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DYNAMIC PROPERTIES OF TALL TIMBER STRUCTURES UNDER WIND-INDUCED VIBRATION

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ABSTRACT: This paper describes a project that aims at evaluating the dynamic properties of tall timber structures under wind-induced vibration in serviceability level from a series of onsite measurements on existing multi-storey timber buildings and timber towers. Ambient vibration measurement was carried out on nine timber towers and three tall timber buildings to derive dynamic parameters including natural frequencies, damping ratios, and mode shapes. The results were analysed by time and frequency domain approach. The factors that influence the dynamic parameters, such as construction type, height, and vibration amplitudes, are discussed. The outcomes of this paper are useful for engineers to evaluate the dynamic parameters in the design of tall timber structures.

KEYWORDS: Tall timber buildings, Timber towers, Ambient vibration testing, Wind-induced vibration, Serviceability

1 INTRODUCTION

Timber is increasingly used as material for the primary structure in multi-storey buildings and tall structures. Compared to high-rises built in concrete and steel, tall timber structures entail some special structural challenges that need to be considered and solved in a smart way. Important aspects are their light weight and flexibility compared to conventional buildings. Thus, they tend to be susceptible to dynamic lateral loads and are likely to react with perceivable or even disturbing acceleration amplitudes under wind-induced vibrations, especially when reaching big heights [1,2]. Serviceability can be seriously affected by building users' discomfort. Therefore, it is crucial to predict the dynamic behaviour of the buildings under wind load at an early stage to design a well-functioning structure and have the possibility to apply improving measures [2]. In order to perform a realistic analysis of the structure's response, the relevant dynamic properties have to be estimated and a profound understanding of the dynamic behaviour is essential [3]. However, current design codes, guidelines, and research give only few indications for the relevant dynamic properties of timber structures under wind load, especially damping, which is the most influential property governing the design [1,4-6]. It is affected by a number of different factors such as activation of friction and yielding, which explains that damping depends on construction type and vibration amplitudes [3]. This effect was also observed by various research projects on the dynamic behaviour of tall timber structures [7-17].

Onsite vibration testing on existing structures has become a powerful method to extract their dynamic parameters and analyse different influence factors as it has been done to establish a data base of damping reference values for steel and concrete structures [3].

This paper describes a project that consists of a series of onsite measurements on existing tall timber structures including multi-storey buildings and towers under wind-induced vibration in serviceability level. It explains the methodology used and provides the theoretical and practical background of ambient vibration testing and analysis methods in Section 2. The results including fundamental frequencies, damping ratios, and mode shapes of the tested structures are presented in Section 3 and discussed in Section 4. Section 5 gives some concluding remarks and suggestions for potential future research. Full details of this project can be found in [18].

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2 METHODOLOGY

2.1 SELECTION OF TALL TIMBER STRUCTURES

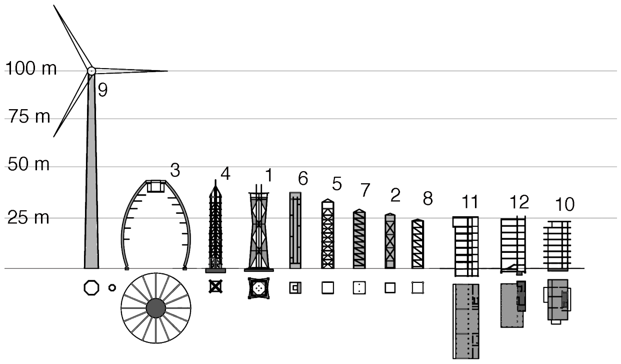

Figure 1: *Tested Tall Timber Structures*

In this project, three multi-storey residential and office timber buildings, eight observation towers, and one wind turbine were selected for the vibration tests. An overview of the geometry is given in Figure 1 and basic information can be found in Table 1. The structures were classified into timber frame, timber frame with cladding, and solid timber tube construction. Therefore, they vary in their structural load bearing system and the proportion of secondary structure. The majority of the structures are located in Germany, while one building is located in Austria. Heights of these structures range from 20 *m* to 100 *m*.

Table 1: *Construction Types and Heights of Tested Structures*

Name of Structure	Height (m)	Number
Towers - Solid timber tube		
Himmelsstürmer	38.4	6
Timber Tower	100	9
Towers - Timber frame		
Baumturm	44.5	3
Blumenthal	45.0	4
Haidelturm	35.2	5
Ochsenstiegl	25	8
Towers - Timber frame with cladding		
Altenbergturm	42.5	1
Augstbergturm	28.0	2
Kadernberg	30	7
Buildings – Solid timber, concrete core		
H8	23.9	10
Buildings – Timber frame, timber core		
Kampa	26.4	11
Buildings – Timber frame, concrete core		
Life Cycle Tower One	26.6	12

2.2 AMBIENT VIBRATION TESTING

Natural vibrations, including wind-, human-, and machine- induced vibrations as well as movements of the soil, are referred to as ambient vibration. These represent the vibrations that a building is exposed to under normal operation. Ambient vibration testing without any forced excitation can be used to derive dynamic properties of a structure such as fundamental frequency, damping ratio, and mode shape. [3,19]

The advantages of this method are the analysis of the building's performance under normal conditions avoiding the influence of artificial excitation, a high efficiency, and no significant disruption of the operation or damage of the structure. The disadvantage of ambient vibration testing is the danger of recording only very small amplitudes which do not excite the structure sufficiently to derive modal parameters. This risk especially applies to small and stiff structures with high fundamental natural frequencies. However, the method is well applicable to large structures with low natural frequencies around or below 1 *Hz*. It has been successfully used for skyscrapers, bridges, and lately also for tall timber buildings. Very sensitive sensors have to be used to record significant data. [15,16,19-23]

The raw data include the random response to ambient vibration and some noise that has to be filtered out. For the latter, efficient algorithms exist. In order to derive modal parameters from ambient vibration testing, the prerequisite of a white noise excitation has to be fulfilled. White noise is characterised by a random excitation signal and a broad frequency spectrum. The mean value of the excitation signal should be zero. These prerequisites are generally assumed to be valid for wind excitation. [19]

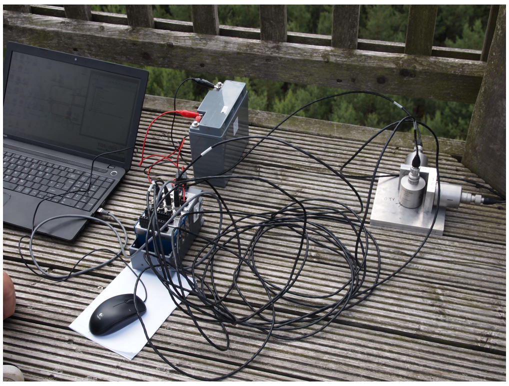

Figure 2: *Measurement Set-up*

The structures were tested between June 18th and July 1st 2015. The measurement set-up and test equipment can be seen in Figure 2. Three piezoelectric accelerometers with a lower frequency limit of 0.1 *Hz* and a nominal sensitivity of 10 *V*/*g* were used in all tests. The accelerometers were connected to a data logger recording data for each channel separately. The data logger was connected to a laptop with the software *LabView* and a battery. This set-up was very convenient, since it did not necessarily need external power supply and could be transported and installed with reasonable effort.

For towers, the measurements were done on the highest accessible storey to record the vibration close to the tip. One point was selected and the acceleration under ambient vibration was recorded in the two horizontal directions for 40 to 60 minutes. The data was sampled with a frequency of 200 *Hz*. According to the *Nyquist Theorem*, this sampling rate allows to display the frequency range of interest correctly without the problem of aliasing. The ambient vibration tests in buildings were done on the roof or the highest storey of the building. This choice depended on the accessibility of the roof and the floor covering. Because of the higher structural complexity of buildings, more measurement points were picked leading to multiple input channels and various data sets. The vibration was measured simultaneously in different parts of the structure e.g. concrete core and timber elements. Each set-up was recorded for 20 to 40 minutes.

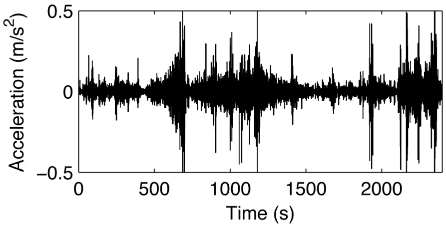

Figure 3: *Time History Record of Himmelsstürmer Tower*

The results obtained from the ambient vibration tests consist of the acceleration response in *m/s*^{2} of the structure to ambient vibration for each measurement channel and each measurement point in time domain. Figure 3 shows a typical time history of acceleration response data taken from *Himmelsstürmer Tower* in horizontal direction. The raw data are contaminated by noise caused by people walking in close proximity of the accelerometers or other local high-frequency excitations and could not be used directly to extract dynamic properties. Therefore, the data were processed by numerical analysis methods.

2.3 ANALYSIS

2.3.1 Overview

Ambient vibration data need to be analysed in a two-step approach as it can be seen in Figure 4. Various methods have been applied to gain more confidence in the results and compare different approaches. In the first step, the random response data were transformed using the *Random Decrement Method* (RD Method). This allows to eliminate the random response of the structure, reduce noise contamination, and derive a data set representing the inherent system vibration. Modal analysis methods can be applied in a second step, either in time domain or in frequency domain. The data from towers were processed in time domain using the *Matrix Pencil Algorithm* (MP Algorithm) and in frequency domain by the *Half Power Bandwidth Method* (HPB Method). These methods derive results for the dynamic properties for each measurement channel separately. Building data were processed the same way. Additionally, the *Ibrahim Time Domain Method* (ITD Method) was applied for buildings taking into account all simultaneously recorded channels. Details on the theoretical background of all methods can be found in the respective references given in each section. Data were processed by a *MATLAB* routine.

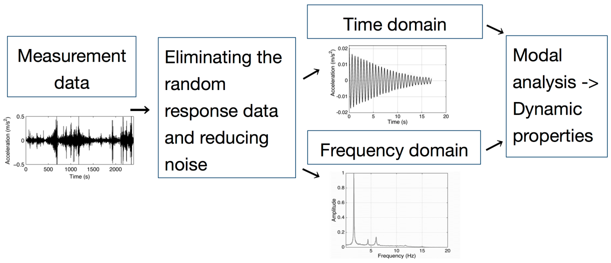

Figure 4: *Two-step Data Processing*

To apply modal analysis methods, the assumption of a linear, time-invariant system needs to be valid [3]. The traditional approach used in codes regards the structural dynamic behaviour under wind-induced vibration to be in the linear elastic range and changes to non-linear, plastic behaviour under much bigger vibration amplitudes like those caused by earthquakes [3,4]. The results in this paper were conducted under these assumptions. However, research has found that structures can behave non-linearly even under wind-induced vibration, which could especially be observed for super-tall buildings and for ambient vibration tests of multi-storey timber buildings [22-25]. Therefore, the data were analysed more critically relating them to the vibration amplitudes.

Since the amplitudes under ambient vibration are relatively small, the structures were assumed to be excited only in the first few modes. This coincides with the methods stated in EC 1 Part 1-4, which only consider the fundamental vibration mode for the analysis of wind-induced vibrations [4]. The reliability of results from ambient vibration testing for higher modes decreases significantly. Thus, the data analysis was performed with the goal to extract fundamental frequencies, associated damping ratios, and mode shapes.

2.3.2 Filtering

A bandpass filter was applied to reduce noise caused by local high-frequent excitations and narrow down the frequency content of the raw data to the frequency range of interest. It does not eliminate noise completely but leads to a much less distorted signal. A 9th-order Butterworth filter was chosen to eliminate frequencies below 0.1 *Hz* and above 12 *Hz*. This range is assumed to include the fundamental frequency of all structures and possibly a few higher modes. The filter type has shown a good ability to reduce noise in previous research [16].

Figure 5 shows the filtered time history record of *Himmelsstürmer Tower* in lateral movement.

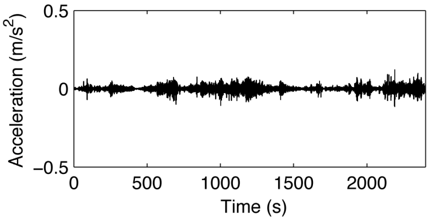

Figure 5: *Filtered Time History Record of Himmelsstürmer Tower*

2.3.3 Random Decrement Method

The RD Method [26,27] is a technique that extracts a pseudo free decay response from random ambient vibration response data called RD signature as it can be seen in Figure 6. This RD signature represents a weighted autocorrelation function. It was found out that it behaves similarly to the structure's free decay and can therefore be used in further data analysis either by means of frequency domain or time domain methods. It is an essential and reliable pre-processing technique for working with ambient vibration data and also allows the investigation of a varying vibration amplitude [26,28].

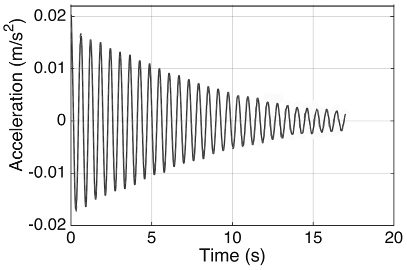

Figure 6: *RD Signature of Himmelsstürmer Tower*

The basic idea of the method is to delete all parts of the signal that are not of interest for further analysis by averaging a large number of segments cut out from the signal at a certain trigger value. The single channel random response signal consist of three parts at time $t + t_0$: the step response from initial displacement at time t_0, the impulse response from the initial velocity at time t_0, and the response from the random excitation between t_0 and $t + t_0$. If there is a sufficient number of segments, the response due to the initial velocity averages out because the sign of the initial velocity of each segment is alternating. The random response also averages out due to its characteristic of being a random response with an average of zero. This explains why the prerequisite of ambient vibration testing is a white noise excitation. Therefore, only the response due to initial displacement remains and results in the RD Signature which can be used for further data analysis.

The RD signature should cover the decaying process sufficiently and therefore, the length of the segments has to be adapted. The trigger value that determines the point of cutting the signal into segments is recommended to be set to 1.5-2.5 times the standard deviation of the signal. A trigger value of $\sqrt{2}$ times the standard deviation was used by Reynolds et al. [16] and has proven to be efficient for selecting enough segments to result in a smooth RD signature after averaging and eliminating noise.

2.3.4 Matrix Pencil Algorithm

The MP Algorithm [29,30] uses noise-contaminated data to construct an eigenvalue problem of a non-square matrix from single channel measurement data. The solution of the eigenvalue problem gives frequencies and damping ratios for each inherent vibration mode, i.e. those, which are not due to noise. To deal with noise contamination, a *Singular Value Decomposition* (SVD) is performed, which is a useful mathematical conversion to reveal the principal inherent system properties.

The MP Algorithm was used to extract fundamental frequencies and associated damping ratios for single channels. The number of modes contributing to the vibration signal has to be assumed. A wrong assumption can lead to biased results of damping ratios. The MP Algorithm includes the calculation of singular values of the SVD-based approach. These give precious hints on a number of modes to assume. Another possibility to avoid the problem of assuming an inappropriate number of modes is to filter the frequency range using a bandpass filter to cover only the fundamental mode. Both approaches were used and compared in the analysis. The algorithm derives fundamental frequencies and associated damping ratios and performs a procedure to compare the fitted signal to the measured signal visually both in time and frequency domain as it is shown in Figure 7.

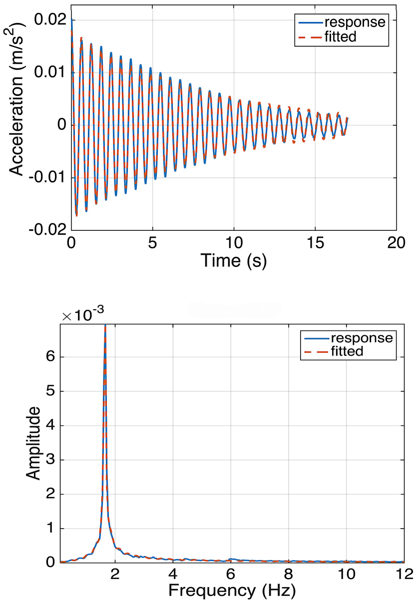

Figure 7: *Fitted RD Signature of Himmelsstürmer Tower in Time and Frequency Domain*

2.3.5 Ibrahim Time Domain Method

The ITD Method [26] uses free decay response data or RD signatures of a multi channel analysis to establish an eigenvalue problem. The solution of the eigenvalue problem contains the natural frequencies and damping ratios for each mode. There are different approaches on how to set up the eigenvalue problem. It is necessary to have a sufficiently large set of data as an input. It is possible to use acceleration, velocity, and displacement response data, or sample data with a time shift to produce more input data, which was used in this project. The ITD Method was used for the multi channel analysis of buildings. It derives fundamental frequencies, associated damping ratios, and modes shapes. The results were verified checking the *Modal Confidence Factor* (MCF) to distinguish between true modes and modes due to numerical calculation. The natural frequencies and damping ratios were directly calculated by the method, whereas the amplitude and phase angle of the eigenvectors had to be derived from the conjugate complex entries of the mode shape matrix.

2.3.6 Half Power Bandwidth Method

The HPB Method [3] is a frequency domain method to estimate the damping at a resonance peak after performing a *Fast Fourier Transformation* (FFT). The width of the frequency peak at an amplitude drop of 3 *dB* from the maximum amplitude, which corresponds to a division by $\sqrt{2}$, is determined and the damping ratio is half the ratio of this width to the resonance frequency [13]. The random response was eliminated by averaging a large number of segments in frequency domain for this approach. Figure 8 shows the averaged frequency spectrum of *Himmelsstürmer Tower*. It is similar to the frequency spectrum of its RD signature and shows a peak at the first fundamental frequency.

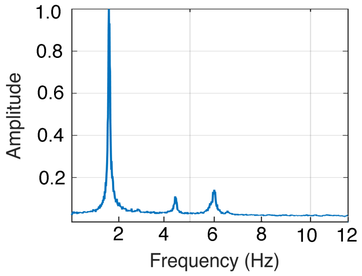

Figure 8: *Averaged and Normalised Frequency Spectrum of Himmelsstürmer Tower*

3 RESULTS

3.1 DYNAMIC PROPERTIES OF TOWERS

The fundamental frequencies and associated damping ratios for all tested towers are shown in Table 2 and Figure 9. They represent an approximation of their RD Signature produced by the MP Algorithm. Since the majority of towers showed the same dynamic behaviour in both measured horizontal directions, the average results of both channels are given here.

Table 2: *Results Towers*

Name of Structure	Frequency (Hz)	Damping Ratio (%)	Number
Altenbergturm	1.88	2.28	1
Augstbergturm	2.72	2.16	2
Baumturm	1.27	2.60	3
Blumenthal	1.90	0.64	4
Haideltum	1.59	1.35	5
Himmelsstürmer	1.65	1.22	6
Kadernberg	2.19	2.70	7
Ochsenstiegl	2.05	2.10	8
Timber Tower	0.33	0.64	9

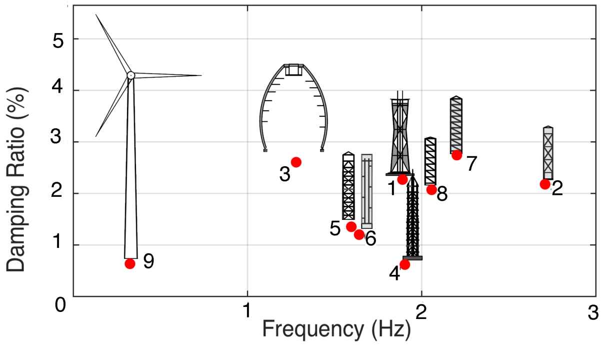

Figure 9: *Results Towers*

3.2 DYNAMIC PROPERTIES OF BUILDINGS

The results including frequencies and damping ratios of the first two modes of all tested buildings are shown in Table 3. To take various results from all performed methods into account, the table shows the 25th percentile (left value) and 75th percentile (right value) which gives a good idea about the scatter of data. The results are based on RD signatures as close to one decay length as possible and represent the approximation produced by the MP Algorithm as well as by the ITD Method.

Result data of *H8 Building* have the worst quality and show the biggest scatter, which is caused by very low excitation amplitudes and a high noise contamination. As expected, the results for the second modes are less precise than for the fundamental modes.

Table 3: *Results Buildings*

Name of Structure 1^{st} mode	Frequency (Hz)	Damping Ratio (%)
H8	2.33/2.34	1.72/2.90
Kampa	1.60/1.60	1.29/1.77
Life Cycle Tower One	1.80/1.85	2.14/2.31
Name of Structure 2^{nd} mode	Frequency (Hz)	Damping Ratio (%)
H8	3.31/3.41	1.50/2.53
Kampa	1.73/1.73	1.55/2.03
Life Cycle Tower One	2.71/2.78	6.34/7.55

4 DISCUSSION

4.1 COMPARISON OF TIME AND FREQUENCY DOMAIN METHODS

A comparison of results between the different methods showed that they produced very well-matching results for frequencies and mostly similar but more scattered results for damping. Deviations were expected due to the different approaches of the methods. The time domain approach is considered to be more accurate since it is eliminating the noise by both the RD Method and the MP Algorithm and therefore has a higher robustness. The HPB Method eliminates noise only by averaging in frequency domain which is susceptible to inaccuracies. However, the HPB Method produces very good results for frequencies and gives a good estimate for damping ratios. For a detailed and precise analysis, the time domain approach is considered to be superior.

4.2 FUNDAMENTAL FREQUENCY

The fundamental frequencies of the tested buildings and towers range from 1-3 *Hz*, while the wind engine has a fundamental natural frequency of approximately 0.3 *Hz*. EC 1 Part 1-4 [4] states the equation $n_1=46/h$ to calculate the fundamental natural frequency n_1 depending on the height h for cantilevering structures over 50 *m* in Section F.2. This equation can also be used to get a rough estimate for the natural frequency of lower structures. In Figure 10, the frequencies of the tested structures are compared with the curve from EC 1 Part 1-4. A least-square curve fit has been done to the data points resulting in a curve defined by $n_1= 53/h$.

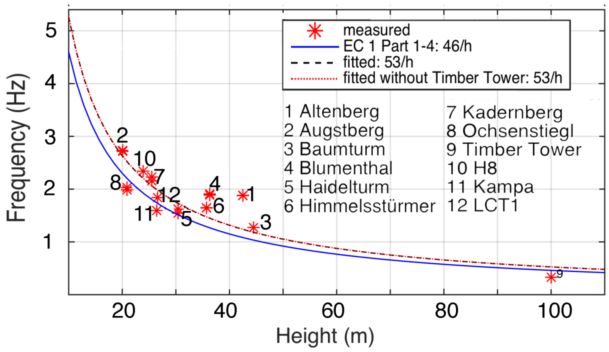

Figure 10: *Frequencies Related to Height*

The formula from EC 1 Part 1-4 gives a good rough estimate for the fundamental frequencies of the tested structures. However, for some towers the fundamental frequency is overestimated. Since structures with lower natural frequencies are more susceptible to wind-induced vibrations, it would be on the unsafe side to rely on the curve from EC 1 Part 1-4 for all tall timber structures. In average, the tested structures follow a trend line giving a slightly higher fundamental frequency than the formula from EC 1 Part 1-4. This can be explained by a higher stiffness-to-mass ratio of tall timber structures. It has to be noted that the tested structures only cover a height range from 20 *m* to 45 *m* and one structure of 100 *m*. Therefore, no conclusions can be drawn about tall timber structures in the height range between 45 *m* and 100 *m*. This height range will be part of future research.

4.3 DAMPING

The derived damping ratios for the fundamental mode cover a range from approximately 0.5-3.0 % as shown in Figure 11. They mostly exceed the damping ratio of 1 % given in EC 5 [5] for timber floors which is not surprising because the type of structure and excitation are different. EC 1 Part 1-4 suggests damping ratios from 0.5-1.6 % for concrete and steel structures which shows that tall timber structures can be superior regarding their capacities to dissipate vibration compared to conventional high-rises. The value given by EC 1 Part 1-4 for timber bridges of 1-2 % seems to be roughly applicable but is not conservative for structures with damping ratio of less than 1% and too conservative for structures with damping ratios over 2%.

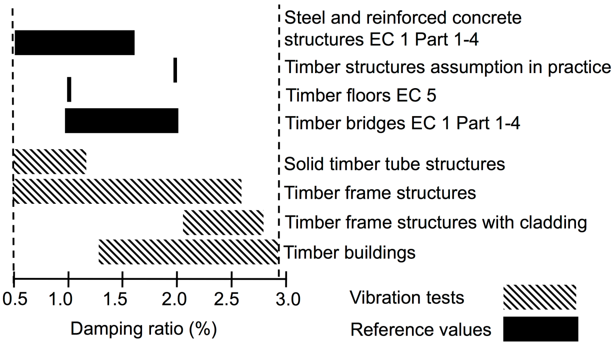

Figure 11: *Damping Ratios from Codes Compared to Results from Vibration Tests*

In Petersen [3], damping values are treated in more detail. The overall damping is a summation of values given for material, type of construction, and foundation. The material damping of timber is given as 0.4-0.8 % which is higher than material damping of steel with 0.1-0.3 % and about the same as damping of reinforced concrete with 0.4-0.9 %. A timber building with dowel-type connections contributes additional 0.6-0.8 % and a timber building with glued elements 0.2-0.4 %. The type of support adds another 0.1-0.3 % to the overall damping. Therefore, the range for timber buildings with dowel-type connections is from 1.1-1.9 % and for timber buildings with glued elements from 0.7-1.5 %. Assuming that the aerodynamic damping is comparably small, these values seem to give a quite good approximation of the damping ratios derived from the tests carried out within this project. However, they also do not cover the range completely. For timber as well as other materials, the construction type affects the damping capacity significantly. From the values given in [3], it can be seen that adding secondary structure can increase the damping ratio by 0.1-0.4 % for steel and concrete structures. The influence of construction type on timber structures was therefore further investigated.

4.4 MODE SHAPES

Mode shapes of buildings were calculated by the application of the ITD Method. The fundamental mode for all buildings is the vibration in short direction with the entire building moving as a whole. If there is an asymmetrical layout of structural components such as bracing and core, small rotation components could be observed as well. The second mode was also reconstructed but since the number of simultaneous channels was limited, the results for higher-order modes are not as precise anymore. The second mode includes a major component of movement in the building's long direction, usually accompanied with rotation to some extent depending on the individual layout of structural elements.

4.5 INFLUENCE OF VIBRATION AMPLITUDE

In this study, it was of interest whether the structures show a non-linear, time-invariant behaviour even under small vibration amplitudes of wind-induced vibration. The wind speeds taken from the nearest wind surveillance stations were all in the range from calm air to moderate breeze according to the *Beaufort Scale*, strong winds or storms did not occur during testing. The data were analysed by relating the dynamic properties to the respective vibration amplitudes. This was done using different approaches. The first approach evaluates not the entire RD signature but two cycles of it separately to check if the structure shows constant dynamic properties throughout its decaying vibration (example of *Timber Tower* in Figure 12). The second approach extracts several RD signatures at different vibration amplitudes from the data by using multiples of the standard trigger value (example of *Timber Tower* in Figure 12). Finally, the entire signal was cut into segments with individual analysis with respect to their acceleration RMS value (Figure 13). [16,20,22-25,31-33]

The detailed methodology and results of all structures can be found in [18].

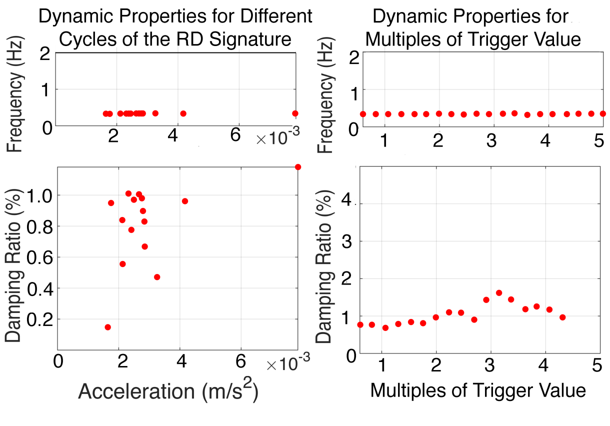

Figure 12: *Influence of Amplitude on Frequency and Damping Ratios from Timber Tower*

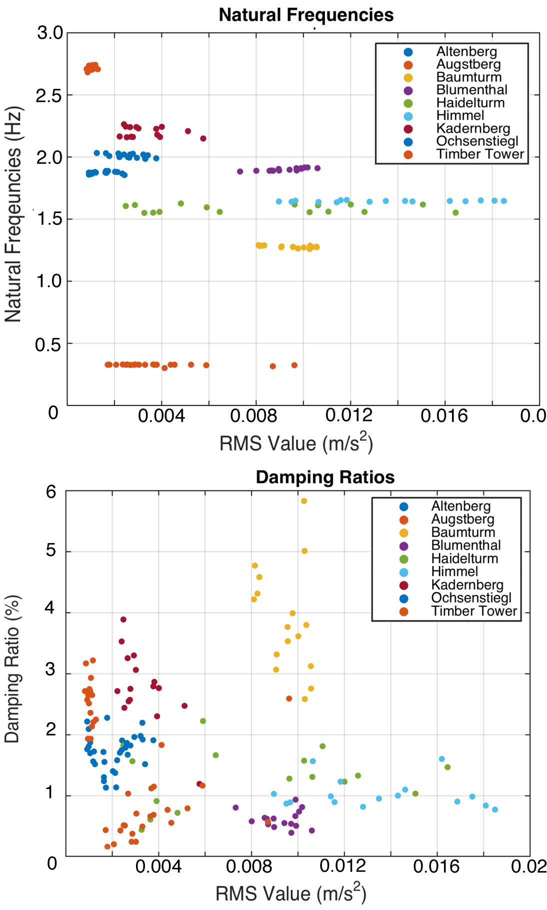

Figure 13: *Frequencies and Damping Ratios of Towers related to Acceleration RMS Value*

The tested structures show a constant fundamental frequency over all amplitudes and hints to non-linearity in their damping capacity. However, no clear trend showing e.g. an increase in damping ratio with higher amplitudes could be clearly determined for all tested structures. The small range of amplitudes measured during testing has to be considered when drawing conclusions. A clear trend might be visible in data sets that cover a wider range of vibration amplitudes. A dependence of damping on the displacement amplitude rather than acceleration amplitudes is possible as well. Therefore, the transformation of the data set into displacement response might reveal an unambiguous relation. Especially the last approach is susceptible to noise contamination because less data were used to average for a smooth RD signature. In future tests, longer measurement time would allow to collect more data and will result in higher precision when studying the influence of vibration amplitudes. Since there are signs of non-linear behaviour, the obtained results from testing should only be considered as reference values for in-service vibration caused by low wind speeds. As it can be seen from the results of all tested structures, non-linearity seems to be an important issue especially for the damping capacities of tall timber structures and should definitely be considered in future research.

4.6 INFLUENCE OF CONSTRUCTION TYPE

The influence of construction type on the dynamic properties was analysed in more detail. The fundamental frequency depends on the stiffness-to-mass ratio. Buildings with a high stiffness-to-mass ratio have higher natural frequencies than buildings with a low stiffness-to-mass ratio. Since the stiffness usually decreases for taller structures and the distributed mass stays the same, the fundamental frequency can be related to the height.

Damping is much harder to predict than fundamental frequencies. It is expected that the ability of the structures to dissipate energy by friction influences their damping the most. The mass of timber elements, steel elements, and cladding elements of the tested towers were estimated based on information provided by operators, plans, and onsite measurements. Their ratio compared to the total mass is shown in Figure 14. A trend of increasing damping ratio with an increasing use of steel for connections and cladding material can be observed. Therefore, the mass ratio of different materials seems to show a strong correlation to the damping ratio.

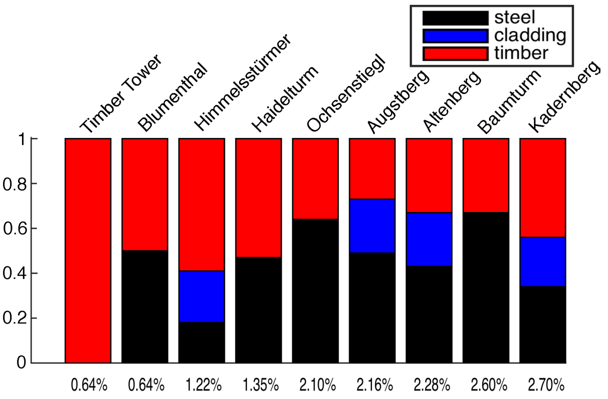

Figure 14: *Damping Related to Ratio of Estimated Mass of Timber, Steel and Cladding of Towers*

Table 4 shows the damping ratio in relation to the construction type and the type of connection. Solid timber towers have the lowest damping ratios, which can be explained by the use of many glued elements. *Timber Tower* is only connected at the bottom and tip by slotted perforated steel plates which are glued into the timber. The rest of the structure consists of glued CLT panels. *Himmelsstürmer Tower* makes use of locking screws, which can explain the higher damping ratio compared to Timber Tower. Timber frame towers have higher damping ratios than solid timber towers which is probably caused by more relative movement between elements and friction through dowel-type connections. *Blumenthal Tower* has a surprisingly low damping ratio for this construction type although it has a large amount of steel connections. However, the timber structure is quite massive as well, which increases the ratio of timber elements to steel elements. Timber frame structures with cladding show a trend for the highest damping ratios within the tested towers, which can be explained by additional friction through secondary structure.

Ochsenstiegl Tower and *Kadernberg Tower* have similar structural systems and connections as it can be seen in Table 4. The cladding seems to add about 0.60 % damping ratio to the structure. Whenever there are slotted steel plates involved, the damping is higher than for the same construction type using dowels only or steel box profiles. The buildings with concrete cores have slightly higher damping ratios than the pure timber building. However, this effect could also emerge from the timber concrete composite action in *Life Cycle Tower One Building* and the vertical tension rods in *H8 Building* which can cause relative movement of structural parts and therefore increase the damping. In general, the damping of buildings is slightly higher than damping of towers, which could be caused by the presence of more non-structural elements such as separating walls.

Table 4: *Damping Related to Type of Construction and Connections*

Damping Ratio (%)	Type of Connection
Towers - Solid timber tube	
0.64	Slotted perforated steel plates, glued into CLT panels on top and bottom, CLT all glued (Timber Tower)
1.22	Slots in CLT elements, CLT all glued (*Himmelsstürmer*)
Towers - Timber frame	
0.64	Steel box profiles, dowels (*Blumenthal*)
1.35	Steel nodes, dowels, steel plates (*Haidel)*
2.10	Dowels and steel brackets (*Ochsenstiegl*)
2.60	Screwed steel plates and threaded rods (*Baumturm*)
Towers - Timber frame with cladding	
2.16	Dowel-type connections (*Augstberg*)
2.28	Steel nodes, slotted steel plates, dowels (*Altenberg*)
2.70	Slotted steel plates with nails, dowels with steel brackets (*Kadernberg*)
Buildings – Solid timber, concrete core	
1.50/2.90	Walls stand on concrete blocks, timber elements are connected with screws, vertical tension rod through building (*H8*)
Buildings – Timber frame, timber core	
2.14/2.31	Screws and grooves for shear coupling of timber concrete composite, timber columns stand on concrete beams and are connected by grouted arbors (*Life Cycle Tower One*)
Buildings – Timber frame, timber core	
1.29/1.77	Groove and tongue, slotted or perforated steel plates (*Kampa*)

5 CONCLUSION

5.1 CONCLUDING REMARKS

Ambient vibration testing was performed on twelve tall timber structures with heights from 20 *m* to 100 *m* and different construction types. The aim of testing was to derive dynamic properties, in particular fundamental frequencies and damping ratios of the structures. All vibration tests were conducted using ambient excitation mainly caused by wind. The results were analysed by time and frequency domain methods that were implemented into a *MATLAB* routine. This procedure proved to be efficient for the experimental testing and was able to generate a large amount of significant data and valuable results even for low wind speeds for all tested structures. It is concluded that ambient vibration testing is a suitable method to analyse existing tall timber structures. Limitations of ambient vibration testing are the restrictions imposed by the equipment regarding simultaneous measurement channels, the range of measurable vibration amplitudes, and the length of recording time.

The results include fundamental frequencies, damping ratios, and mode shapes. Frequencies range from 0.3 *Hz* to 3 *Hz* and damping ratios from 0.5 % to 3 %. These data related to vibration amplitude and construction type can build a database with reference values for dynamic properties of tall timber buildings which can be extended by future research. Time and frequency domain methods produced rather well-matching results, however time domain analysis is regarded as superior. The results were analysed with regard to current design approaches and reference values as well. EC 1 Part 1-4 provides methods for the analysis of the susceptibility of structures to wind-induced vibration which give detailed procedures to evaluate the characteristics of wind load. However, they do not give sufficient guidance on the dynamic performance of tall timber structures under wind load and lack in providing significant reference values for their damping. Applying EC 1 Part 1-4 bears the risk of an overly conservative design that could lead to higher costs or a non-conservative design that might cause serviceability problems.

According to the building users' statements, perceptible and partially disturbing acceleration amplitudes have occurred during very strong winds. This underlines the significance of the evaluation of the vibration serviceability in residential and office buildings when building tall with timber. Due to their flexibility and comparably high damping capacity, timber buildings dissipate the energy by a decaying vibration rather than inducing stress to the structural members. A deep understanding of the contribution of different mechanisms to the damping capacity is the key to limiting the acceleration amplitudes to acceptable levels.

The results show constant frequencies over all amplitudes and an indication of the presence of a non-linear behaviour of the structures regarding their damping capacity. A direct relation between acceleration amplitudes and damping ratio could not be established. To study the amplitude dependence of damping in more detail, a broader range of excitation amplitudes is necessary. It can be concluded that the results stated in this paper are valid for small vibration amplitudes and can not be transferred directly to other vibration levels without detailed investigation. An assumption of a constant damping ratio is highly questionable, especially for a wider range of wind speeds. The construction type of tall timber structures has proven to influence the damping capacity significantly. Findings of this paper show a trend towards a positive correlation of damping ratio and the use of steel and non-structural elements. Additionally, damping was observed to be higher for structures with connections that allow relative movement and friction between elements.

5.2 POTENTIAL FUTURE RESEARCH

The focus of the data analysis and discussion of results was the comparison of twelve tested structures. Therefore, the obtained data still allow more investigation to a higher degree of detail for each structure. To foster the development of the tall timber building sector, future research needs to continue investigation of the dynamic behaviour under wind load and especially focus on the influence of non-linear behaviour and construction types. To cover a broader range of excitation amplitudes, long-term testing or forced excitation testing should be realised. A long-term goal should be to implement a reliable design approach for tall timber buildings into EC 1 Part 1-4.

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