Wind-Induced Vibration of Cross-laminated Timber and Light Timber Frame Structures

Introduction

Dr Tom Reynolds spent 10 days in May 2014 working with the research group led by Dr Roberto Tomasi at the University of Trento. They collaborated on modal testing and analysis of two five-storey timber apartment buildings, and on comparison of a range of output-only modal analysis techniques applicable to measurements of structures excited by ambient loads.

Collaborative compatibility

The universities of Bath and Trento have established research groups in timber engineering. Research at the University of Bath has investigated non-metallic connections, timber-concrete composites, fire and creep performance of connections and serviceability behaviour of timber structures. The latter is the subject of Tom Reynolds's research, and in his ongoing research, he is using the results of modal tests of multi-storey timber buildings to better understand their in-service movement. Through this work, he hopes to inform the design of taller timber buildings in the future, by providing information on damping ratios and lateral stiffness.

The University of Trento has been an important centre of research into the behaviour of timber structural systems under cyclic load [1-4], through the work carried out there on seismic loading, led by Dr Roberto Tomasi. A notable aspect of their current research is the development of design equations for strength and stiffness of timber shear wall systems constructed using either sheathed stud-and-rail walls or cross-laminated timber [2]. The equations are based on the standardised properties of the timber and connectors, and therefore can provide a valuable tool to engineers for building design. So far, this research has focussed on the strength and stiffness under seismic load, and so incorporates plastic behaviour of connections, but neglects frictional effects.

Under the lower loads and displacements associated with serviceability vibration, particularly in CLT construction, friction between elements may mean that connections are not loaded at all, and require a different formulation of stiffness. This formulation was discussed as a potential area for collaborative work, and experimental work planned at both institutions has the potential to help develop such equations. Tom Reynolds and Daniele Casagrande will continue to look for opportunities for joint work and publications in this field.

Dr Tomasi's research group is currently studying dynamic behaviour in a pair of 5-storey buildings, both of which have a timber structure resisting gravity loads and a reinforced concrete core. The buildings are shown in Figure 1. One of the buildings has a CLT structure, and one a sheathed stud-and-rail timber frame. This visit has enabled measurement of natural frequency and damping in both of these buildings by an ambient vibration method established on a previous STSM to Linnaeus University in Sweden. This has given a valuable insight into the relative performance of the two systems, and served to validate numerical models created for the two buildings by Masters students at the University of Trento.

Figure 1 - The ITEA buildings in Gardolo, Trento

Summary of achievements

The key achievements of the STSM were:

- to measure vibration, and identify basic modal properties, including natural frequency, damping and mode shapes, in both plan and elevation of the two 5-storey timber buildings;
- collaboration with Dr Tomasi and Daniele Casagrande in applying output-only analysis methods to these measurements, and discussing the potential for use of such methods for the floor vibration measurements they will carry out on the same buildings;
- discussion of future experimental and analytical work on CLT shear wall systems in with Dr. Tomasi's research group at the University of Trento;
- a funding application for the Council for Tall Buildings and Urban Habitat (CTBUH) Research Seed Funding, for a study into megaframe timber structures for tall buildings; and
- a planned jointly-authored journal paper in the Construction and Building Materials special edition on structural health assessment of timber structures.

Previous and planned research by the University of Trento

The ITEA buildings in Gardolo, Trento, were a particularly good opportunity for application of output-only ambient vibration analysis to timber structures, since they enabled comparison of the behaviour of sheathed stud-and-rail timber shear walls with cross-laminated timber shear walls. As a result of competing political influences, this pair of apartment buildings was built in two different structural systems, whilst being otherwise identical in their floor plans, window and door openings etc.

Dr. Tomasi's research group has carried out extensive research into the behaviour of timber shear wall systems, both in CLT and sheathed stud-and-rail systems. The design equations developed by the group are verified by full-scale tests on shear walls. The group's commitment to timber engineering is shown by the fact that their reaction frame is constructed from glulam rather than steel, as shown in Figure 2.

The two ITEA buildings had been a subject of research work at the University of Trento into their lateral vibration under seismic action. Numerical models for modal analysis were created for each building based on the theoretical models for timber shear walls stiffness developed by the timber research group. It was anticipated that these models would not correspond precisely with the ambient vibration tests, since they were intended to represent the behaviour under seismic action, in which frictional contact contributes little to the transfer of forces between elements, meaning that the stiffness is defined by the stiffness of the nailed or screwed connections. Under the conditions of the ambient vibration tests, in which gravity loads would be high in comparison with the lateral loads, it was expected that the majority of lateral shear loads would be transferred by direct contact and friction, resulting in a higher stiffness than the connections would provide.

Figure 2 - Glulam reaction frame in the University of Trento's structural laboratory

Researchers at the University of Trento had already planned a series of tests comparing the performance of the floors in each building. The CLT building has CLT floor panels, while the light timber frame building has floor joists. Both have a concrete topping with shear connectors to give composite action between the floor and the topping. The building structures were complete at the time of the tests. Cladding, plastering and floor finishes had been applied, but the buildings were unfurnished, and some plumbing work was in progress. The equipment used for the tests is shown in Figure 3.

Figure 3 - Test equipment in place on the top storey of the CLT building – the reference accelerometers are shown, as is the battery, data acquisition system and laptop, with the roving accelerometers elsewhere on the structure

Ambient vibration tests

Measurements were taken at the locations around the structure shown in Figure 4. Four accelerometers were used. Two were placed at the reference location 4A, and remained in place there for every test. The other pair of accelerometers were moved between each test. Thus the results at each location could be scaled based on the magnitude of the response in the reference channel, and the reference channel was chosen as one of the two channels at location 4A. The reference channel was chosen based on the measured results, ensuring that a significant contribution was observed in each mode in that channel, so that each mode could be accurately scaled.

The accelerometers were placed at the locations around the structure in sequence, recording for 30 minutes at each location. Measurements were taken at pairs of locations simultaneously, with cables running between the two locations in the pair. The accelerometers are not attached to the structure, they are simply placed on the floor on an aluminium bracket, and the weight of the accelerometer and bracket holds them in place.

The accelerometer locations are shown in Figure 2. The location on the 4th floor is chosen for the reference channel, since it is a location which is expected to move significantly in the first lateral and torsional modes of vibration. Measurements at the three other corners of the building enable plan mode shapes to be estimated.

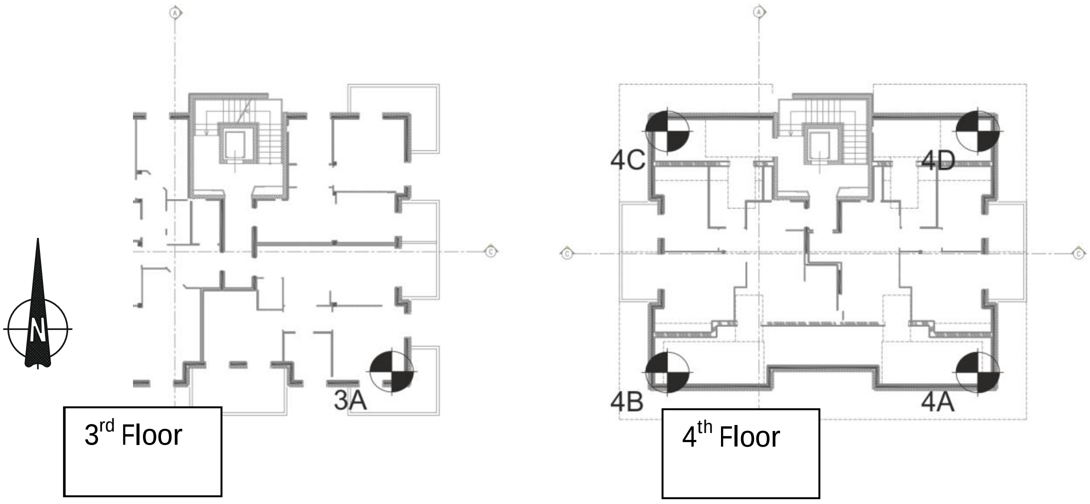

Figure 4 - Accelerometer locations

The tests were carried out as shown in Table 1. Locations 2A and 1A were located on the 1st and 2nd storeys under 4A and 3A for inspection of vertical mode shapes. Tests 4 to 6 were carried out only in the CLT building. For each test, 30 minutes of data was recorded at 1500Hz. This data could then be resampled to lower sampling frequency, with appropriate filtering to avoid aliasing, for the purpose of analysis. It was useful to have raw data at a high sampling frequency, which could be resampled to a range of different frequencies, since the sampling frequency was seen to have an effect on the results of the numerical modal analysis techniques, as described below.

Theory of Modal Analysis

A key element of the collaborative work between Tom Reynolds and the research group at Trento was the comparison of the time-domain modal analysis methods applied by Tom for ambient vibration testing of buildings with the frequency-domain methods used by Trento for analysis of shake-table tests on CLT buildings. Tom had applied the Ibrahim Time Domain (ITD) method [6] and Stochastic Subspace Identification (SSI) [7], while the Trento group had an established method for application of Frequency Domain Decomposition (FDD) [8]. All methods are suitable for output-only modal analysis, which means that they can be used without information about the excitation applied to the structure.

Table 1 - Test schedule

Test Number	Locations (Directions)
1	4A(N+W) and 4B(N+W)
2	4A(N+W) and 4C(N+W)
3	4A(N+W) and 4D(N+W)
4	4A(N+W) and 3A(N+W)
5	4A(N+W) and 2A(N+W)
6	4A(N+W) and 1A(N+W)

Tom and Dr Casagrande applied all of these methods to a set of synthesized data for a multi-degree-of-freedom system, so that the modal properties to be identified were known in advance. This process gave a valuable insight into the limitations of each method. Particularly important was the sensitivity of the ITD and SSI methods to the sampling frequency. As a result, Tom's methods were modified to ensure that the ITD and SSI methods could be applied to resampled data at different sampling frequencies to ensure that all relevant modes were identified.

Application of the FDD method to the measured ambient vibration data from the buildings showed the potential for use of that method for ambient vibration testing.

The ITD method is applied to the free-decay response of a system, and Tom was able to introduce the Trento group to an averaging process used to extract a signal closely related to the free-decay response from ambient vibration data. This process is called the random decrement method [5], and uses the averaging of a series of samples taken from the data, all of which start with a particular trigger value of acceleration.

Results

The first three modes of vibration of the timber frame building are shown in Figure 5. It can be seen that the first two modes are primarily lateral movement of the structure. The first mode includes some rotation due to the eccentric stiffness provided by the concrete core, which is in the middle of the right hand edge of the rectangle. The third mode is torsional. This type of information is useful for seismic engineering of the structure, since design for seismic forces aims to ensure that the first two modes of a multi-storey building are lateral movement. This is done because seismic forces in torsional modes of vibration lead to high shear forces in the lateral-load resisting system. While seismic design is not the primary focus of this work, it is noted as a potential further application of the results.

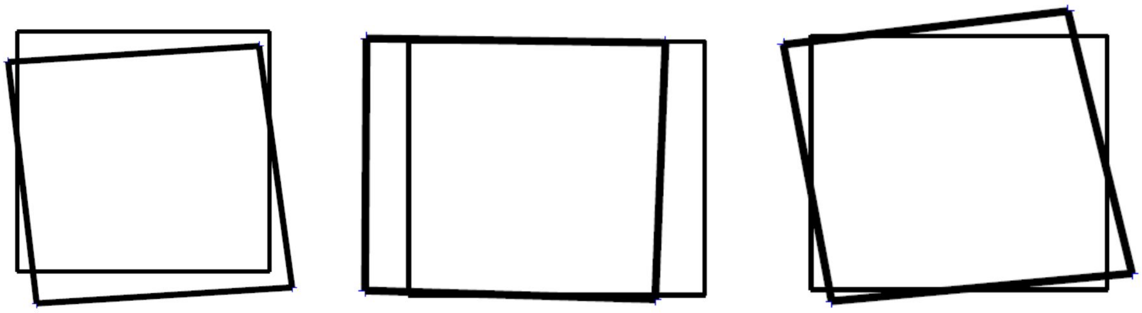

Figure 5 - The first three modes of vibration of the timber frame building

The first three modes of vibration were all characterised by in-phase movement of all the accelerometers placed vertically through the building at points 4A to 1A, as shown in the left-hand plot of Figure 6. A fourth mode of vibration was also evident, which exhibited out-of-phase movement, with points moving in opposing directions.

Figure 6 - The first and fourth modes of vibration measured through the height of the building

The frequencies of the modes which were measured are shown in Table 2. In both structures, the order of the mode shapes is the same as in Figure 5. There is only a substantial difference in the natural frequency for the third, torsional mode of vibration. It is considered that the higher frequency in the frame structure may be due to the lower mass of the frame walls around the outer edges of the buildings in comparison with the solid CLT walls.

Table 2 - Modes of vibration obtained from the global Ibrahim Time Domain method

	CLT		Frame	
Mode	Frequency	Damping	Frequency	Damping
	Hz		Hz	
1	4.02	8.29%	4.15	5.19%
2	5.01	7.48%	4.88	7.86%
3	5.65	4.74%	6.26	5.05%

Outputs of STSM

The STSM is expected to produce the following outputs over the course of the coming months:

An immediate opportunity for dissemination of the results of this STSM was given by the COST early stage researchers' conference on Experimental Methods in Timber Engineering in Prague in May 2014. Tom attended that conference to present this work.

For input-output modal testing using a shake table, the Trento research group had developed a graphical user interface (GUI) in Matlab, to allow fast processing of data to obtain modal properties. This had proved useful for streamlining the modal analysis process, particularly for obtaining results during the testing process, to check the quality of data obtained. It was agreed that it would be beneficial to both research groups to develop a GUI to carry out the range of output-only techniques used during this mission. The aim is to produce this code before the end of Tom's current postdoctoral role in October 2014.

It was considered that the comparison between the numerical modelling carried out by the University of Trento and the test results obtained during this mission could form the basis of a paper submission to a peer-reviewed journal. The forthcoming special issue of Construction and Building Materials on timber structures, which is open for submissions until the end of 2014, is targeted.

References

[1] Casagrande, D. (2014). Study of Timber-frame Building Seismic Behaviour by means of Numerical Modelling and Full-scale Shake Table Testing. Ph.D., University of Trento.

[2] Casagrande, D., S. Rossi, T. Sartori and P. R. Tomasi (2014). "Analytical and backup Numerical Modelling for Linear Elastic Response of Single-storey Timber Shear Walls Subject to Horizontal Force: a Unified-iterative Approach. Engineering Structures (under review).

[3] Tomasi, R. and T. Sartori (2013). "Mechanical behaviour of connections between wood framed shear walls and foundations under monotonic and cyclic load." Construction and Building Materials **44**: 682-690.

[4] Piazza, M., Polastri, A. & Tomasi, R. Ductility of timber joints under static and cyclic loads. Proceedings of the ICE - Structures and Buildings, 164 (2): 79-90, 2011,

[5] Brincker, R., Kirkegaard, P. H. & Rytter, A.: Identification of System Parameters by the Random Decrement Technique. Instituttet for Bygningsteknik, Aalborg Universitetscenter 1991.

[6] Ibrahim, S. R. 1999. Fundamentals of Time Domain Modal Identification. In: SILVA, J. M. & MAIA, N. M. (eds.) Modal Analysis and Testing. Springer Netherlands.

[7] Ceravolo, R. and G. Abbiati (2012). "Time Domain Identification of Structures: Comparative Analysis of Output-Only Methods." Journal of Engineering Mechanics **139**(4): 537-544.

[8] Brincker, R., L. Zhang and P. Andersen (2001). "Modal identification of output-only systems using frequency domain decomposition." Smart materials and structures **10**(3): 441.