



Dynamic Properties of Treet

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1 Introduction

The Treet building in Bergen is the tallest habitable timber building in the world at 14 storeys high. It resists lateral loads through glulam trusses in the facades, a system which has only been used before in buildings up to about five storeys. The unusual nature of the building and the light weight of the wood construction led to a detailed study of its dynamic behaviour, carried out by Sweco and NTNU (Utne, 2013; Bjertnaes and Malo, 2014).

Our objective in this study was to experimentally measure the natural frequencies and damping ratios for the first three modes of vibration of the building. These parameters are then compared with those predicted theoretically in design for wind-induced vibration.

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1.1 Definitions

Accelerometer A device for measuring acceleration.

Channel A stream of data measured from a particular accelerometer in a particular direction.

Random decrement A method to analyse random vibrations in structures.

2 Method

Our main measurement consisted of two hours of data measured at a rate of 1700Hz, with accelerometers positioned at the outer edge of the 14th floor. The accelerometers were placed in a utility room at the end of the corridor, with the intention of measuring at a location closely connected to the glulam frame. This is the location of channels 1 and 2 in Figure 1. In this first test, three accelerometers were placed in this location, two measuring horizontally, and one measuring vertically.

We are confident that the floor finishes and any connection between the corridor, the frame and the modules which form the apartments will give sufficient diaphragm action to ensure that the measurements we have taken are representative of the whole floor, including the apartments.

A secondary measurement of half an hour's data was taken on the tenth floor, below the power storey, in the same plan location. This was to ensure that the signals we measured represented movement of the building as a whole, and not any local effects on one floor, or one stack of floors above the power storey. In this measurement, one accelerometer was moved along the corridor to a location approximately at the centre of the building, at channel 3 in Figure 1. This helped to confirm the torsional mode of vibration, since we would expect very little movement at the centre of the building in the torsional mode.



Figure 1: Plan of a typical storey, showing the location and direction of accelerometers and their channel numbers

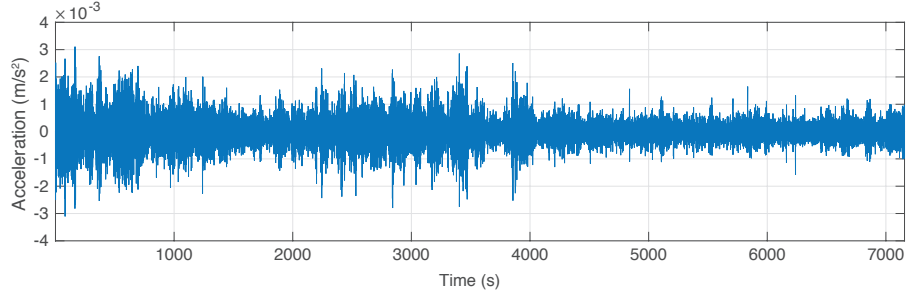


Figure 2: Measured acceleration over a two hour period for channel 1 as shown in Figure 1

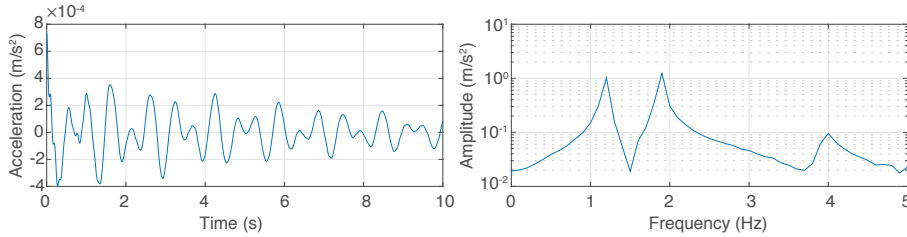


Figure 3: The estimate of the free vibration curve obtained using the random decrement technique for channel 1

A one-minute average wind-speed was measured with a simple rotational anemometer at three times during the afternoon. While this does not allow for a thorough comparison of

3 Results

The measured acceleration plot is shown in Figure 2. We used the Random Decrement technique (Cole, 1973) to obtain an estimate of the free vibration curve from the random vibration shown in Figure 2. In the left hand graphs of Figures 3 and 4 are the estimates of the decaying free vibration curves (acceleration against time), and on the right the frequency spectra for those curves. There is one pair of graphs for each perpendicular direction.

The frequency spectra show that the accelerometers were closely aligned with the direction of the first two modes of vibration, so that there is one clear peak at around 1Hz for each channel. That is, there is one mode of vibration in the north-south direction, and one in the east-west direction. In the north-south direction, there is a second peak at around 2Hz. Looking at Figure 1, we can see that the channel in the north-south direction would participate in a torsional mode, while the channel in the east-west direction would not. The peak at 2Hz

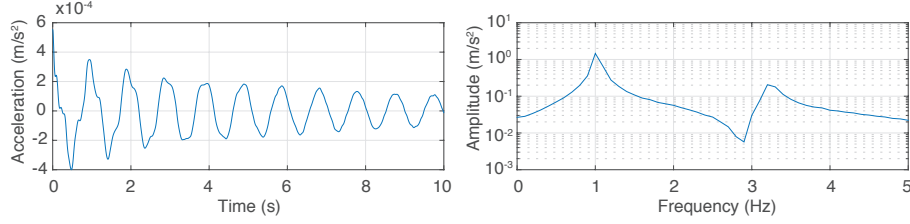


Figure 4: The estimate of the free vibration curve obtained using the random decrement technique for channel 2

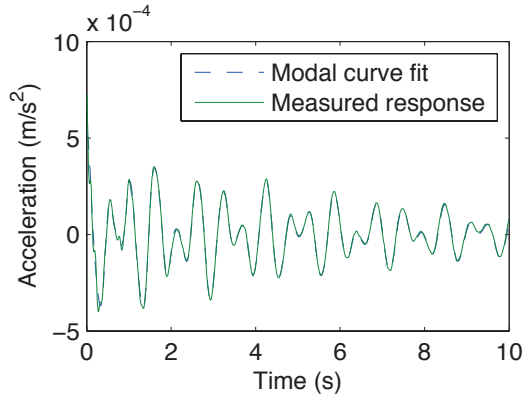


Figure 5: Fitting a theoretical curve for a three degree-of-freedom system to the estimated free vibration curve for channel 1

therefore seems a good candidate for the torsional mode.

The results in the two channels appear quite independent from one another, with different resonant frequencies in each one. It was therefore appropriate to analyse each channel independently using a single-channel model analysis technique. We used the Matrix Pencil algorithm. This fits a theoretical curve to the free-decay curve estimated using the Random Decrement technique. The fitting for the channel in the north-south direction is shown in Figure 5. The theoretical and measured curve can then both be transformed into the frequency domain to investigate the accuracy of the fitting of each frequency peak. This is shown in Figure 6, with magnitude plotted on a logarithmic scale.

This fitting allows the natural frequency and damping to be estimated from the tests, and the estimates are shown in Table 1. It is important that we note the amplitude of vibration at which these estimates were made, since it is well known that both frequency and, to a greater extent, damping vary with amplitude, so these measurements only strictly apply to the conditions at which they are measured.

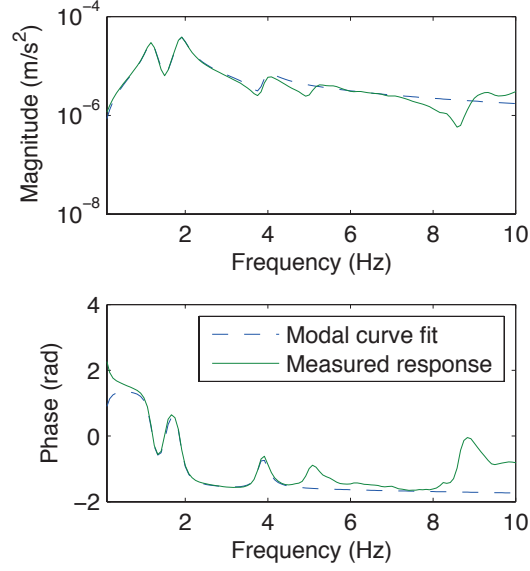


Figure 6: The frequency spectra for the measured and fitted curves in Figure 5

Table 1: Estimates of natural frequency and damping ratio for each of the first three modes of vibration based on these tests, along with the associated root mean square (RMS) magnitude of the vibration measured in that channel

	RMS Amplitude mm/s ²	Frequency Hz	Damping %
Mode I (North-south)	0.1-0.8	1.02-1.03	1.6-2.4
Mode II (East-west)	0.2-1.4	1.17-1.19	1.1-1.6
Mode III (Torsion)	0.2-1.4	1.86-1.89	0.7-1.4

4 Discussion

Bjertnaes and Malo (2014) predicted the modal properties of the building based on stick-frame modelling. The predicted natural frequencies are shown in Table 2. The model predicts the order of the modes correctly, with the lowest frequency in the north-south direction, then the east-west lateral mode, followed by the torsional mode. The difference between frequencies is also well predicted.

Experimental natural frequencies are consistently about 30 to 35% higher than those predicted. Since the frequency is proportional to the square root of stiffness, this suggests a stiffness approximately 90% higher than predicted. There are two possible reasons for this:

- for the very small movements associated with wind-induced vibration, it may be that non-structural elements make a substantial contribution to the dynamic stiffness of the building;
- the stiffness of this structure is largely dependent on the stiffness of the dowel-type connections, and the Eurocode 5 prediction of stiffness may be a substantial underestimate in this case.

For cyclic loading under serviceability loads, it has been shown that the stiffness of dowel-type connections can be far higher (by as much as five times) than its stiffness under static loads (Reynolds et al., 2013a). Consequently, the Eurocode 5 prediction of stiffness of dowel type connections, which was intended to predict static stiffness, can be a substantial underestimate (Reynolds et al., 2013b).

The damping ratios measured during these tests were in some cases lower than the 1.9% used in design, which was based on guidance in Eurocode 5 (BSI, 2009) for timber bridges. As noted in the previous section, however, the damping ratio is particularly sensitive to amplitude of vibration, and damping increasing with amplitude.

The root mean square amplitude of vibration during these tests rose to about 1.4 mm/s^2 , as shown in Table 1. Assuming a peak factor of four, approximately the value calculated for this location by Bjertnaes and Malo (2014), this would correspond to a peak amplitude of about 5.6 mm/s^2 . This is about a tenth of the limiting vibration given in ISO 10134 ISO (2007). It is reasonable to assume that the damping ratio would have risen above 1.9% in all modes with this tenfold increase in amplitude. The value of damping used in design therefore appears to be an appropriate, and not over-conservative value. It is notable that the damping in this fitted-out building is not higher than that for a bridge, which contains far fewer non-structural elements.

5 Conclusion

Our results show that the results of modelling carried out during the design of this building are reflected in its measured behaviour. The true dynamic stiffness

Table 2: Comparison of predicted natural frequency and damping ratio with those estimated based on these tests

	Measured Frequency Hz	Predicted Frequency Hz	Measured Damping %	Design Damping %
Mode I (North-south)	1.02-1.03	0.75	1.6-2.4	1.9
Mode II (East-west)	1.17-1.19	0.89	1.1-1.6	1.9
Mode III (Torsion)	1.86-1.89	1.37	0.7-1.4	-

of the building is substantially higher than the model suggested, however. We suggest that an underestimate of the dynamic stiffness of the connections may go some way to explaining this difference, and the authors would be pleased to work with the engineers and NTNU to investigate this further.

Damping ratios are notoriously difficult to estimate, but it seems the value used in design, based on guidance for bridges, was reasonable. Further experimental studies could instrument the building over a longer time, therefore capturing the movement of the building under higher wind loads and measuring the damping at higher amplitudes. A continuous measurement of wind speed could also correlate the magnitude of vibration with wind speed for comparison with theoretical predictions. The more sophisticated study proposed by NTNU could bring out this information, as well giving more detail, in the form of mode shapes, on how the building is moving, and therefore on the contribution of different parts of the structure to its stiffness.

References

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