Model Validation for the Wind Response of Modular High-Rise Buildings through Full Scale Monitoring

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ABSTRACT: For many tall building forms, habitability requirements associated with excessive acceleration response become a governing design criterion as building heights increase. This study considers the wind-induced acceleration response of tall modular buildings and validates computational model predictions using recorded acceleration responses obtained from full-scale monitoring of high-rise buildings. The modelled mechanical behaviour of these steel framed module and RC core buildings and their predicted acceleration response, natural frequency and damping ratio are compared to the actual measured responses.

The acceleration response of a full-scale tall modular building experiencing ambient wind excitation is obtained through a monitoring campaign employing two triaxial accelerometers located at the top of the structure, a data acquisition system and a data storage system; wind speed and direction are also recorded. The acceleration response is processed using modal identification techniques to obtain the natural frequency and damping ratio of the completed structure. The acceleration response, natural frequencies and damping ratios are then compared to the outputs from a previously developed ETABS model of the structure.

The comparison between the model and the full-scale monitoring campaign provides insight into model accuracy and identifies opportunities for further refinement of the modelling of tall modular buildings to reduce model size, run time and computational expense, without loss of accuracy in wind-induced response prediction. The validation of the model supports structural optimisation analyses and the numerical investigations required to include vibration response mitigation measures in future designs.

KEY WORDS: Modular Construction, Tall Buildings, Wind-Induced Vibration, Structural Modelling, Natural Frequency

1 INTRODUCTION

In recent years modular buildings have experienced increased interest due to their reduced environmental impact, improved quality and accuracy, and speed of construction [1-4]. 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 results in a significant saving in on site construction time, less labour being required, and more accuracy, less injuries and less waste in the construction process [5]. Whilst modular construction is predominantly used in low to medium rise construction projects such as multi-unit residential accommodation, it is a relatively new concept for taller buildings [1, 5, 6]. Modular construction continues to increase in height due to economic drivers, with building heights of over 130m now realised [7, 8]. However, as with other structural forms, habitability requirements associated with excessive acceleration response become the governing design criterion as building heights increase. Hence, it is crucial for the further development of modular construction that modelling techniques used to identify inherent properties are validated and that the limits of this form of construction are better understood and characterised.

As the construction of modular buildings to new heights continues, issues with applying traditional modelling techniques to these structures are becoming apparent. It has been found that current modelling techniques do not cater for the variety of elements and connections seen in modular buildings and they do not capture the dynamic behaviour of modular buildings sufficiently [9, 10]. There is a significant lack of standards for modular buildings; both in the case of design and applications of BIM [11-13]. Design of modular buildings is currently completed using traditional, non-specific design codes and there are no standards for the modelling of modular buildings resulting in traditional BIM techniques being applied [9,11]. Using practices which were not created for this type of construction leads to inefficiency in design and modelling processes, impeding the progression of this form of construction [9,11].

A significant issue with using current modelling practices arises from the nature of volumetric modular construction. A typical modular building has a double member at every external beam and column and results in the doubling of double member, resulting in quadruple members, in place of every internal beam and column and doubles of all bracing members. This is due to each module being a separate structural system with a full set of members of its own. The stacking and aligning of modules next to each other to complete the finished structure results in duplicates of every member. There is also a significant increase in the number and complexity of the connections throughout a modular structure and replicating the connections with current finite element software can prove difficult-. Whilst using current techniques to model a modular building, in which every element is modelled individually, may be possible for smaller modular structures, modelling of each element in tall modular buildings with over 40 storeys becomes problematic. The number of elements needed to be modelled becomes considerably large and requires significant computational power and run time to analyse the model, to the point where the practicality of modelling every element becomes questionable. A PC with 32 GB of RAM and an 8 core Intel i9 processor takes approximately 180 minutes to run eigen modal analysis on such a model, and up to ten hours to produce the tables of results. The accuracy this type of model provides is not noteworthy with regards to global dynamic behaviour especially when the significant time producing and running the model are considered. Whilst a global model of a modular structure with every element modelled individually is useful for checking capacities, stresses and the localised behaviour of members, it is worth exploring whether such an extensive model is necessary to represent the properties of a modular structure for the specific purpose of ensuring that habitability requirements are satisfied. This is important because the computational demands associated with the dynamic analysis of the response of buildings to wind loading can be much greater than those required for static analysis of gravity load response. On the other hand, the low amplitude vibrations associated with habitability requirements imply small displacement, elastic response that can be well represented by modal properties, suggesting considerable scope for computational efficiency.

Given the nature of modular buildings as repeatable units stacked around a lateral stability system, there is considerable capacity for efficient modelling techniques to be employed [9]. The purpose of this paper is to consider one such technique in which a macro 'module' element is created and used in the ETABS model of a 135m tall modular building. The modal properties of the model are identified and the model validated using acceleration responses from the in situ 135m tall modular structure. Validation of this modelling technique creates a more accessible method for the dynamic modelling of modular structures and identification of modal properties in the design stage.

2 METHODOLOGY

2.1 Description of In-Situ Structure

The full-scale in-situ structure which is used for validation is a 44 storey, 135m tall modular building. The structure consists of a slip formed concrete core, transfer slab at level 4 and two adjoined towers of 37 and 44 stories that consist of volumetric corner post modules stacked around and connected to two concrete cores. The concrete cores are approximately 8 x 8 m in plan and have walls which vary in thickness between 300mm to 450mm. The landing slabs within the core are 300mm thick. For design purposes, the concrete core is assumed to act as the primary element for lateral load resistance.

The modules are typically 2.875m tall, are limited in length and width to 13m and 6m respectively due to transportation, and have a typical self-weight of 7kN/m. The structure has an overall slenderness ratio (Height/Breadth) of 8. The contribution of the modules to the overall stiffness of the structure, and hence, the lateral load resistance of the modules is so far unknown and is a topic of current research by the authors.

Monitoring of the structure was undertaken over a two month period, beginning in late August 2019 and ending in late October 2019. Two three-axis accelerometers and tilt sensors were directly mounted on a rigid support at approximately 1.84m height from the floor slab at level 43. One accelerometer was located at the center of the concrete core and the other at the edge of the core so as torsional modes were captured. The sampling rate for the accelerometers was 20 Hz; given the height and slenderness of the structure and initial modal analysis, low natural frequencies were expected.

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.

In total acceleration time history data was recorded for ten periods of 12 hours in which the structure's acceleration due to ambient white noise excitation from the wind exceeded a threshold value. Each of these acceleration time histories have been assessed using the Bayesian Fast Fourier Transform (BFFT) and Random Decrement Technique (RDT) in order to identify the natural frequency and damping ratio of the structure. The BFFT was applied as described by Au, 2012 [14], and the RDT was applied as described by Wang, 2013 [15]. The estimated natural frequency and damping ratio in the first mode of the structure in both the x and y horizontal directions were identified and verified using these two methods. The estimated values obtained as the average value from the ten 12 hour monitoring periods are listed in Table 1.

Table 1. Modal properties of in-situ structure

	X-X Direction	Y-Y Direction
Natural Frequency	0.316 Hz	0.326 Hz
Damping Ratio	1.1 %	1.28 %

2.2 Macro Module Element

The macro module element is not an existing element within ETABs software and was created within ETABs from replicating properties from a full ETABs model of a typical individual module. The size, mass, stiffness and natural frequency of the typical module were replicated in the macro module element. The mass of the macro module was extracted from an ETABS analysis of a model of a typical module by considering the base reactions under dead loading. This mass is representative of the mass of the module including the self-weight of non-structural elements as each module arrives to site fully fitted out. The stiffness of the module was found by applying a 100 kN force to the top of the model and recording the deflection; the stiffness could then be calculated using Equation 1.

$$k = \frac{F}{\delta} \tag{1}$$

Where k is the stiffness in N/m, F is the applied lateral force, in this case 100 kN and δ is the lateral deflection in mm.

A modal analysis was run using ETABs in order to obtain the natural frequency of the individual module. The stiffness, mass and natural circular frequency of the module were verified using Equation 2.

$$k = {\omega_n}^2 m \tag{2}$$

Where ω_n is the natural circular frequency in rad/sec, k is the stiffness of the module in N/m and m is the total mass of the module in kg.

Once the stiffness was found, the Modulus of Elasticity, E, of the macro module was found using Equation 3.

$$E = \frac{k\,L}{I} \tag{3}$$

Where E is the Modulus of Elasticity in MPa, L is the length of the module in m and I is the Second Moment of Area of the module in m^4 is calculated using Equation 3.

$$I = \frac{b\,d^3}{12} \tag{4}$$

Where b is the total breadth of the module (m) and d is the total depth of the module (m).

The properties derived from the detailed model of the individual module and adopted for use in the macro module element are shown in Table 2.

Table 2 - Properties of a typical module

Property	Value
Length, L	8.887 m
Breadth, b	3.472 m
Depth, d	2.875 m
Second Moment of Area, I	6.876 m^4
Mass, m	16,927 kg
Stiffness, k	89134223 N/m
Natural Frequency, ω_n	72.5652 rad/sec
Modulus of Elasticity, E	115 MPa

Figure 1 shows the model of a typical individual module whilst Figure 2 shows the macro module element. There are a total of 19 beam, column and shell elements in the detailed model of a typical module, whereas the macro module element consists of only one shell element representing the entire module. When this is considered over the entire scale of the structure, with 1,248 modules in total, this implies a difference of over 22,000 beam, column and shell elements. This does not account for joint and connection elements which are also greatly reduced when the macro module element approach is employed.

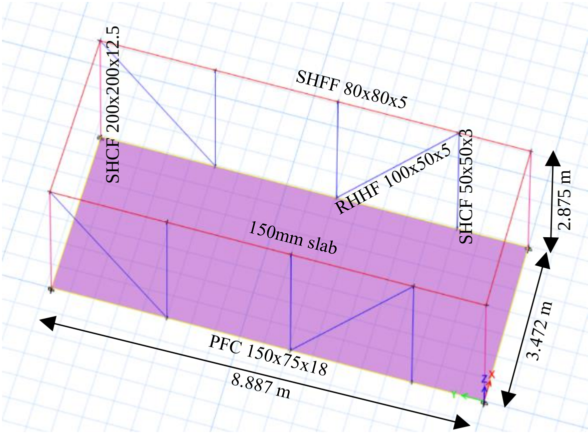

Figure 1. Model of Typical Module

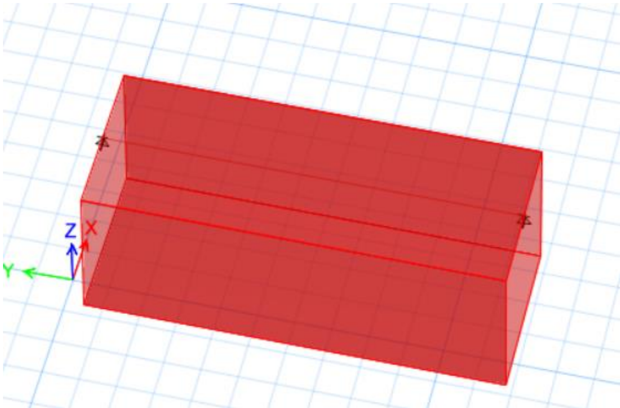

Figure 2. Macro Module Element

2.3 *ETABS Model*

An ETABS model of the concrete cores was built to replicate the actual as built concrete cores of the in-situ building. The model of the concrete cores is shown in Figure 3. In place of a detailed model of each module, one macro module element is used. Single bar elements of steel plates 150mm x 5mm were used to connect the module elements to one another and back to the core. These bar elements represent a simplification of the actual connection between modules. The use of the macro module element reduced the number of elements in the model from over 260,000 to just over 60,000 when compared to using a detailed model with each member of each module being modelled. The run time for eigen value computation reduces from over 180 minutes to 10 minutes. A typical floor plan from a previously developed full model including all module elements is seen in Figure 5. This is in stark contrast to the typical floor plan when macro module elements are used, as shown in Figure 6.

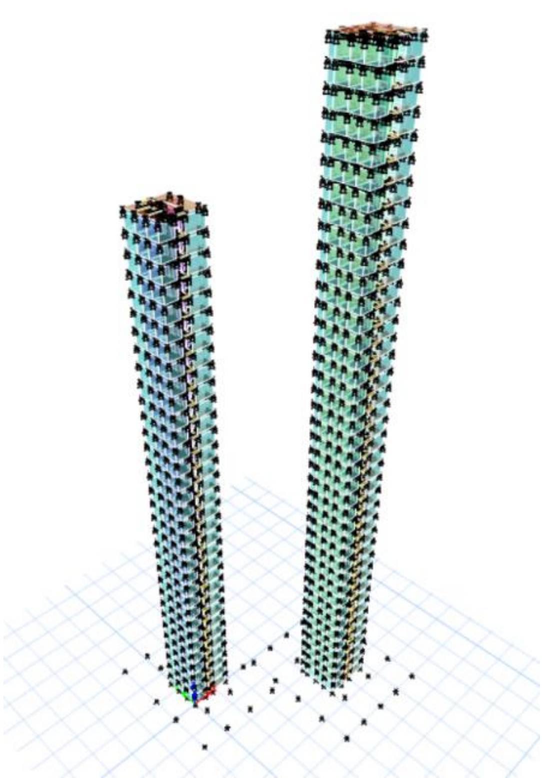

Figure 3. Model of Concrete Cores

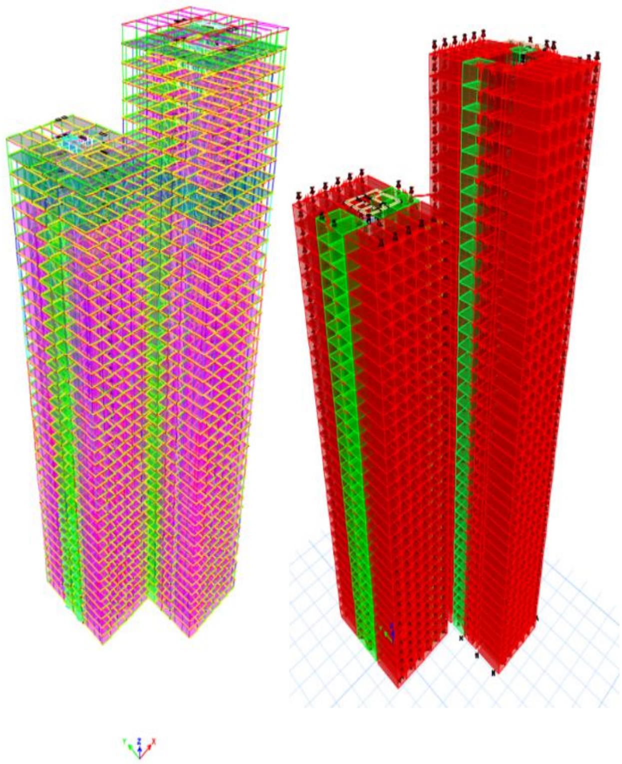

Figure 4 - Full model including all module elements (left) and full model employing macro elements (right)

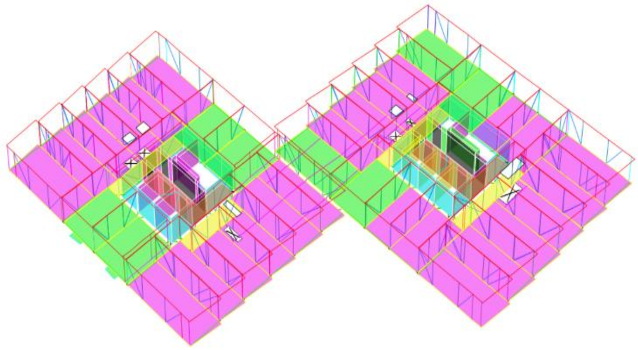

Figure 5. Typical floor plan from full model including all module elements

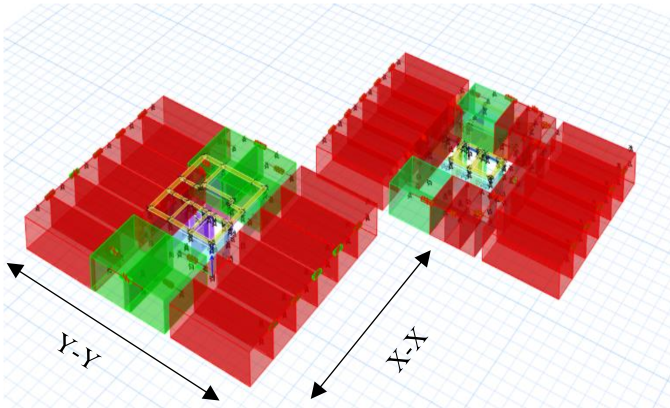

Figure 6. Typical floor plan from model employing macro elements

3. RESULTS

3.1 Validation of Full Module Model

Prior to verifying the macro module element and the full-scale model including the macro module element, the full-scale detailed model including all the individual module elements that the macro module element was created to replace must be validated. To this end, the natural frequencies in the first mode in both the x and y directions of the full model were obtained by completing a modal analysis in ETABs. These values are then compared to the actual measured natural frequencies in the x and y direction of the in-situ building obtained by performing modal identification techniques on its recorded acceleration response, as described in Section 2.1.

Table 3 compares the natural frequencies estimated from the measured in situ response and the ETABs model.

Table 3. Natural frequencies obtained from in-situ data and from full scale model

	X-X Direction	Y-Y Direction
Natural Frequency from modal identification of in-situ acceleration response	0.316 Hz	0.326 Hz
Natural Frequency from modal analysis of full-scale model including all module elements	0.29 Hz	0.31 Hz

It is clear that the modal properties of the full-scale model are in good agreement with the observed dynamic response of the in-situ structure. The natural frequencies obtained from the model are slightly lower than the actual natural frequencies. The actual structure is likely to be somewhat stiffer than is accounted for in the model. The complexity of the connection types used in the construction of the modular building is difficult to represent in an ETABs model and instead a single steel flat plate is used to represent connections. The steel plate is assigned an estimated stiffness value close to what the actual stiffness of the connection is thought to be. There is the potential to tune the modal properties of the model by adjusting this estimated value.

Whilst the natural frequencies estimated from the full ETABs model are slightly lower, it remains an accurate representation of the dynamic behavior of the actual structure. It can be concluded that the detailed model of the module including each member is an accurate representation of the dynamic behavior of an individual model and this is sufficient for use in creation of a macro module element.

3.2 Validation of the Macro Module Element

ETABS modal analyses were performed to identify the first lateral modes on both a model of an individual module with each element modelled and a model consisting of a single macro module element. The results are shown in Table 4.

Table 4. Natural frequencies of alternative module models

	X-X Direction	Y-Y Direction
Full module model with each element modelled	16.95 Hz	12.34 Hz
Macro module element	16.99 Hz	12.36 Hz

It is clear that the natural frequencies obtained from both models lie close in value with very little error. Although the properties of the macro module element were set to reflect the full module model, there is still a slight error in the natural frequency of the macro element. This is likely due to the lumped mass of the macro module element and negligible rounding of values. It is evident that the macro module element can be a suitable substitute for a full model of a single module, indicating that there is significant scope for the macro module element to replace full models of individual modules in a full-scale model of the structure.

3.3 Validation of Macro Module Element Model

The validation of a full model including the macro module element is ongoing. This process involves validation of the full model including the macro element at different stages of construction.

In total, in-situ data was recorded for 10 periods of 12 hours when the structure's acceleration exceeded a threshold value. When the threshold value for acceleration was exceeded, 6 hours of data from before and after the exceedance was used for analysis. The structure was still under construction while a number of these acceleration responses were being recorded and not all modules were installed. The dates in which each 12 hour period began recording and the number of modules installed at this date can be seen in Table 5.

A natural frequency in the first mode in x and y directions was obtained for each of the twelve-hour periods and it is seen to decrease as more stories of modules are installed. ETABS models of the modular structure using macro module elements for each set of conditions in Table 5 are being assessed in order to validate the model, and hence the macro module element at each stage of construction. The verification of the macro module element in each of these conditions will provide more confidence in its effectiveness for a wider variety of structures.

Table 5. Dates in-situ data was recorded and the number of floors of modules installed

Date	Number of Modules Installed	
	Tower A	Tower B
31/08/2019	32	32
02/09/2019	33	32
06/09/2019	34	34
09/09/2019	35	34
11/09/2019	36	34
27/09/2019	41	34
29/09/2019	42	34
11/10/2019	44	37
13/10/2019	44	37
26/10/2019	44	37

4. CONCLUSIONS

A macro module element has been created using properties and modal analysis results from a full model of an individual module employed in high-rise volumetric modular construction. The macro module element has been used to replace the intricate module in full scale modelling of a modular structure. By using the macro module element in the full-scale model, the number of elements reduces from approximately 260,000 to 60,000. This yields a significant reduction in model complexity and run time.

Modal analysis was performed on a full scale ETABs model of a 44-storey modular building to obtain the natural frequency in the first mode of the structure in the x and y directions. These natural frequencies were compared to natural frequencies obtained through performing modal identification on acceleration responses from the actual in situ modular structure. It was found that the natural frequencies of the model were quite close to the actual values. Hence, this verified the intricate model of the individual module.

The macro module element was verified by performing modal analysis on both the ETABs intricate model of a single module and the ETABs model of a single macro module element. It was found that the natural frequencies were in good agreement, hence validating the macro module element.

Work is continuing on validating full scale ETABS models of the in-situ modular structure at different stages of construction. The acceleration responses of the in-situ structure at these stages are being used to compare the natural frequencies and acceleration responses of the models with the macro elements.

It is evident that the use of a macro module element greatly improves the efficiency of modelling a modular structure. It has been shown that a macro module element can accurately represent the global dynamic behavior of a typical module. The use of macro module elements in full models of modular buildings will lead to easier assessment of the dynamic behavior of modular structures and their ability to meet habitability requirements.

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