Wind-induced vibration response of modular high-rise buildings

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Introduction

This article, based on the winning entry to the Institution of Structural Engineers Research into Practice case study competition 2024, describes the collaboration between Tide Construction, Barrett Mahony Consulting Engineers (BMCE), Trinity College Dublin and BMT Fluid Dynamics examining the dynamic behaviour of tall modular buildings. Primarily, the research has addressed uncertainty about the level of inherent damping in volumetric mixed steel-and-concrete modular buildings and has been used to ensure acceptable serviceability performance of tall modular structures. Particular focus has been on the Ten Degrees development in Croydon, London.

FIGURE 1: Europe's tallest modular buildings: College Road (l) and Ten Degrees (r), in Croydon, south London

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Over recent years, interest in modular buildings has increased 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 three-dimensional modules in a controlled factory environment, before modules are transported to site and combined to create a useable building.

The deployment of modular construction for tall buildings is relatively novel[2,3,5]. BMCE, alongside partners at Tide Construction Ltd, Vision Volumetric, and off-site and modular design specialists MJH Structural Engineers, have been at the forefront of tall volumetric modular construction in the UK. Having previously delivered two projects in London: Mapleton Crescent, a 27-storey development in Wandsworth, and Apex House, a 29-storey development in Wembley, in 2020 this partnership completed the Ten Degrees project, which at 43 storeys and 135m high became the tallest volumetric modular building in the world at the time of completion. In 2022, this project was awarded the Council of Tall Buildings and Urban Habitat's Structure Award[6]. Since then, BMCE, Tide, Vision and MJH have partnered again to develop the Lewisham Exchange, and then to surpass the Ten Degrees development with the neighbouring 163m high College Road project (Figure 1).

Ten Degrees comprises two adjoined volumetric modular towers surrounding reinforced concrete cores. Vertical loads are transferred to the ground through the steel-framed modules, with lateral stability provided by the reinforced concrete cores. The construction sequence involved completing the cores to full height before installing modules using cranes erected on top of the cores (Figure 2). This basic structural scheme and construction methodology has been employed in each tall modular project undertaken by BMCE.

Research question

Habitability requirements associated

with excessive acceleration response can become the governing design criterion as building height increases. ISO 10137:2007 stipulates maximum allowable values for peak floor acceleration under a 1-in-1-year wind load[7]. Ensuring volumetric modular buildings meet these requirements is more challenging than for buildings constructed using traditional techniques. There are several reasons for this.

1) The nature of modular construction, where natural divisions exist between modules, means that it is more amenable to residential developments than offices. From a dynamic response viewpoint, this means that modular structures are often required to meet the more stringent vibration criteria imposed for residential buildings, typically limiting acceptable response acceleration to less than 5 milli-*g*.
2) The structural schemes in modular buildings mean that methods to provide lateral stiffness employed in other building types, such as outrigger columns, are difficult to realise.
3) The level of inherent damping in tall modular structures is not well known. It can be hypothesised that the large number of connections and the vertical movement joints between the concrete core and modular steel frames allow for greater levels of hysteretic energy dissipation than in regular construction. However, no value for damping in modular structures had been reported in the literature and this value was a major source of uncertainty in the Ten Degrees project.

Acceleration of tall buildings can be calculated using the results of wind tunnel tests. However, the uncertainty around damping introduces uncertainty into this calculation method for tall modular structures. Unlike mass or frequency, damping does not relate to a unique physical phenomenon, and values cannot be calculated theoretically. Therefore, the only accurate method for obtaining the damping ratio of a building is from full-scale monitoring of the completed structure[8–10]. For conventional structures, various codes and literature recommend suitable values to use in design based on previous monitoring campaigns. However, before Ten Degrees, no such monitoring had been reported for tall modular buildings, meaning that there were no specific recommended values.

Dynamic behaviour of Ten Degrees

Preconstruction, dynamic analysis and design of the Ten Degrees development was undertaken using a series of wind tunnel tests performed by BMT Fluid Dynamics. Results indicated that under a 1-in-1-year wind event there was the possibility of the peak acceleration exceeding the limiting value specified by the ISO 10137:2007 standard. As a precautionary measure, preliminary design of a tuned liquid damper (TLD) was undertaken by BMT **(Figure 3)**. The TLD was limited in size to fit on top of the reinforced concrete core of the taller tower, as there was redundancy in the load capacity due to the crane mounted on top of the core during construction.

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↗FIGURE 2: Volumetric modules being lifted into place around reinforced concrete cores during construction of Ten Degrees

The initial TLD was designed to provide 1.1% additional damping and was validated using shake table tests.

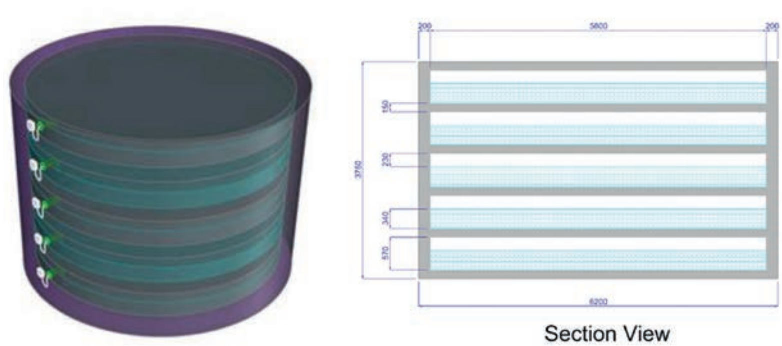
The conclusion of the wind tunnel study and the need for a suitable control measure was dependent on the modal damping ratio, with the building 'passing' at higher levels of damping but 'failing' at lower values. As discussed above, given the novelty of the development, the true value of damping was uncertain, meaning the serviceability performance of the building was unknown.

Driven by this uncertainty, BMCE partnered with academics at Trinity College Dublin specialising in structural dynamics. Collaboratively, a structural response monitoring campaign was developed to obtain modal response parameters, particularly damping. If this damping value was sufficiently high, the building would perform adequately at the serviceability limit state. However, if not, it was proposed to construct an auxiliary TLD to increase the overall effective damping and bring peak acceleration within the ISO limits.

The monitoring campaign, executed by BMT in late 2019, saw two accelerometers installed just below roof level in the taller core to record floor acceleration. A weather station was also installed on the roof to record wind speed and direction. For further details on the monitoring and results from this campaign readers, see Hickey *et al.*[11].

Natural frequencies and modal damping ratios were estimated using the recorded accelerations. The first two natural frequencies of the building were identified as 0.31 and 0.37Hz. There are a variety of techniques available for estimating damping; however, many are not applicable here due to the closely spaced natural frequencies which can cause beating in the signal. Therefore, analytical mode decomposition combined with the random decrement technique (AMD-RDT), which was developed especially to remove beating from the random decrement signal, was employed. The advantage of AMD-RDT for cleaning the

↗FIGURE 3: Proposed tuned liquid damper designed by BMT Fluid Dynamics



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signal can be seen in **Figure 4**. From this, the modal damping ratios were estimated as 1.0–1.1% for the first mode and 1.0–1.3% for the second mode.

Using these results, it was demonstrated that serviceability issues were unlikely to be encountered for Ten Degrees. This informed the final structural design, with the construction of the proposed auxiliary TLD device deemed unnecessary. Thus, thanks to the research, the cost and challenge of damper construction and installation was avoided, representing a favourable outcome for the client.

Wider research impact

The damping values recorded at Ten Degrees represent the first reported value of structural damping for tall modular construction. Interestingly, these values are close to the value of 1.27% recommended for use in mixed steel-and-concrete structures by Eurocode BS EN 1991-1-4[12]. The study found that despite the potential presence of many more friction movement joints, there is no evidence that damping ratios are higher in modular buildings than in their conventional counterparts. Thus, the value recommended by BS EN 1991-1-4 appears sensible for use in design, at least until further data becomes available.

Analysis of the monitored data from Ten Degrees showed that acceleration was unlikely to exceed the allowable threshold. This was due partly to the structure having a sufficient level of inherent damping, but also partly to the stiffness and natural frequency of the finished building being slightly higher than initially anticipated. This is attributable to the contribution of modules to lateral stiffness, which was conservatively assumed as negligible in the initial design phase.

Therefore, in addition to the direct influence on the design, the results also raised further questions which have motivated the continuation of the research partnership for the College Road development. In particular, a detailed investigation of finite-element modelling strategies for tall modular buildings has been undertaken. This has led to the development of a macro-element to represent modules in the ETABS software; work which was named best paper at the Civil Engineering Research Association of Ireland (CERAI) conference in 2022.

A monitoring campaign has recently been undertaken for the College Road development. Due to its larger mass, this project is less likely to be susceptible to serviceability issues; however, it still provides a useful opportunity to gather data that can be used to inform design in the future. The first phase of monitoring involved recording acceleration of the structural cores before and during module installation, while the second phase has involved monitoring the completed structure.

The combination of results from the two phases will allow the impact of lateral stiffness of the modules on the overall natural frequency to be assessed, which will further inform the dynamic design of modular buildings in the future. Additionally, damping values obtained will provide additional knowledge about the typical levels of damping in modular structures and will allow the main conclusions for the Ten Degrees project to be further verified.

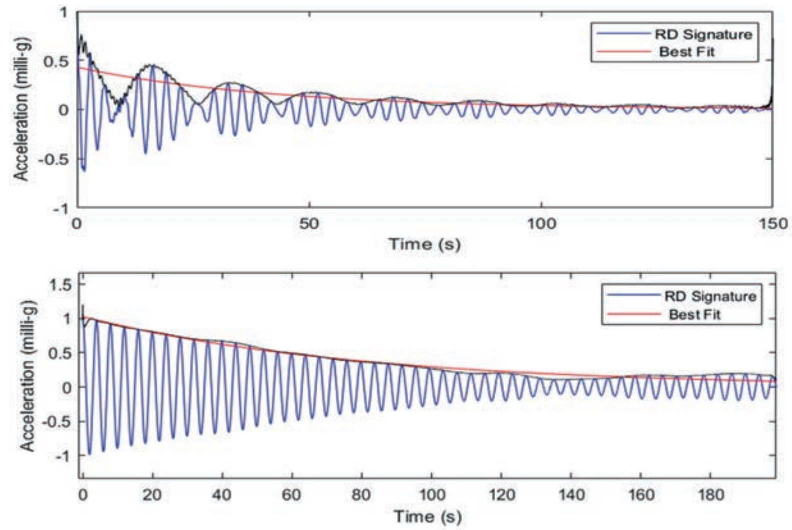

FIGURE 4: Random decrement signal with beating (top) and without beating (bottom)

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REFERENCES

1) Gunawardena T., Ngo T., Mendis P. and Alfano J. (2016) 'Innovative flexible structural system using prefabricated modules', *J. Archit. Eng.*, 22 (4), p. 05016003; https://doi.org/10.1061/(ASCE)AE.1943-5568.0000214

2) Hough M.J. and Lawson R.M. (2019) 'Design and construction of high-rise modular buildings based on recent projects', *Proc. ICE – Civ. Eng.*, 172 (6), pp. 37–44; https://doi.org/10.1680/jcien.18.00058

3) Lawson R.M., Ogden R.G. and Bergin R. (2012) 'Application of modular construction in high-rise buildings', *J. Archit. Eng.*, 18 (2), pp. 148–154; https://doi.org/10.1061/(ASCE)AE.1943-5568.0000057

4) Lacey A.W., Chen W., Hao H. and Bi K. (2018) 'Structural response of modular buildings – An overview', *J. Build. Eng.*, 16, pp. 45–56; https://doi.org/10.1016/j.jobe.2017.12.008

5) Ferdous W., Bai Y., Ngo T.D., Manalo A. and Mendis P. (2019) 'New advancements, challenges and opportunities of multi-storey modular buildings – A state-of-the-art review', *Eng. Struct.*, 183, pp. 883–893; https://doi.org/10.1016/j.engstruct.2019.01.061

6) Council of Tall Buildings and Urban Habitats (2025) *CTBUH Annual Awards: Winners (2022)* [Online] Available at: https://awards.ctbuh.org/winners/?award-year=2022#tabs-winners (Accessed: April 2025)

7) International Organization for Standardization (2007) *ISO 10137:2007 Bases for design of structures - Serviceability of buildings and walkways against vibrations*, Geneva: ISO

8) Feng Z.Q., Zhao B., Hua X.G. and Chen Z.Q. (2019) 'Enhanced EMD-RDT method for output-only ambient modal identification of structures', *J. Aerosp. Eng.*, 32 (4), p. 04019046; https://doi.org/10.1061/(ASCE)AS.1943-5525.0001034

9) Ivanovic S.S., Trifunac M.D. and Todorovska M.I. (2000) 'Ambient vibration tests of structures – a review', *ISET J. Earthq. Technol.*, 37 (4), pp. 165–197

10) Kijewski-Correa T., Kilpatrick J., Kareem A. et al. (2006) 'Validating wind-induced response of tall buildings: Synopsis of the Chicago full-scale monitoring program', *J. Struct. Eng.*, 132 (10), pp. 1509–1523; https://doi.org/10.1061/(ASCE)0733-9445(2006)132:10(1509)

11) Hickey J., Moore H., Broderick B. and Fitzgerald B. (2023) 'Structural damping estimation from live monitoring of a tall modular building', *Struct. Des. Tall Spec.*, 33 (1), e2067; https://doi.org/10.1002/tal.2067

12) British Standards Institution (2005) *BS EN 1991-1-4:2005+A1:2010 Eurocode 1. Actions on structures - General actions - Wind actions,* London: BSI