Modal analysis of cross-laminated timber buildings

Short term scientific mission by Thomas Reynolds, of the University of Bath, UK to Linnaeus University, Växjö, Sweden, between 5th and 19th June 2013

Purpose of the Short Term Scientific Mission

The enhancement of particular structures, or of current materials and design practices, requires a clear understanding of their performance in their current state. The structural investigation into that state may, for simple structures or those in which visible decay or damage is to be remedied, take the form of visual inspection. An investigation of new structural forms might include load testing of components or complete structures, but to more thoroughly understand the way a new structural material or system behaves as part of a complete building, it is necessary to carry out tests once it is fully constructed, fitted-out and occupied.

Under this short term scientific mission, a test method particularly well-suited to completed, occupied structures was used: modal analysis by ambient vibration measurement. It was applied to one of the Limnologen buildings, in Växjö, Sweden, a structure which uses cross-laminated timber and post-tensioning in a structural system capable of creating efficient mid-rise timber buildings. At 8 storeys, the building is among the tallest timber buildings in the world, so presents a valuable opportunity to understand how this enhanced structural form is behaving in service.

Description of Research

The analysis of the Limnologen building is described as output-only modal testing. This is because the input forces which cause the movement of the building are not quantitatively known: the movement of the building is measured using accelerometers placed on the structure to record its vibration due to the ambient dynamic loads applied to it, such as turbulent wind load, footfall of building occupants and vibration of machinery. A photograph of the sensors and data acquisition equipment is shown in Figure 1.

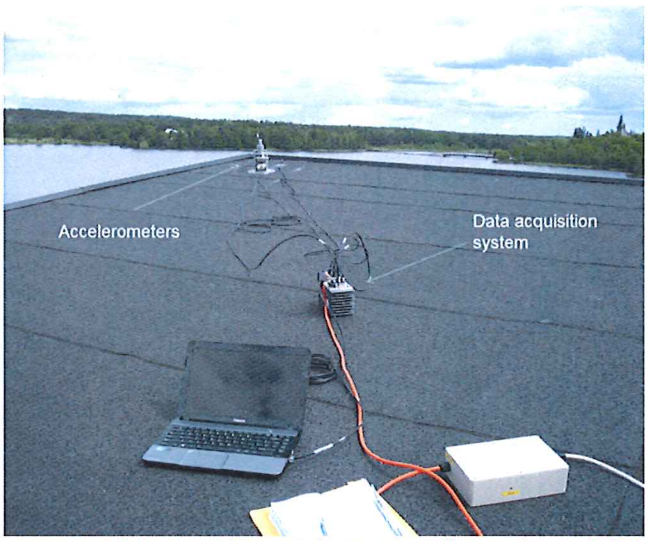

Figure 1 - Sensors and data acquisition equipment installed on the roof of the structure

The accelerometers used were specific to low-frequency small-amplitude vibration, designed to measure frequencies between 0.1Hz and 1500Hz. Three of these uniaxial accelerometers were available, and so in order to correlate sufficient measurements for estimation of the mode shapes of the structure, a technique was used in which a single accelerometer was used as a common reference point, while the others were moved to different points around the roof of the structure.

This method presents very little disruption to the normal use of the structure. In fact, the normal use of the structure is useful in providing the excitation force. The measured accelerations could then be used with modern output-only modal analysis techniques to identify the natural frequencies and mode shapes of the structure, which describe the real as-constructed distribution of stiffness in the structure and the way it deforms under load. The results are particularly applicable to the lateral in-service vibration of the structure, which, as taller timber structures are envisaged and designed, has the potential to become an important design criterion.

Another product of the analysis is the damping ratios for each mode of vibration. These are parameters which are crucial for the design of a structure for vibration, but which are very difficult to predict at the design stage. In conventional structural materials for multi-storey construction, tests have been carried out on many buildings completed in that form, so that approximate values of damping can be provided in design codes. The Eurocode gives no guidance on damping for multi-storey timber buildings, and so these results give a new insight into the behaviour of an enhanced structural form using cross-laminated timber and prestressing.

Results

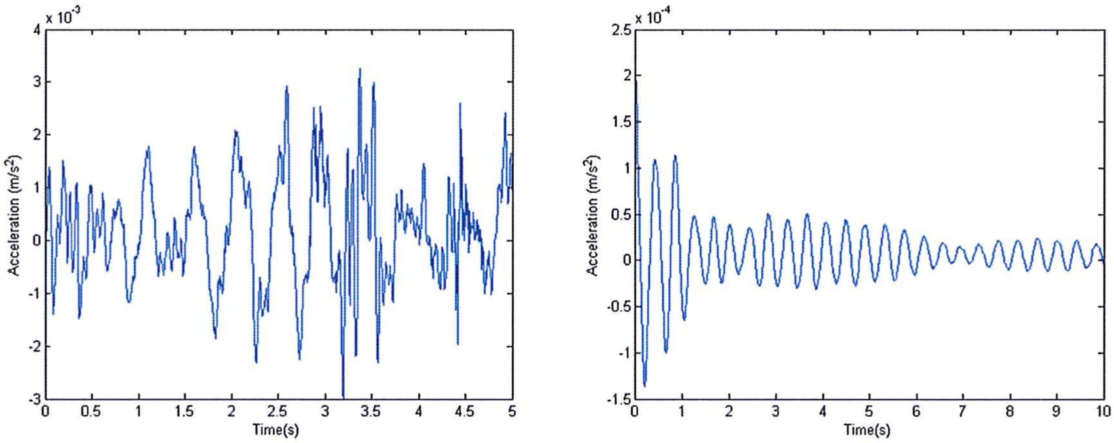

Figure 2 - Measured acceleration under ambient load (left hand plot), and free decay data extracted by averaging (right hand plot)

The first result of the experimental work was to show that output-only modal analysis clearly identified the dynamic response of the structure in its lateral modes of vibration. Figure 2 shows the free-decay response extracted from the measured accelerations. The beating phenomenon, in which the amplitude of the signal increases and decreases, indicates two closely spaced modes of vibration. A range of vibration modes were identified, giving a clear frequency response function for the structure at several points up to a frequency of 100Hz. The frequency response functions in the three orthogonal directions for a point on the outer edge of the roof of the structure are shown in Figure 3. The accelerometers proved sensitive enough to measure this response even in the very light winds of the first day of testing, which were around 2 or 3ms^{-1}.

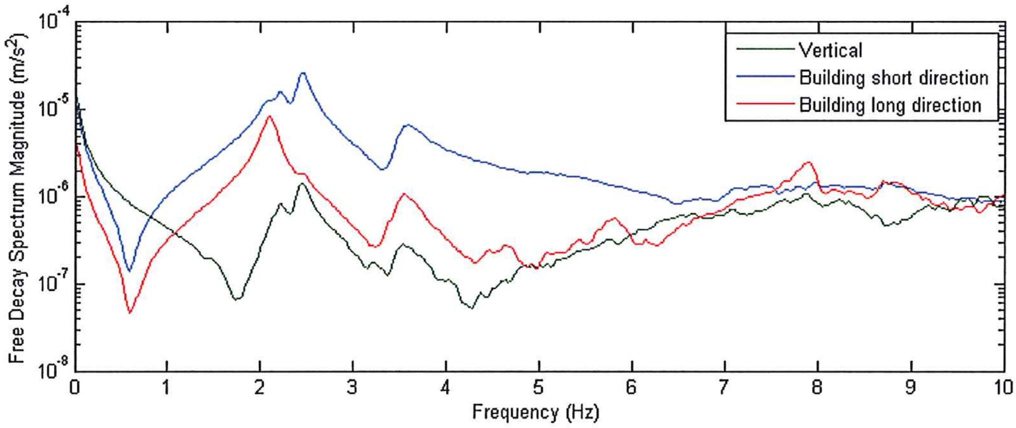

Figure 3 - Frequency spectra for three orthogonal directions for a single point on the outer edge of the roof

The lowest natural frequency of the structure was apparent at approximately 2Hz, though the largest amplitude of movement was measured at another very close mode. Correlation of these measurements from around the structure showed that these two modes represented global movement of the structure, showing that, while the structure had been designed for lateral stability in three separate units, the non-structural connection between them provided enough stiffness under small-amplitude movement to ensure that the whole building acted as a complete structural unit.

Future collaboration

This project has represented a sharing of resources and knowledge between the University of Bath and Linnaeus University for the purpose of understanding how contemporary multi-storey timber buildings behave. It has revealed a shared interest in more thoroughly understanding their dynamic behaviour, and filling the gap in knowledge regarding their true stiffness and damping, which currently prevents accurate design by engineers.

Initially, collaboration between the institutions will continue on the further analysis and presentation of results from these tests. There exist opportunities for further analysis of these structures, and the expertise gained by researchers from both institutions can potentially be used to study modern timber structures in the UK and Sweden.

Publication

It is intended that these results be published to disseminate the details of the method successfully used on this mission, and to form a basis for further study which could lead to accurate design criteria as the cutting-edge design methods in the Limnologen buildings are further refined and enhanced to create the multi-storey timber buildings of the future.

Confirmation by the host institution (by Prof. Erik Serrano)

Mr Thomas Reynolds has during his two-week stay at Linnaeus University, from June 5th – June 19th, been able to perform the work set out in the planning of this STSM. The work performed has contributed in general to our knowledge about measurement methods available, and in particular to our knowledge about the dynamic behaviour of mid-rise timber buildings. Mr. Reynolds has shown excellent collaboration skills, and with his open-minded approach I can foresee great potential in future collaboration between the research groups of the University of Bath and Linnaeus University.

On behalf of the host institution:

Erik Serrano, Professor