COST Action FP1402

Basis of structural timber design - from research to standards

Short Term Scientific Mission Report

Measuring wind-induced vibration of tall timber buildings and towers

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Contents

1. Purpose of the Short Term Scientific Mission (STSM)

As a widely used construction material, timber has been applied to building structures around the world. With ongoing development and research in timber products and material science, today timber has the potential to be widely used in tall structures. Tall timber buildings offer the benefits of a sustainable, carbon storing material for the load-bearing as well as secondary structure, efficient prefabrication and transport, a high quality interior climate and room atmosphere, and flexibility in architectural design. The development of modern wood-based products like Glulam or CLT makes it possible to improve material strength and create all types of construction elements like efficient cross sections or timber-based slabs and plates. This opens up new possibilities for construction types of timber buildings that have been applied in conventional high-rise buildings made of steel or concrete using higher strength columns in frame construction or planar elements in solid timber construction (Kolb et al., 2008).

The strength-weight ratio of timber is quite favourable compared to steel and concrete, which makes it possible to also aim for economical buildings constructed of timber. However, one of the key issues when designing a tall timber building is its lateral stiffness and response to horizontal loads. Since timber buildings have a lower stiffness and inertia than conventional high-rise structures, they are more sensitive to lateral loads and horizontal vibrations. Concerning the wind-induced lateral movement of tall timber structure during normal operation, the vibration can cause discomfort to residents or building occupants. Furthermore, wind-induced vibration can also lead to the damage of non-structural elements. For timber buildings, these serviceability design criteria might become decisive for much lower heights than for conventional tall buildings. Especially with plans to increase the height of timber buildings even more, it is significant to study their dynamic behaviour under wind load in design stage like it is done for conventional high-rise buildings. The designer can access reference values given in design codes for e.g. the damping factor of steel and concrete buildings depending on construction type. However, there is only little knowledge about the dynamic properties of tall timber structures under wind load (Smith and Frangi, 2008, Reynolds et al., 2015, BSI, 2005).

The key dynamic properties of a structure are natural frequency, lateral stiffness and damping capacity. The natural frequency depends on the lateral stiffness and the mass of structure, e.g. Xue et al. (2009) tested a 3-storey timber structure and found the natural frequency could be changed by adding bracings and causing damage to the structure. Brincker et al. (2004) demonstrated that the natural frequency decreased with the increasing of mass. Damping ratio can present the ability in energy dissipation. According to Reynolds et al. (2015), damping measurements are in dependence of amplitude of excitation. It is important to get a deep understanding of the influence of structural types, connection types, non-structural elements, excitation amplitude etc. on natural frequency, lateral stiffness and damping capacity. Therefore, it is vital to study the performances of existing tall timber buildings and towers exposed to wind-induced vibration so as to relate these to design stage.

Vibration testing of existing structures offers a great potential in gaining knowledge about dynamic properties. There is a wide variety of methods to conduct the tests and to analyse data after measurement. Experience has shown that ambient vibration testing is applicable to derive dynamic properties of especially large, flexible structures with low natural frequencies and therefore suitable for testing timber buildings. In contrast to forced vibration testing, ambient vibration testing makes use of the natural vibrations of a structure. Therefore the structure does not have to be excited artificially, which offers the advantages of higher efficiency, less disruption of the normal building operation, no damage to the structural members and the possibility of a dynamic analysis under normal conditions without influence of forced excitation (Geier, 2004, Reynolds et al., 2015).

The research group, which applicant belongs to, has already measured 5 multi-storey timber structures in Italy, the UK and Sweden. A database has been built so as to inform engineers about these important information. The data measured from the structures financed by this STSM can greatly contribute to this database, because there are different types of timber buildings and towers in Germany which can be thoroughly studied and compared. The host institute, ARUP Berlin, is a leading institute for structural design, and has a professional group developing timber structures. Through the collaboration with ARUP Berlin, they can provide the permission to LCT ONE building for measurement and also the information from engineering aspects. Constructive suggestions from ARUP Berlin concerning the measurements can help to close the gap between design practice and academic research. The results from this STSM will inform the host institute the performances of existing timber structures as well as their modal properties after analysis. Engineers can relate these useful information to design criterion. From the view of research, the understanding of real performances of timber structures helps the verification for structural modelling and explores the potential for developing new structural forms and elements.

2. Description of the work carried out during the STSTM

In this STSM, a total of 12 tall timber structures including timber towers and tall timber buildings in Germany and Austria were measured in order to study the dynamic response. ARUP Berlin offered the permission and information of LCT ONE, and advised during the selection of tall buildings and towers in Germany.

2.1 Timber structures measured in this STSM

11 timber structures with different types in Germany and one in Austria were measured, and the information are tabulated in Table 1. The locations of these timber structures are marked on a map in Figure 1.

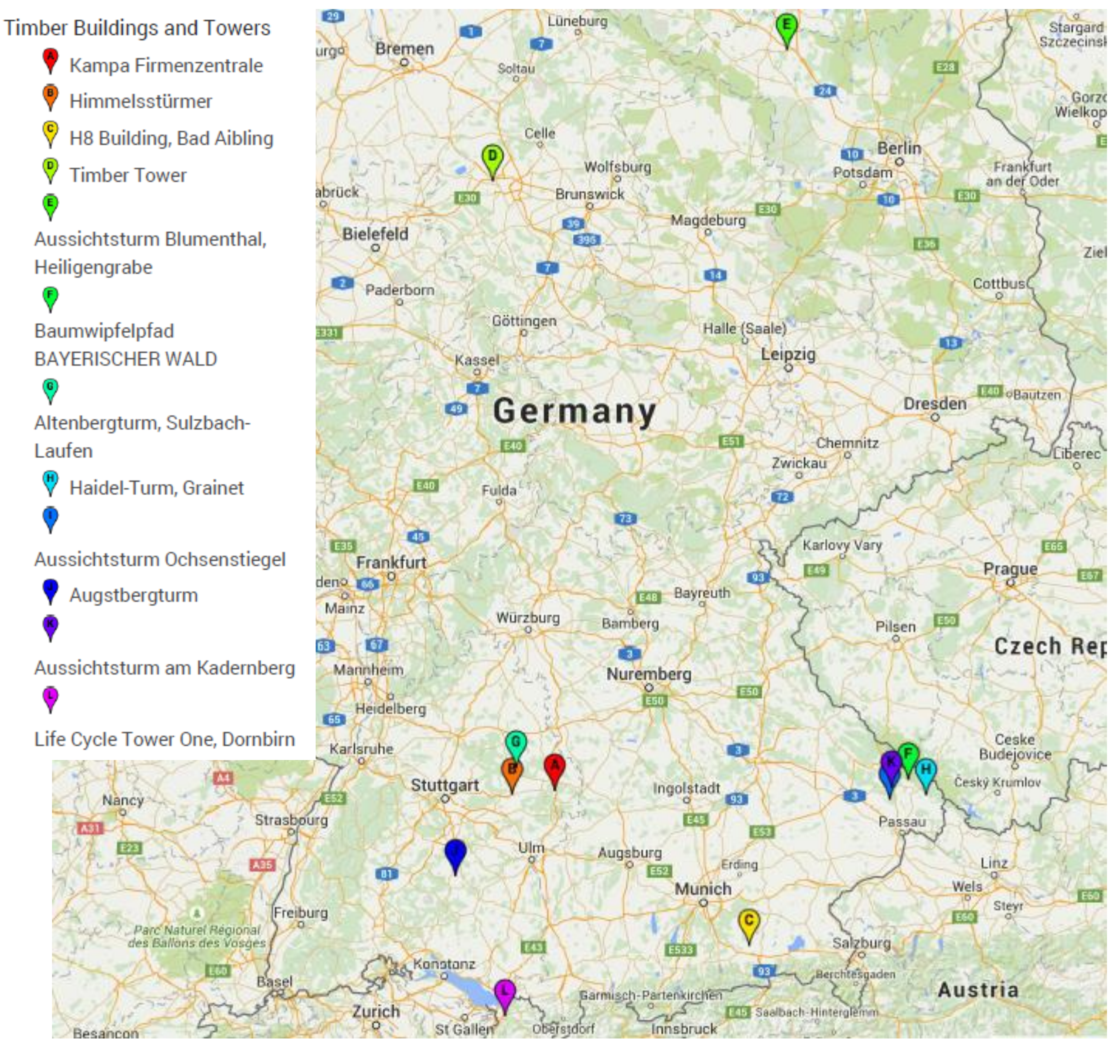

Figure 1 Locations of measured timber buildings and towers

Table 1 Information of the timber structures measured in this STSM

	Name of building/tower	Location	Pictures	Height [m]	Width [m]	Length [m]
Building	LCT ONE	Dornbirn, Austria	 (Müller et al.)	26.8	12.2	23
	KAMPA	Aalen, Germany	 (GmbH, 2015)	26.4	11.8	38
	H8	Bad Aibling, Germany		24.4	12.1	21
Tower	Altenbergturm	Sulzbach-Laufen, Germany		38.3	8.6	8.6
	Himmelsstürmer	Schwäbisch-Gmünd, Germany		38.3	5.4	5.4

Augstbergturm	Trochtelfingen-Steinhilben, Germany		20	4.4	4.4
Blumenthaler Aussichtsturm	Heiligengrabe, Germany		45	5	5
Timber Tower	Hannover, Germany		100	7	7
Ochsenstiegl	Thurmansbang, Germany		25	5.5	5.5
Aussichtsturm am Kadernberg	Schönberg, Germany		30	5.5	5.5

Haidelturm	Grainet, Germany		30	5.75	5.75
Baumturm	Neuschönau, Germany		44	35.5	35.5

2.2 Measurement set-up

The equipment used in these vibration measurements can be divided into three parts, which function in data input, data logging and data output, respectively. Data input part consists of three piezoelectric accelerometers as shown in Figure 2 (a). They have a nominal sensitivity of 10V/g and a lower frequency limit of 0.1Hz. The supports for the accelerometers are made of aluminium and are heavy enough to prevent relative motion to the surface. The vibration acceleration can be recorded in three dimensions in one point, or in one direction in three points. The data collected by the accelerometers are saved in the data logger powered by a battery as presented in Figure 2 (b). A software LABVIEW operated on the laptop in Figure 2 (c) can show the real-time vibration acceleration, and is used for setting measurement duration and sampling rate. For each measurement, the duration is 40 minutes. The final data exported from the laptop are acceleration over time in the unit of m/s^2.

2.3 Measurement procedure

2.3.1 Timber buildings

For timber buildings measurement, the sensors are expected to be placed on the highest position of the structure such as roof, as it helps to assess the highest vibration amplitude of the whole structure especially in first mode shape. For some timber buildings like KAMPA building and H8 building, the roof was hard to access because of the occupation of the solar power equipment, the accelerometers therefore were placed on the top floor.

A reference measurement point was set in timber buildings measurement. As shown in Figure 3, the measurement reference point is marked as B on the roof plan and top floor plan of LCT ONE building and H8 building. For each point measurement, the reference point was measured in two horizontal directions and measurement is able to be transformed into a common scale. In terms of the concrete core or timber core in the timber structure, they play an important role in the lateral vibration as they have higher stiffness than timber part; measurements in point A and point B therefore can be compared (Figure 3). All measurement tests for timber buildings are tabulated in Table 2.

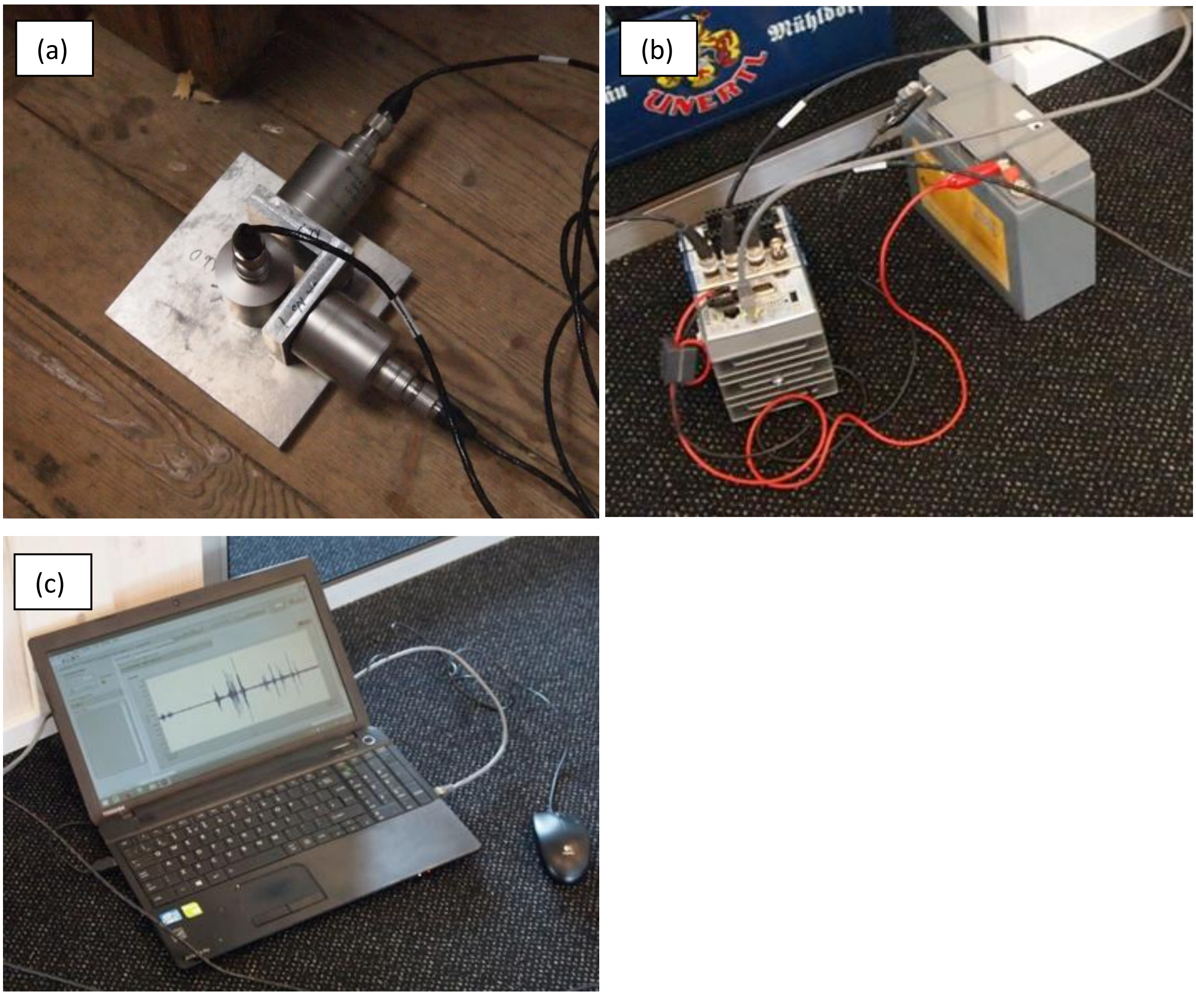

Figure 2 Vibration measurement equipment (a) Accelerometers; (b) Data logger and battery; (c) Laptop

Concerning the long length in longitudinal direction of KAMPA building which is 38 meters, it is important to measure, if asymmetrical movement occurs in short direction. Therefore, measurement points were distributed along longitudinal length as seen in Figure 4 marked as C, D and E, and the ambient vibration in short direction were measured. The same measurement was done in H8 building as well. Points F, J and K allocated on 6th, 5th and 4th floor respectively were measured in two horizontal directions in KAMPA building shown in Figure 4. Measurements in different height can contribute to study the mode shape.

For each building, the timber floor vibration was also measured in order to examine the damping capacity. The measurement duration was one minute, and the direction of accelerometer was vertical. In the first half minute, the floor vibration was triggered by jumping for three times, and the person walked around in last half minute.

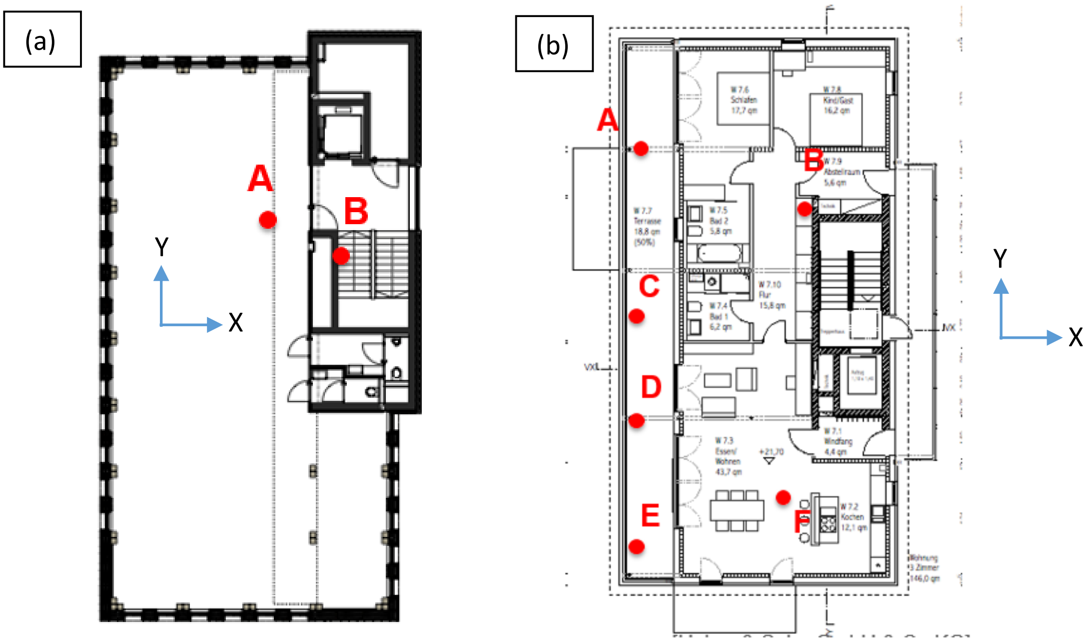

Figure 3 (a) Roof plan of LCT ONE building; (b) Top floor plan of H8 building

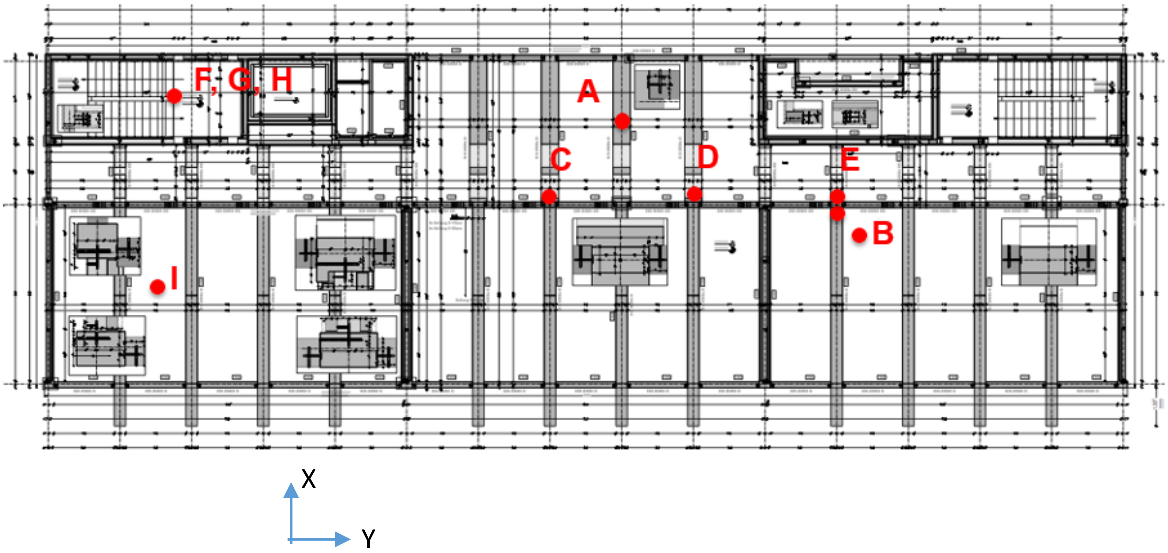

Figure 4 Top floor plan of KAMPA building

Table 2 Summary of the measurements of timber buildings

Building	Test	Point	Directions
LCT ONE building	1	A	Y
		B (Reference point)	X,Y
	2	A	X
		B (Reference point)	X,Y
	3	Top floor	Vertical
H8 building	1	A	X
		B (Reference point)	X,Y
	2	A	Y
		B (Reference point)	X,Y
	3	C	X
		D	X
		E	X
	4	F	Vertical
KAMPA building	1	A (Reference point)	X, Y
		B	Y
	2	A (Reference point)	X, Y
		B	X
	3	C	Y
		D	Y
		E	Y
	4	C	X
		D	X
		E	X
	5	F	Y
		G	Y

	H	Y
6	F	X
	G	X
	H	X
7	I	Vertical

2.3.2 Timber Towers

There are 9 timber towers in Germany which were measured in this STSM. For timber towers, the measurement is simpler, and the main measurement was only carried out in one point for three directions. The time duration for each measurement was 40 minutes.

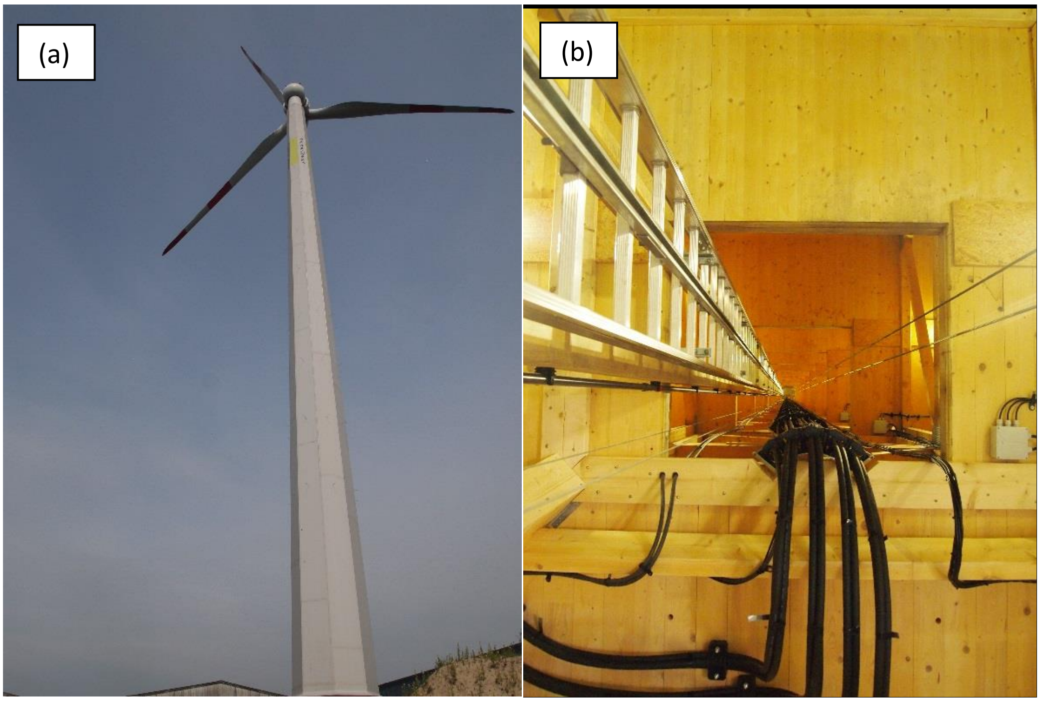

Figure 5 Timber Tower in Hanover (a) Outside view; (b) Inside view

It is worth mentioned that a timber wind turbine called Timber Tower was measured in Hanover as seen in Figure 5. The influence of the blade rotation on vibration was studied in two tests; in the first, the blade was moving and in the second its movement was restricted by shifting the blade.

For each tower, after 40-minute measurement, an additional test was carried out. An actively induced vibration excited by shaking the tower at top floor for 20 seconds at its natural frequency as well as the free vibration afterwards were measured. The natural frequency can be assessed approximately through a fast Fourier transform (FFT) computation on site. The same active-induced tests were done twice at two frequencies other than the natural frequency.

3. Description of the main results obtained

After measurements on these timber structures, acceleration over time in each channel has been exported at a sampling rate of 200 Hz. A variety of analytical methods can be applied to obtain structural dynamic properties from raw data, thus it is significant that these data from this STSM can contribute to the database and engineers are able to download and analyse for their own purposes. The key properties this report concerns are natural frequency and damping ratio which are closely related to structural design and engineers are capable to compare these values with the predicted from design criterion.

In this report, a better filter, the random decrement method and the flowing matrix pencil method are employed for modal properties analysis. The function of a better filter is to reduce the noise at high frequency and random decrement method extracts free vibration from ambient vibration (He and Fu, 2001). Matrix pencil method is a frequency-domain analytical method using curve fitting for free decaying wave, and natural frequency and damping ratio can be calculated (Zielinski and Duda, 2011). Results in flowing sections are computed using these methods operating in MATLAB.

3.1 Timber buildings

Analytical results of CLT ONE building designed by ARUP are shown here as an example. By analysing the measurement data from point A in Figure 3 (a), structural response in frequency domain of X and Y directions are plotted in Figure 6. Matrix pencil method is able to extract natural frequency and damping ratio from modal curve fitting as shown in Figure 6 and these values are tabulated in Table 3. It can be seen that in longitudinal direction the structure has higher stiffness and damping capacity as well as smaller vibration amplitude. The lateral stiffness therefore can be worked out by estimating the mass of the structure based on the equation:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

where k and m present the lateral stiffness and mass, and f means the natural frequency in the unit of Hz. Comparing the predicted natural frequency in design processes with the values of existing tall timber structures, the over or less-estimation might be examined. It is vital that studies from existing structures can give more understanding to analyse more accurate natural frequency and damping capacity in design stage. For example, in the design of tuned mass damper (TMD), the natural frequency of TMD should accurately depend on the natural frequency of the main structure otherwise the efficiency would be reduced greatly.

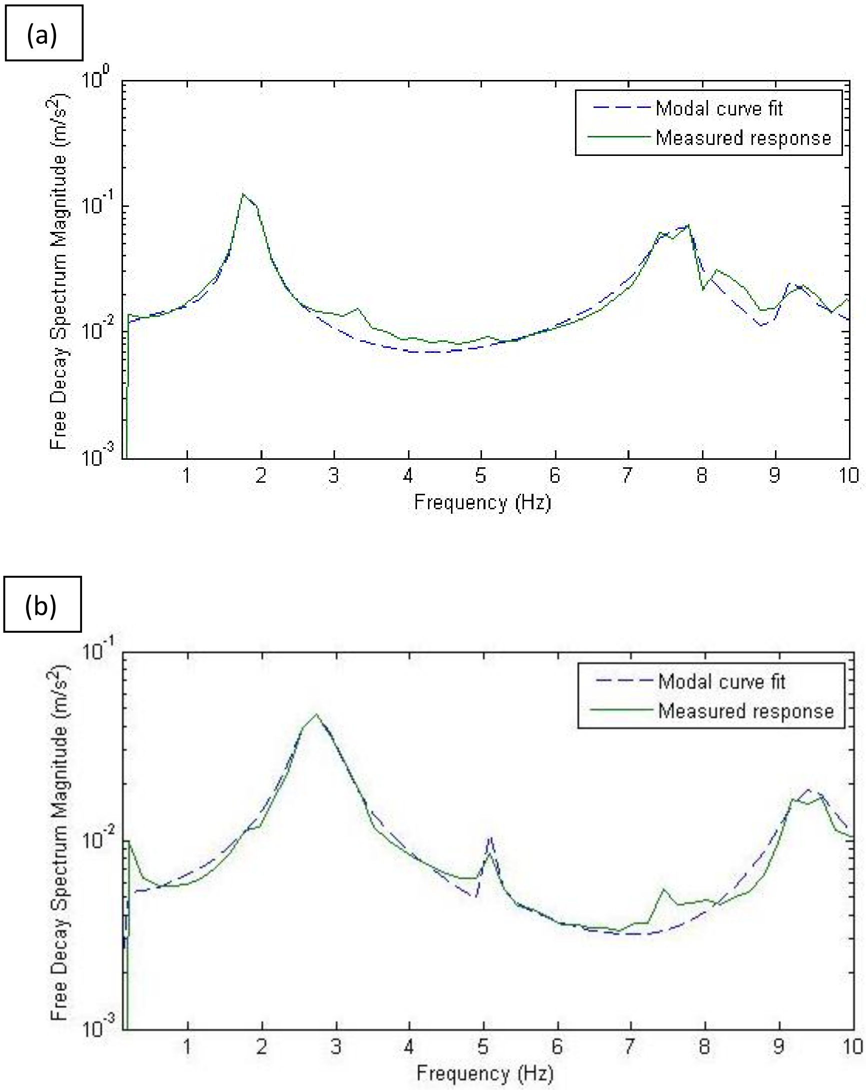

Figure 6 Fitted spectrum in frequency domain of point A in (a) X direction; (b) Y direction

Table 3 Analytical results of LCT ONE building

Directions	Natural frequency (Hz)	Damping ratio (%)	Free decay spectrum amplitude (m/s^2)
X	1.84	2.17	0.1244
Y	2.73	7.72	0.0463

The data can also be used in the research studying the effect of concrete core, timber core and shear walls on structural performances. The torsion performances of the long timber structure like KAMPA building can be studied using three distributed measurement points in one direction.

3.2 Timber towers

Same analytical methods are carried out on timber towers, and the frequency domain response of Augstberg tower is shown in Figure 7 as an example. Because the structural shape of timber towers is symmetrical, the results only show the measurement in one horizontal direction in this report. All analytical results are presented in Table 4.

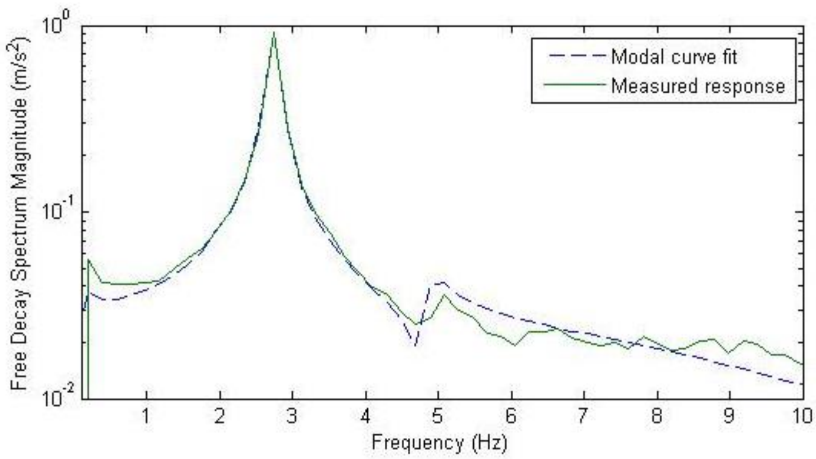

Figure 7 Fitted spectrum in frequency domain of Augstberg tower

Table 4 Natural frequency and damping ratio of all timber towers

Tower	Natural frequency [Hz]	Damping ratio [%]
Altenbergturm	1.88	2.24
Himmelsstürmer	1.65	1.07
Augstbergturm	2.74	2.10

Blumenthaler Aussichtsturm	1.91	0.70
Timber Tower	0.33	0.78
Ochsenstiegl	1.99	2.08
Aussichtsturm am Kadernberg	2.15	1.39
Haidelturm	1.62	1.40
Baumturm	1.27	2.90

4. Conclusion

In this STSM, the wind-induced vibration measurements on 12 tall timber buildings and towers were carried out in Germany and Austria. Through the collaboration with ARUP Berlin, different types of tall timber structures were selected and studied. For buildings, ambient vibration in two horizontal directions with reference point, ambient vibration along the structural length and height and excited floor vibration were measured for duration of maximum 40 minutes at sampling rate of 200 Hz. In terms of towers, three-dimensional measurements were carried out at the top. The data from this STSM can contribute to the database which has been built by the institute the applicant belongs to. Engineers can analyse these data using a variety of methods for their own purposes. The applicant and the team belongs to focus on the structural dynamic properties such as natural frequency, lateral stiffness and damping ration, and developed analytical methods in MATLAB for computation. These values from existing tall timber structures can give engineers and researchers an understanding how tall timber structure behaves in ambient vibration as there are short knowledge currently. Further studies will be carried out and be related to the results of engineering design practice.

5. Future collaboration with the host institution

In the meeting with Mr Carsten Hein and the timber group in Berlin, we discussed our further collaboration and we are interested in the measurement of a timber building TCC designed by ARUP in Münster. Based on the good collaboration between home institute and host institute, we agreed to continue cooperation and more timber structures could be measured in the future.

6. Foreseen publications

Based on the data from this STSM, further analytical methods aiming for noise reduction and dynamic properties determination in frequency and time domain will be applied for different purposes. Furthermore, studies for the influence of vibration amplitudes and types of construction will be carried out in the future. It is hoped a journal paper will be published.

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20th July 2015

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Confirmation by the host institution (by Mr Carsten Hein)

In the name of the **host institution**, ARUP Berlin, the undersigned ***Carsten Hein*** confirms that Haoyu Huang has undertaken the above-described STSM within COST Action FP1402 successfully. The actual duration of this STSM is 15 days from 15th June to 1st July 2015.

22/07/15

Mr Carsten Hein
Associate Director
ARUP Berlin,
Germany