Damping Ratio Estimation for a Slender Modular Building from Full Scale Ambient Response Monitoring

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Abstract. The application of modular construction in tall slender structures is a relatively novel concept. Modular buildings with heights exceeding 130m have been successfully constructed by combining reinforced concrete cores with steel-framed volumetric modules. Slender structures typically have an increased susceptibility to wind-induced acceleration responses which may give rise to occupant discomfort, and modular structures are no exception. The lightweight nature of modular buildings implies that they are more likely to exhibit large horizontal accelerations than other more traditional forms of construction. As modular construction techniques are employed in ever taller, more slender buildings, design analysis requires better understanding and information about the dynamic behaviour of modular structures. The damping ratio of a structure is one of the key parameters in predicting its acceleration response. Typically, empirical damping ratio values obtained from previous full-scale testing are used when analysing the acceleration response of a structure and its compliance with habitability requirements. However, no suitable previous full scale monitoring campaigns have been carried out on tall modular buildings. This paper presents data obtained from a full-scale vibration monitoring campaign on the world's tallest modular building. The ambient acceleration response of the 135m tall modular structure was recorded over a three-month period. These data are processed using modal analysis techniques to estimate the fundamental natural frequency and damping ratio of the structure. The results obtained using Bayesian and random decrement-based techniques are compared and the amplitude dependence of the modal properties is evaluated. The measurements were obtained when the building was in both partially- and fully constructed conditions, allowing the relative stiffness and damping contributions of the core and modules to be investigated. The results of this research provide greater insight into the dynamic behaviour of modular buildings increasing confidence in design analysis results and enabling modular construction to be pushed to new heights.

Keywords: Tall Volumetric Modular Construction, Damping Ratio, Ambient Vibration Monitoring, Tall Buildings, Wind-Induced Acceleration Response, Modal Identification.

1 Introduction

Advancements in structural engineering, including new materials, construction methods and computational power, has led to the ability to construct super-tall, slender and striking structures which are often inherently lightweight with lower natural frequencies and damping ratios [1, 2]. This leads to a possible increased susceptibility to wind-induced accelerations and in some cases, occupant discomfort in the form of fear, inability to focus and motion sickness [1]. It is widely acknowledged that the damping ratio is a key parameter in the dynamic analysis of a structure in order to assess susceptibility to wind induced response [2]. Therefore, determining the damping ratio is imperative in assessing the habitability of a structure.

Modular Construction is a lightweight and innovative form of construction which has seen increased interest in the last two decades due to having a lower environmental impact, improved quality and accuracy and a rapid speed of construction [3]. Volumetric modular construction typically involves the off-site manufacture of individual modules in a controlled factory environment. The modules are then transported to site where they are constructed around an in-situ lateral stability element, such as a reinforced concrete core, to complete a finished building. The construction of the modules in a factory means that a significant amount of construction time is saved on site, less labour is required and there is more accuracy, less injuries and less waste in the construction process [4, 5]. Whilst the use of modular construction is traditionally in low- to medium-rise structures, the use of modular construction in high-rise structures is limited and a relatively novel concept which is now pushing heights of up to 135m [5, 6]. While there is a small amount of literature discussing the potential of high-rise modular construction [4], there is little or no work reporting results of field measurements or modal properties for this type of structure. It is crucial for the further development of modular construction that the inherent properties, namely the damping ratio, and hence the wind-induced acceleration response is better understood and characterised.

Theoretical calculations to estimate damping are limited as damping does not directly relate to a unique physical phenomenon [7]. Damping estimation relies on empirical data from previous full-scale testing of structures with design codes offering values based on construction material [7, 8]. Wind-tunnel tests and advanced modelling assume a damping value based on these empirical values and are not sufficient in estimating damping of modular structures. Therefore, the only true method for identifying a modular structures damping ratio is through full-scale field monitoring of the structure [9]. To the best of the authors knowledge, there have been no previous damping ratios from full-scale monitoring campaigns of tall modular structures reported in literature. Therefore, designers of modular buildings are forced to use estimates based on other forms of construction. Table 1 presents values for damping ratios recommended by various design codes. It can be seen that values for steel are generally lower than those for concrete with recommended values for composite structures lying somewhere between the two. However, it is worth noting that there is variation in recommended values across design codes even for structures with the same construction materials.

Table 1. Damping Ratios recommended by design codes

Building Type	Recommended Damping Ratio	Design Code
Mixed steel and concrete	1.27%	Eurocode 1991-1- 4 [10]
Steel	0.8 %	Eurocode 1991-1- 4 [10]
Concrete	1.59 %	Eurocode 1991-1- 4 [10]
Steel	1%	ASCE 7 - 10 [11]
Concrete	1.5%	ASCE 7 - 10 [11]
Steel	1%	ISO 4354:2009 [12]
Concrete	1.2%	ISO 4354:2009 [12]

It is clear that there is significant uncertainty in the critical damping ratio of structures. Whilst design codes and equations provide estimates of critical damping ratios based on empirical data, the variability between these estimates is evident. Considering the novelty of modular construction for high-rise buildings, it is important to investigate the damping ratio of this new form of structure, especially due to the importance of the damping ratio in the dynamic response of a structure.

This paper uses three modal identification methods to identify the modal damping ratio of a high-rise modular building from ambient wind-induced acceleration response data obtained through full-scale testing of the world's tallest modular structure, *Ten Degrees*, located in Croydon, London in the United Kingdom. Reporting values of modal damping ratios obtained from live monitoring is an important advancement for modular construction and, ultimately, will allow for more informed designs in the future.

2 In Situ Testing

2.1 Description of the instrumented building

The structure monitored by this study was the *Ten Degrees* building located in Croydon, London, UK. Upon completion in 2021 it was the world's tallest modular building standing at 135m tall. The structure consists of two slip-formed concrete cores measuring approximately 8 x 8m in plan, a transfer slab at level four and two adjoined towers of 37 and 44 storeys that consist of volumetric corner post modules stacked around and connected to the two concrete cores. The thickness of the core walls ranges from 300mm to 450mm. The concrete cores act as the main element for lateral load resistance. The structure has a slenderness ratio (Height/Breadth) of 8. The volumetric modules are typically 2.875m tall and are limited in length and width to 13m and 6m respectively, due to transportation and lifting. They have a typical self-weight of 7kN/m^2. An image of the structure is shown in Fig. 1. alongside its location.

Fig. 1. View of the Ten Degrees Tower and location [18]

2.2 Instrumentation Overview

Two three-axis MEMS accelerometers, (CX1 Structural Response Monitor, resolution $0.00001g$, range $\pm 1.5g$, frequency range $DC - 200Hz$) were directly mounted approximately 1.84m above the floor slab at level 43, i.e. just below roof level in the taller core. The location of the accelerometers is shown in Figure The sampling rates for the accelerometers was 20 Hz. The accelerometers were installed off centre to capture lateral and torsional vibrations. On the roof of the core, a weather station was installed to record 10-minute averaging wind speed and direction, maximum/minimum wind speed and direction within each 10-minute window, temperature, humidity, atmospheric pressure, rain and its duration. A 3G router was also installed to allow for remote access to all data. Data from the weather station was continuously monitored.

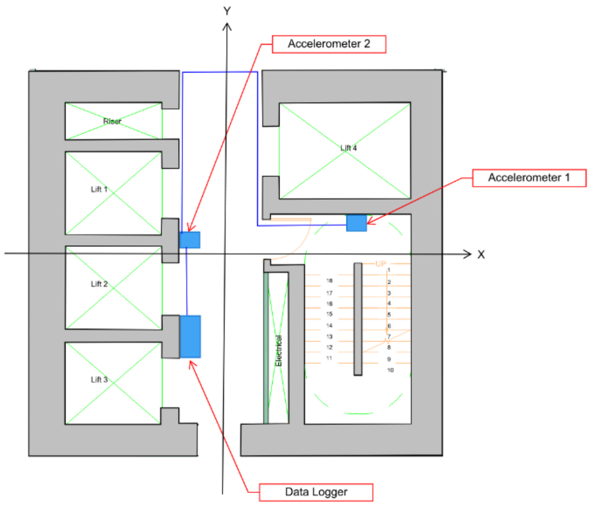

Fig. 2. Location of accelerometers and data logger in plan view

The cores were constructed to full height in late 2018, before any modules were installed. Monitoring of the structure was undertaken over a two-month period, beginning in late August 2019 and ending in late October 2019. The structure was not yet fully complete when monitoring began i.e. not all levels of modules were installed, and modules continued to be installed as monitoring commenced. In total, 10 sets of measurement data were recorded. A measurement set comprises of 12 hours of acceleration and wind speed data from before and after an instance in which the recorded acceleration exceeded a predetermined threshold value for at least 10 seconds. Of the ten sets of measurement data recorded, the final three, measurements 8, 9 and 10, were recorded on the completed structure. Table *2* shows the number of storeys of modules installed and the date each measurement was taken. It can be seen from Table 2 that there was a significant increase in the number of storeys of modules installed between measurement 5 and 6. The extent of this increase is also evident in Fig. 3.

Table 2. Dates in-situ measurement data recorded and number of storeys of modules installed

Measurement	Date	Number of stroreys Installed	
		Tower A	Tower B
1	31/08/2019	32	32
2	02/09/2019	33	32
3	06/09/2019	34	34
4	09/09/2019	35	34
5	11/09/2019	36	34
6	27/09/2019	41	34
7	29/09/2019	42	34
8	11/10/2019	44	37
9	13/10/2019	44	37
10	26/10/2019	44	37

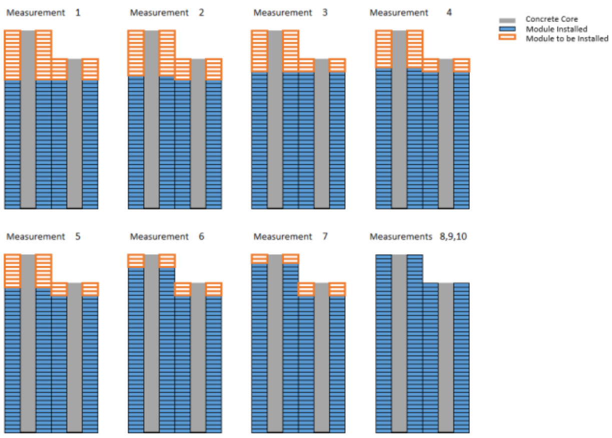

Fig. 3. Graphical representation of the number of storeys of modules installed for each set of measurement data

3 Analysis of Data for Modal Identification

The data recorded is ambient and not a result of a controlled test, therefore the wind exciting the structure and the accelerations experienced vary across measurements. Qualitative analysis of the raw acceleration response is necessary in order to identify any significant noise in the signals recorded. Fig. 4 shows the acceleration response and average 10-minute wind speed data recorded across all measurements for accelerometer 1. The x-direction represents approximately East West, the y-direction represents approximately North-South and the z-direction represents vertical response.

For context, it is worth highlighting that the basic 10-minute average 50-year wind speed at 10m is approximately 21.5m/s and the one-year 10-minute average wind speed at 10m used to assess serviceability limit state performance is approximately 17m/s; wind speeds did not exceed these values for any of the recorded measurements. For Measurements 1, 6 and 8 significant construction noise was identified. This noise can distort peak response values, however it is does not appear to be influential on the damping or frequency estimates as analysis not included in the paper for brevity has shown that examining smaller sub-segments of the recorded data, where noise is not prevalent, does not impact the estimated values significantly. Additionally, in the AMD-RDT method the AMD acts like a filter, meaning noise at different frequencies does not impact modal parameter estimates.

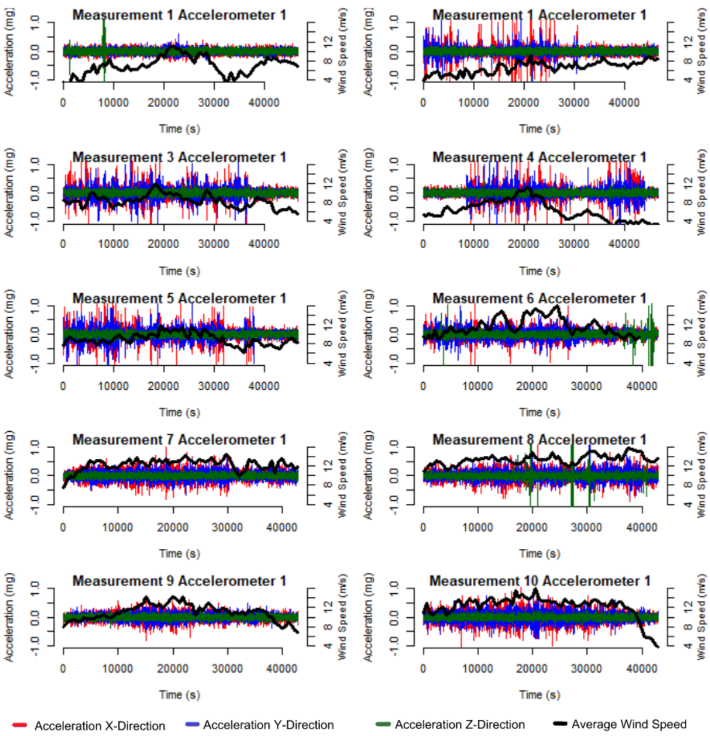

Fig. 4. Acceleration and wind time histories for accelerometer 1

Three modal analysis identification were employed to estimate modal parameters from the ambient data. Firstly, the frequency-domain Bayesian Fast Fourier Transform (BFFT) approach [13] was used to calculate natural frequency and structural damping. Damping was also calculated using the commonly employed time-domain Random Decrement Technique (RDT) [8, 9]. However, the Random Decrement Technique can be inaccurate when modes are closely spaced together. Hence, it is often combined with an anterior signal decomposition method. [14]. Analytical Mode Decomposition has been found to be effective for signals with highly coupled modes [15]. This paper combines AMD with the RDT, termed AMD-RDT, for modal identification from ambient data. For brevity, the underlying mathematics of these techniques are not presented in detail here, but the reader is referred to the work of Au [20] for this information for BFFT and to Wang et al. [25] for the AMD-RDT.

Fig. 5 shows the natural frequency calculated using the BFFT methods in the first translational modes two, x (EW) and y (NS), for each of the two accelerometers. In general, it can be seen that the values are in close agreement between the two accelerometers. The natural frequency in the NS direction is slightly higher than that of the EW direction, likely due to the arrangement of the structure.

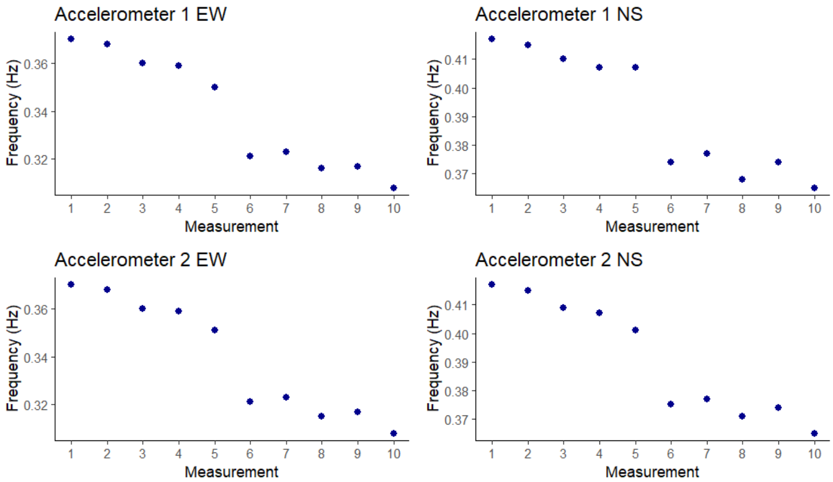

Fig. 5. Calculated natural frequency for each measurement

It is apparent that the natural frequency decreases as the measurements progress. This is to be expected due to the evolving nature of the structure as measurements were taken; there is even a significant jump between measurements 5 and 6 when the largest number of storeys were added between measurements. For earlier measurements there are less modules and therefore, less mass and stiffness. As modules are added, the mass of the structure increases, as does the stiffness. The natural frequency reduces as more modules are added. Therefore, it can be concluded that the impact on natural frequency of any increase in the stiffness of the structure due to the additional modules is not as significant as the impact due to increased mass, resulting in lower natural frequencies for later measurements. There is variation to this downward trend which is likely due to variation in the ambient excitations experienced for each measurement.

The structure was completed for measurements 8, 9 and 10. The average natural frequency for these measurements in the EW direction is 0.316 Hz and in the NS direction is 0.372 Hz.

Fig. 6 shows the damping ratio as calculated by both the BFFT and AMD-RDT methods for the first two translational modes for each accelerometer. Close agreement in the estimates from the two methods can be seen with convergence for later measurements. The Coefficient of Variation (CV) found for the measurements were found to be < 8% for all measurements, in line with CV reported by other operational modal analysis studies [8, 13]. Considering the damping ratio for measurements 8, 9 and 10, all taken on the completed structure, the damping ratio of the structure is approximately 1.10% in the EW direction and 1.2% in the NS direction. Notably, these values lie close to the Eurocode 1991-1-4 recommended value for a stell and concrete composite structure of 1.27%. The estimated damping ratios also lie within the range of values recommended by ASCE 7-10 of 1% for steel and 1.5% for concrete structures, and only slightly higher than the range of 1% - 1.2% recommended by ISO 4354:2009 in the NS direction. At least for the levels of excitation examined during this monitoring campaign, there appears to be no evidence of damping being higher than in other forms of construction.
While damping values are highly specific to individual structures, the results from this monitoring campaign appear to suggest that it is reasonable to apply the values proposed by codes for mixed buildings to modular structures. However, results from further monitoring of tall modular structures are needed to fully validate this conclusion. Additionally, given literature has shown damping can depend on response amplitude, continued monitoring to capture response under more extreme events than those captured during this monitoring campaign is also required.

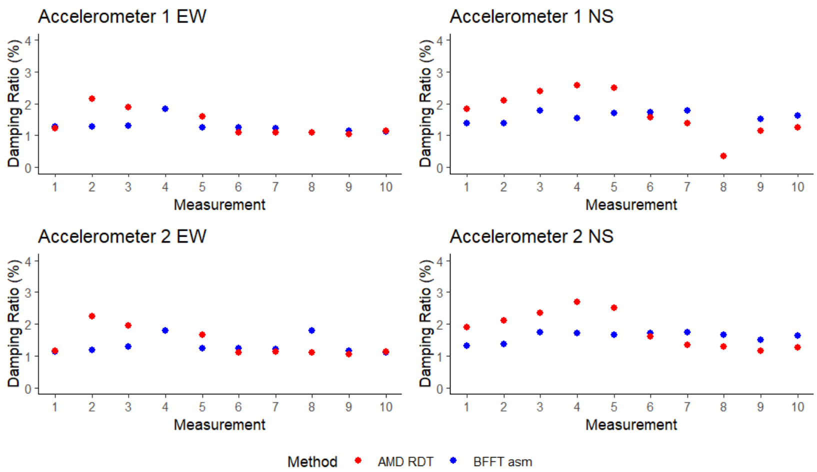

Fig. 6. Calculated damping ratio for each measurement

Fig. 7 shows the calculated damping ratios plotted against the calculated natural frequencies. In this case, the calculated natural frequency from the BFFT method is used for both sets of calculated damping ratios. There appears to be a very weak correlation between increased natural frequency and increased damping ratio, more so for the AMD-RDT method. The BFFT is more sensitive to frequency bands set when applying the method and hence is less likely to pick up on small variances in the structural response then the AMD-RDT which has proven more effective for structures with closely spaced modes [14].

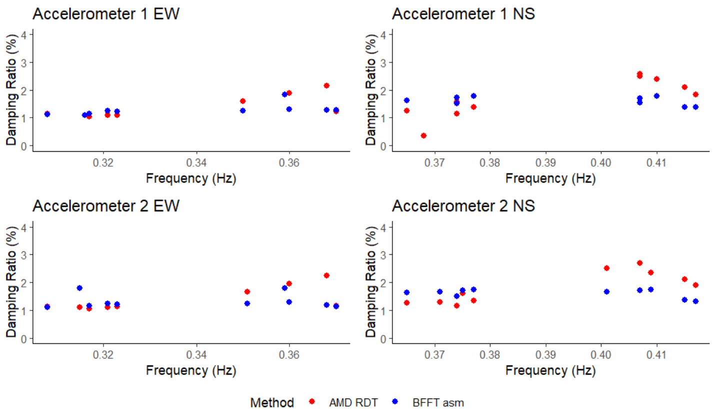

Fig. 7. Calculated natural frequency vs calculated damping ratio for each measurement

4 Conclusion

The application of modular construction to buildings of increasing height requires specific information on the vibration properties of this relatively new structural form. This paper has addressed the need for data on the in-situ damping ratios of tall modular buildings subjected to wind loading. Two modal identification methods, the BFFT and AMD-RDT, were applied to 10 sets of ambient acceleration responses recorded from a tall modular structure as it neared completed and was in a completed state.

The first two natural frequencies of the completed structure were identified as 0.316 Hz and 0.371 Hz. It was shown that the natural frequency of the structure decreased as more storeys of modules were added, demonstrating that the mass added by the modules was more significant than the stiffness contribution of the additional structure.

The damping ratio in the first two modes was found to be 1.10% and 1.2% respectively. The damping ratios calculated lie very close to those recommended for composite structures by design codes and by literature. There is no evidence that damping ratios are higher in modular buildings than in their more conventional counterparts, however, further full-scale studies of tall modular buildings are required to confirm this.

The damping ratios reported here represent the first values obtained from ambient vibration monitoring of tall modular structures during wind loading events. They provide greater confidence in the modal properties used in dynamic response assessments of future modular structures, supporting further design innovation. However, further full-scale monitoring of a wider range of modular structures and loading conditions is required to fully characterise their dynamic behaviour.

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