level 1, internal plasterboard was installed from the ground up to level 3, and there was no external render or cladding applied. By the time of the second test, the screed, plasterboard and external render were complete throughout the building.

3.3 The random decrement technique

The random decrement technique averages many short samples of a vibration record, all of which start at the same initial value, and was first proposed by Cole (1973). These samples may overlap, so the algorithm identifies each occasion on which the measured acceleration crosses a threshold equal to the desired initial value, and takes a sample of a given length, in this case, 4 s, starting immediately after the crossing. Several thousand such samples are taken from the 30 min time-history of acceleration measured at each point, and averaged. The result is a weighted autocorrelation function.

The random decrement method is useful for output-only analysis of structural vibration because the weighted autocorrelation function it generates, known as the random decrement signature, behaves similarly to the free-decay response of the structure at that point, and can be analysed using modal analysis techniques developed for the free-decay response.

In this study, when a single-channel modal analysis method is to be used, the random decrement method is applied

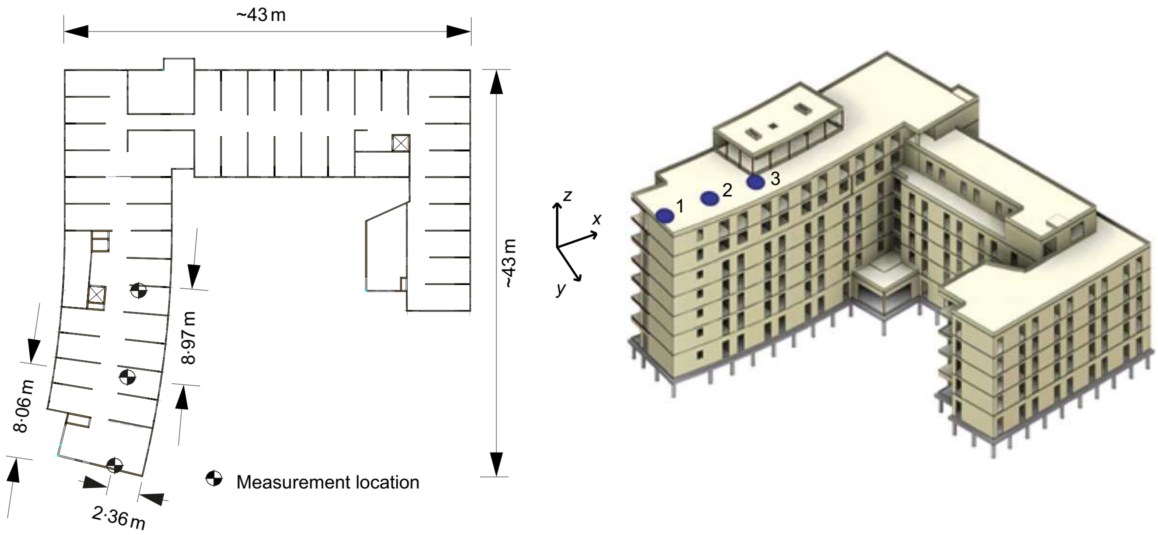

Figure 2. Schematic diagram of the building structure, with accelerometer positions indicated by the numbered locations, and measurement directions *x* and *y*; concrete piles are shown on the isometric view

independently to each channel. When a multi-output method is to be used, then one channel, identified as the one which moves with the greatest amplitude in the fundamental mode of vibration, is used as the trigger channel, and samples are taken from every channel at the time corresponding to the threshold-crossing in the trigger channel.

A 'weakly non-linear' structure can be defined as one in which linear modal parameters can be identified at a given amplitude of vibration, but there may be a variation in those parameters as the amplitude of vibration changes. The random decrement method is useful in the analysis of weakly non-linear structures, since the averaging process can be restricted to samples with a particular amplitude of vibration, related to the chosen threshold acceleration. This ensures stationarity in the data to be analysed (Jeary, 1996). That is, it ensures that all the samples taken from the data express the same modal parameters.

Test	Point	Directions
1	1	*x*, *y*, *z*
2	1	*y*
	2	*x*, *y*
3	1	*y*
	2	*x*, *y*

Table 1. Test configurations, with the channel used as the trigger channel for each test underlined, and point and direction labels as in Figure 2

By varying the threshold value of acceleration, it has been shown that it is possible to investigate the variation of modal parameters with amplitude (Jeary, 1992, 1996). The modal parameters associated with a particular threshold value can be plotted, and the variation in natural frequency or damping with the magnitude of the threshold value can be plotted.

3.4 Modal analysis techniques

Two modal analysis techniques were applied in this study. Both are time-domain techniques, which can be applied directly to the random decrement signature. One, the matrix pencil algorith, (Hua and Sarkar, 1990), is a single-channel technique, developed to extract natural frequencies and damping ratios from the free-decay response of a structure at a single point, in a single direction. The second, the Ibrahim time domain (ITD) method (Ibrahim, 1999), was developed to analyse a matrix formed from the free-decay response of a series of measurement channels, and can therefore extract natural frequencies, damping ratios and mode shapes from the data.

Harmonic excitation was observed at approximately 30 to 40 Hz, which was assumed to be due to the generator running near the building to power the construction work. Harmonic excitation was not observed between 0·1 and 10 Hz; these were used as the lower and upper frequency limits for the initial band-pass filter, and therefore did not interfere with the measurement of the fundamental mode of vibration between 2 and 3 Hz.

The ITD method was used to extract natural frequencies and damping ratios using the data from all six channels simultaneously, using the random decrement signature as the input for modal analysis. The ITD method uses an eigenvalue analysis of a matrix formed from the free-decay responses in each measurement channel, or in this case, the random decrement signatures in each channel, allowing plan mode shapes to be drawn for the fundamental mode. In order to do so, the results from the three separate tests were scaled using the common channel between them. The scaling was carried out by obtaining a mode shape in the fundamental mode for each of the three tests, and scaling those mode shapes so that the amplitude of the common channel matched in each case.

3.5 Prediction of the fundamental natural frequency

A simplified dynamic calculation was carried out for the building, to investigate the extent to which the dynamic lateral stiffness of the building could be estimated using hand calculations, and related to the measured natural frequencies. The calculation is based on a two-dimensional representation of a shear wall and the mass it supports, and so considers just one lateral mode of vibration, and not any torsional modes. It is suitable, therefore, for use with the method for determining the vibration of a building due to wind turbulence given in Eurocode 1, Part 1–4 (BSI, 2005), for example, which takes into account only the fundamental mode.

The fundamental mode of vibration of the part of the building under consideration was expected to be in the y direction, since the building is much more slender and flexible in that direction: its slenderness ratio of height divided by plan dimension is approximately 1·7 in the y direction, but only 0·5 in the x direction. The lateral stiffness was only investigated in the y direction, since the x direction was considered to be far stiffer due to its lower slenderness. This assumption was justified by the fact that the only measurable lateral movement was in the y direction. The lateral stiffness of the building in the y direction is provided by shear wall systems formed by the walls separating each room. The stiffness of these shear wall systems was estimated based on the assumption that each wall acts as a separate vertical cantilever through the building, with the shear connection provided between these cantilevers by the floor panels considered to be negligible.

Figure 3 shows the deformation mechanisms in a shear wall panel. The simplified calculation presented here assumes that the lateral load applied to the structure is sufficiently small in comparison to the vertical load that uplift does not occur in the panels, and that friction prevents lateral sliding.

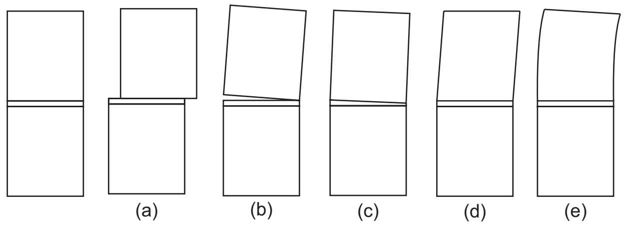

Figure 3. Deformation mechanisms for a panel supported on a floor below: (a) rigid-body sliding; (b) rigid-body rotation; (c) deformation of supporting floor; (d) shear deformation of panel; (e) bending deformation of panel

Mechanisms shown in Figures 3(a) and 3(b) do not, therefore, occur, and since those are the only mechanisms which rely on the connections for stiffness, it is not considered necessary to know the connection stiffness to estimate the natural frequency under the wind loads considered.

The vertical cantilever is 19·2 m high, and an equivalent section modulus was calculated to take into account the different stiffnesses of the wall panels loaded in their in-plane direction, and the floor panels loaded out-of-plane. The shear deformation of the panels was neglected to simplify the calculation of natural frequency, since it contributed less than 10% to the static deflection of the shear wall system.

The natural frequency f of a vertical cantilever height h_T in bending is given by Equation 1, where E is the elastic modulus of the section and I is the second moment of area of the complete wall cross-section.

$$1.\quad f = \frac{3{\cdot}52}{2\pi}\sqrt{\frac{EI}{mh_T^4}}$$

Considering the second moment of area of the section to be constant throughout the height of the building, an equivalent elastic modulus can be calculated to take into account the different values for the panels loaded in-plane and out-of-plane. For a vertical strip, this equivalent elastic modulus may be defined as the ratio between the total applied stress σ and the mean strain ε_m.

$$2.\quad E_T = \frac{\sigma}{\varepsilon_m}$$

The mean strain is given by the total deformation e_T divided by the height over which it occurs, h_T, and e_T can be expressed in terms of the height of each of the panels and their elastic moduli h_n and E_n.

Element	Total height: m	Elastic modulus: GPa
Vertical wall panel	19·6	7·37
Horizontal floor panel	0·98	0·34
Total equivalent elastic modulus		3·37

Table 2. Equivalent elastic modulus for vertical cantilever wall

3. $$\varepsilon_{\mathrm{m}} = \frac{e_{\mathrm{T}}}{h_{\mathrm{T}}} = \frac{\sigma \sum_{n} \frac{h_n}{E_n}}{h_{\mathrm{T}}}$$

Using Equations 2 and 3, the equivalent elastic modulus for the wall section is given by

4. $$E_{\mathrm{T}} = \frac{h_{\mathrm{T}}}{\sum_{n} \frac{h_n}{E_n}}$$

Using Equation 4, the equivalent elastic modulus of the shear wall system in the UEA student residence can be calculated as shown in Table 2. The timber forming the CLT panels was classed by the supplier as C24 according to EN 338 (BSI, 2009) in three 40 mm layers. The in-plane elastic modulus of the wall panel can therefore be estimated using the values given in BS EN 338: 11 GPa parallel to grain, E_1, and 0·34 GPa perpendicular, E_2. The elastic modulus for the three-layer section in-plane can then be calculated as $E_s = 2E_1/3 + E_2/3$, giving 7·37 GPa.

It is notable in Table 2 that despite making up only 5% of the total height of the structure, the perpendicular-to-grain loading in the floor panels is responsible for a 43% reduction in the overall stiffness of the vertical cantilever.

Given the stiffness of each shear wall system, in order to estimate the natural frequency of the structure, it is necessary to estimate its mass. This was done by a load run-down for the structure, as shown in Table 3.

The fundamental frequency of the structure could then be estimated using Equation 1, which represents the simplifying assumption that the stiffening effect of the connection to the adjoining structure was small, so that the frequency could be estimated based on the seven-storey block moving independently.

The estimate of the building mass can be used to calculate an equivalent density within the building envelope. Before the non-structural concrete floor screed, the density of this building is calculated as 79 kg/m^3. Including the floor screed, it is 126 kg/m^3. This makes the building a relatively lightweight structure. The Commonwealth Advisory Aeronautical Research Council standard tall building, for example, is a reinforced concrete structure used as a benchmark wind-excitable tall building, and has a density of 160 kg/m^3 (Huang *et al.*, 2007; Yang *et al.*, 2004). This is notable, because a low mass tends to increase the accelerations caused by wind-induced vibration.

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 results are shown in Table 4, which shows the effect of the additional mass provided by the cement floor screed in reducing the estimated natural frequency of the structure.

Level	Item	Detail	Quantity: m^2	Unit mass: kg/m^2	Mass: kg
2–7	Floor	140 mm CLT plank	15·4	67·3	1035·4
		Insulation, cladding and services	15·4	29·6	455·0
		55 mm cement screed	15·4	127·4	1961·0
	Walls (internal)	Insulation, cladding and services	7·0	43·9	307·7
		120 mm CLT wall panel	7·0	61·2	429·4
	Walls (external)	Insulation, cladding and services	12·0	32·6	390·1
		120 mm CLT wall panel	12·0	61·2	731·5
	Imposed	Bathroom unit	1 per storey	450 kg	450·0
8	Roof	Insulation, cladding and services	15·4	70·3	1082·6
		140 mm CLT plank	15·4	67·3	1035·4
Total (all floors)					36 678
Total (Day 1)					23 415
Total (Day 2)					36 678

Table 3. Load run-down for the area restrained by a single shear wall in the UEA building

	Wall second moment of area: m^4	Vertically distributed mass supported by each wall: kg/m	Frequency of fundamental lateral mode: Hz
Day 1	0·057	1195	2·58
Day 2	0·057	1871	2·05

Table 4. Estimated natural frequencies

4. Results

4.1 Single-channel analysis

This single-channel analysis was carried out on all six of the measurement channels for the building. The data were first filtered numerically, using a ninth-order Butterworth filter in Matlab, to isolate the range of frequencies of interest, between 0·1 Hz and 10 Hz. The random decrement technique was then applied, using a threshold value of $\sqrt{2\sigma_x}$, where σ_x is the variance of the acceleration, to give a reasonable balance between obtaining sufficient samples for averaging, and to minimise the variance of the parameters estimated using the technique (Asmussen, 1997; Rodrigues and Brincker, 2005). Any samples containing accelerations greater than ten times the threshold level were discarded, since they were likely to be a result of local excitation, such as an impact due to construction work, rather than a resonant response of the building.

For the channel in the y direction at point 1, the fitted time-domain response using the matrix pencil algorithm is shown in Figure 4.

The response is dominated by a single mode of vibration, and therefore takes the form of a decaying sinusoid. Only one mode of vibration was clearly identifiable, although the frequency-domain representation of the response shown in Figure 5 shows some evidence of higher frequency, lower amplitude modes. The time- and frequency-domain representation of the same data shows that the fundamental mode of vibration is well represented by the modal parameters generated by curve-fitting.

The frequency of the fundamental mode of vibration, and its damping ratio, could therefore be calculated for each channel separately. Figure 6 illustrates the variation in those estimates, and shows that the estimates in natural frequency in each measurement channel agree closely. The estimates of damping vary considerably, ranging from 3·2% to 5·6% for day 1, and 5·2% to 9·1% for day 2. This variation is considered to result in part from the fact that, since the data from the six measurement channels were collected in three separate tests, the amplitude of vibration of the building on which each damping estimate was based will have varied. Any variation of damping with amplitude would therefore result in a scatter of the measured damping estimates. The random decrement technique allows investigation of the variation of damping with amplitude, as presented in Section 4.3.

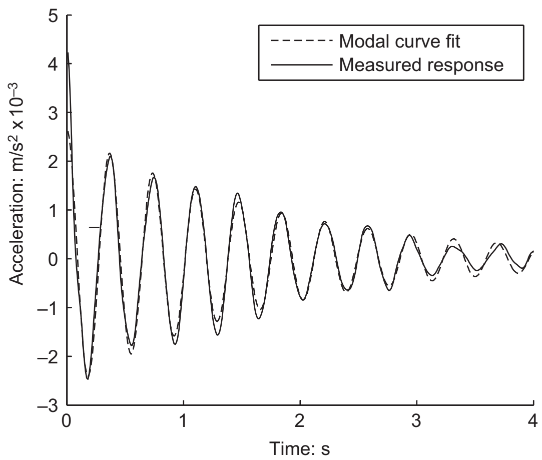

Figure 4. Fitted time-domain response for point 1 in the y direction

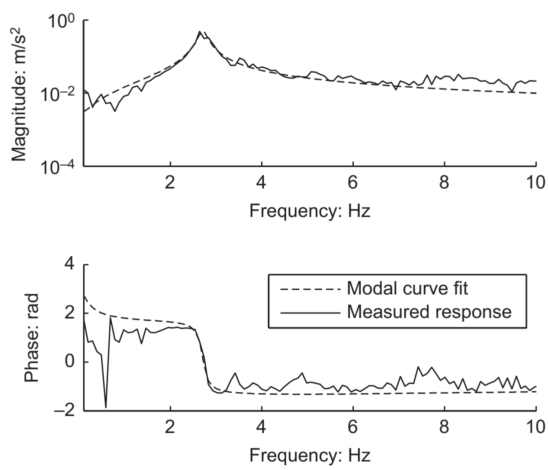

Figure 5. Fitted spectrum for point 1 in the y direction

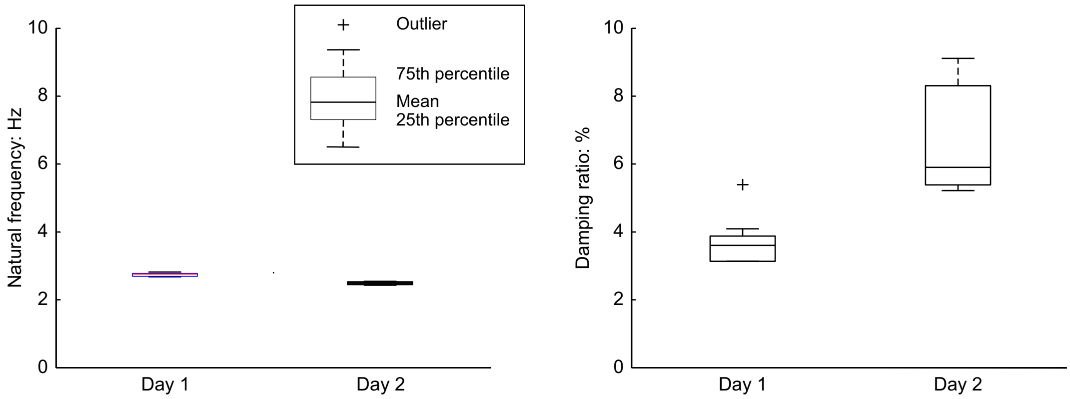

Figure 6. Natural frequency and damping estimates for all measurement channels on day 1

4.2 Multi-channel analysis

The multi-channel analysis carried out using the ITD method uses data from each measurement location, and in each direction. Any non-linearity 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 tests. The ITD method therefore produces a linearised estimate of the modal parameters.

As envisaged in the predictive calculations in Section 3.5, the effect of the additional non-structural elements added between day 1 and day 2 was to reduce the fundamental frequency. This is therefore 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. Comparison of these measured natural frequencies with those predicted in Table 4, shows a close agreement for day 1. For day 2, it is possible that the stiffening effect of the non-structural cladding and finishes is apparent, since the measured natural frequency is higher than predicted.

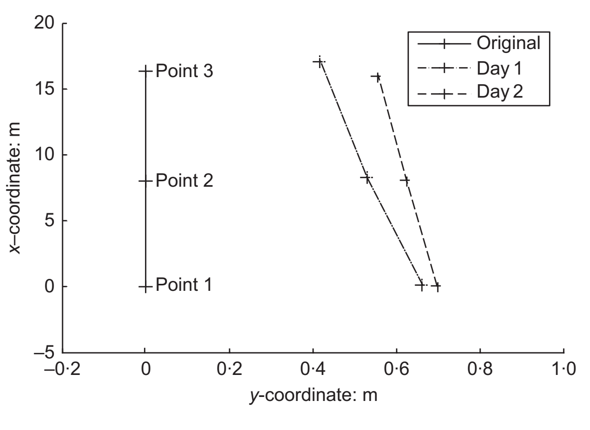

Figure 7. Mode shapes for the fundamental mode of vibration on each day

The additional non-structural elements may also have had the effect of increasing the damping in the building. This variation is investigated further in Section 4.3.

The mode shapes calculated for each test are shown in Figure 7. They show that there is a greater rotation of this part of the building on day 1. This is considered to be indicative of the diaphragm action of the concrete screed applied to the floors before day 2, which may reduce the extent to which the seven-storey block can bend in plan, and rotate relative to the five-storey block.

4.3 Analysis of weak non-linearity

The random decrement method was used to investigate the variation of modal parameters in the structure due to its weak non-linearity. The random decrement signature was obtained based on a pair of tests for point 1 in Figure 2 in the y direction, on each of the 2 days for which tests were carried out. Two tests, labelled test A and test B, were therefore carried out on the building on each day, at each stage of construction, to investigate the repeatability of the method. In each case, the random decrement signature was obtained using a range of threshold values. The single-channel modal analysis technique was then applied for each threshold level, and the variation of the calculated damping ratio with threshold level is plotted in Figure 8.

The range of threshold values which could be applied depended on the range of excitation during each test, and so the range varies between tests, as can be seen in Figure 8. It

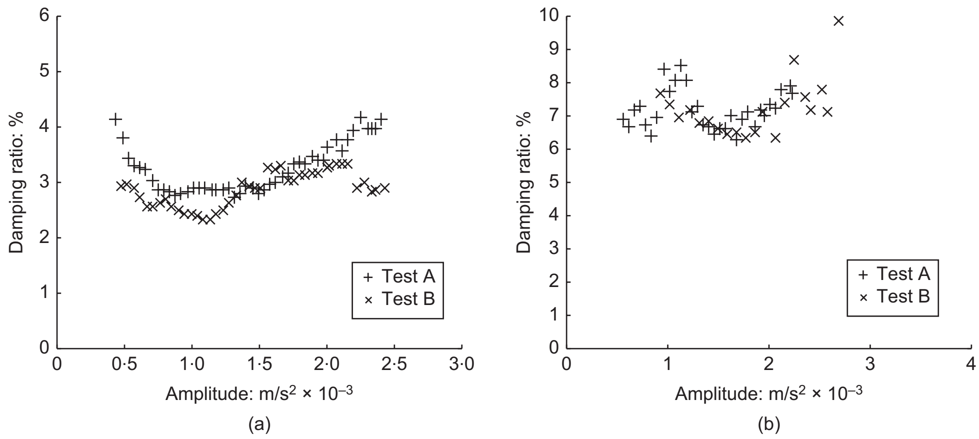

Figure 8. Varation of damping with random decrement threshold level for point 1 in the *y* direction on (a) day 1 and (b) day 2

can be seen that the damping for the day 1 tests tends to increase slightly with the magnitude of the threshold value. The results suggest some repeatability in damping ratios between the tests once the values of damping are related to amplitude in this way, as reported by Jeary (1996), although there is clearly still variation between the two tests on each day. The results are considered to be less reliable where the results from the two repetitions diverge at the higher and lower amplitudes. This magnitude of variation between tests on the same structure is otherwise consistent with other results in the literature (Li *et al.*, 2002; Tamura and Suganuma, 1996).

The results show that, that the measured damping ratios are substantially higher on day 2, and this is considered to reflect additional damping introduced by the non-structural elements added between day 1 and day 2.

5. Conclusion

This study has shown that output-only modal testing can be used to identify modal parameters for a multi-storey CLT building during construction. The unobtrusive nature of the test means that it is 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.

Tests on the same building at two stages of construction have shown the effect of non-structural elements, and of the amplitude of excitation, on natural frequency and 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. This study presents a set of measurements for a single building, and highlights the strong variation of damping with amplitude. This variation must be considered in tests on multi-storey timber buildings in the future, and damping measurements must be appropriately related to amplitude.

A simple predictive calculation has been carried out to assess the stiffness of the lateral load-resisting system, and estimate the natural frequency. Further study into frictional behaviour in the shear wall system, the behaviour of connections and the influence of perpendicular-to-grain loading under wind load would help to improve the accuracy of such calculations. The simplifications used in this analysis, however, have been justified by the accuracy of the predictions.

The effect of non-structural elements on the dynamic properties of this structure is substantial, and can be seen in changes in its natural frequency, damping ratio and mode shape. It is considered that, in the case of the natural frequency and mode shape, the changes are primarily due to the 55 mm concrete floor screed, which adds substantial mass, thus reducing the natural frequency, as is predicted by analytical calculation. It appears that there is also an effect on the mode shape, perhaps due to a diaphragm effect across the structure. In damping, an increase was observed after the application of various non-structural elements.

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