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Seismic Performance of Composite Modular Buildings with CFST Columns

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Abstract

Modular construction is the off-site production and assembly of building components in a regulated factory setting. It offers an appealing alternative to traditional building in terms of time efficiency, quality control, and addresses labour shortage. Although a few studies have assessed the seismic performance of steel modular buildings, none have been undertaken on composite modular buildings (CMBs) that use concrete-filled steel tubes (CFST). In the present study, the seismic performance of a 10-storey CMB with CFST columns has been investigated. With the use of advanced material models and modelling techniques, nonlinear response of the CFST columns, beams, connections, and braces was simulated by using the OpenSees software through a 3D finite element model. The model was then evaluated by pushover analysis and nonlinear time history analyses for a suite of ground motions. Pushover analysis revealed that the Australian Standards underestimates the ductility and overstrength of CMB systems. Strong performances of the CMB were observed where inter-storey drifts remained within life safety limits. Residual inter-storey drifts were generally small, indicating no to low permanent deformations. The overall promising seismic performance of the mid-rise CMBs with CFST columns represented in this study underlines future research need in the expansion of the current design Standards to include modular structures.

Keywords: Modular buildings, CFST columns, Inter-modular connections, Seismic analysis

1 Introduction

As an alternative to traditional building methods, modular construction involves the production of building components in a factory setting, built into separate modules, and transported to the construction site for final assembly. Fig. 1 shows the corner-supported and the continuous supported modules which are the two types of volumetric modules. Corner-supported modules are picked over continuous-supported modules due to their direct load transfer paths and the lack of continuous support, which allows for greater flexibility in meeting architectural demands. The distinctive features of modular building leads to structural behaviour that differs from traditional construction methods. The disparities can be seen in the structural lateral response. The many connections, beams, columns, and structural discontinuities are the main sources of the disparities. In modular construction, each module has its own set of columns, which later are connected to the columns of other modules at module interfaces. Unlike traditional construction methods, this leads to the concentration of stress at the connections, making them significant in determining the lateral resistance modular structures.

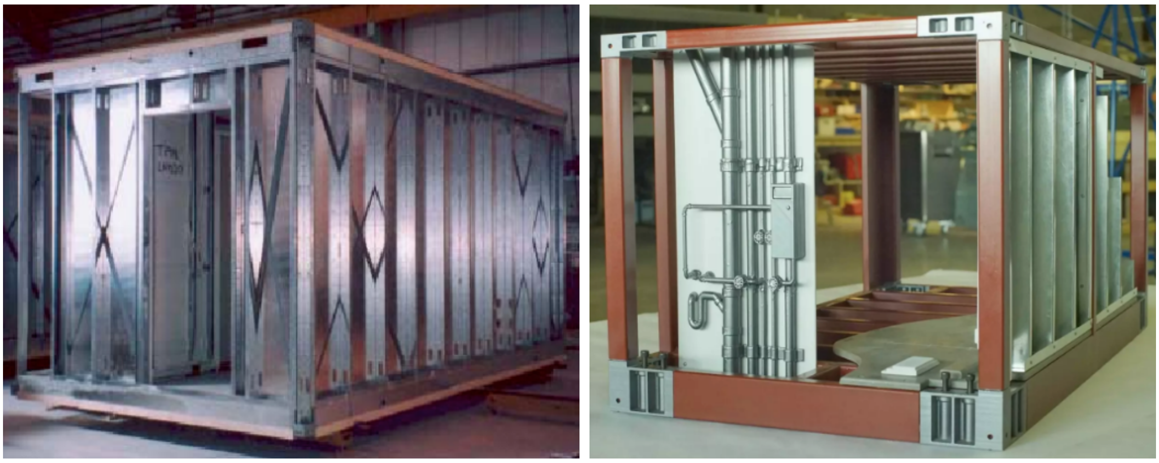


Fig. 1 Continuous-supported modules (left) and the corner-supported module (right) (Thai et al., 2020)

Most research has concentrated on the application of steel in modular buildings. A few research studies (Deng et al., 2020; Farajian et al., 2022; Fathieh & Mercan, 2016; Gunawardena, 2016; Sanches et al., 2021) have examined the seismic behaviour of steel modular buildings, and the results have been favourable in terms of improved seismic performance and reduced damage during severe earthquakes. However, the drawbacks of steel, such as poor heat resistance and low buckling strength, turned the focus to the use of steel-concrete composites. This would improve the benefits of modular buildings by minimising the inherited unfavourable properties of steel through the use of concrete, while avoiding the time-consuming processes required for building concrete elements. Concrete-filled steel tube (CFST) columns is an effective way to incorporate steel-concrete composites into modular construction. Studies on CFST columns (Cai et al., 2021; Tao et al., 2013; Tran et al., 2021) have revealed seismic-resistant features such as enhanced strength, ductility, and fire resistance. However, the seismic performance of composite modular buildings (CMBs) that incorporates CFST columns, remains uninvestigated.

This paper presents an assessment of the seismic performance of mid-rise composite modular buildings in Melbourne, featuring concrete-filled steel tubular columns and designed to Australian Standards (*AS 4100*, 2020; *AS/NZS 2327*, 2017). A detailed three-dimensional (3D) model of a 10-storey building was analysed by pushover and nonlinear time history analyses using the Open System for Earthquake Engineering Simulation (OpenSees) software (McKenna et al., 2010). Using pushover analysis, the strength and ductility of the model was investigated, while seismic performance was assessed based on inter-storey drift (ISD) and residual inter-storey drift (RISD) in both moderate and high seismic regions. The results were then compared to the *FEMA 356* (2000) performance levels and the *FEMA P58-1* (2018) damage states. The findings of this study demonstrate not only the viability of CFST columns in modular buildings but also highlight potential limitations in using the current design standards and the need to expand the current design to incorporate CMBs.

2 Composite modular building case study

2.1 Design and modelling

Australian Standards were used in the design of a 10-story office CMB (*AS 4100*, 2020; *AS/NZS 2327*, 2017). Each floor had thirty corner-supported modules, as shown Fig. 2. The centreline dimensions of each module are 3m wide, 3m high, and 6m long. With a 20mm horizontal gap between each column. Half the depth of the beam, plus a welding gap and the tie plate thickness, was used in calculating the vertical distance between the centrelines of the ceiling and floor beams. While the columns and braces have been designed to withstand lateral forces and adhere to wind serviceability limit state, the beams were designed to for gravity loads only. The building was given a level 3 importance and was located in

Melbourne, Australia, on subsoil class D_e with terrain category 3. The Live load for the floor slabs was determined to be 3 kN/m^2 and 0.75 kN/m^2 for ceiling slabs in accordance with the Standard (*AS/NZS 1170.1*, 2002). The super-imposed dead load for floor and ceiling slabs is 1kN/m^2. The cross-sectional area and material of the element were used to compute the dead load. Table 1 summarises the size and material properties of the structural elements used in the numerical model.

To accurately simulate the behaviour of the building and incorporate the influence of torsional modes a 3D model was used as shown in Fig. 3. The CFST columns were modelled by using the fibre-based distributed plasticity approach, where the steel tube and the concrete core were modelled as fibres with specific assigned stress-strain relationships developed from confined concrete and steel material models. A single "forceBeamColumn" element was used, as illustrated in Fig. 4, which had five Gauss-Lobatto integration points. As can also be seen in Fig. 4, the concentrated plasticity approach was used to simulate the potential development of plastic hinges by modelling the hollow steel beams as an elastic element with two rotational springs at the two ends. Modular construction involves connecting structural components in factories (intra-modular connection) to create modules, which are subsequently assembled and connected on-site (inter-modular connection) and to the foundation (module-to-foundation connection) to form the building. Fig. 5 shows the innovative connection modelling approach used in the case study model. The efficiency of these modelling approaches has been validated in our previous paper (Morsy et al., 2024).

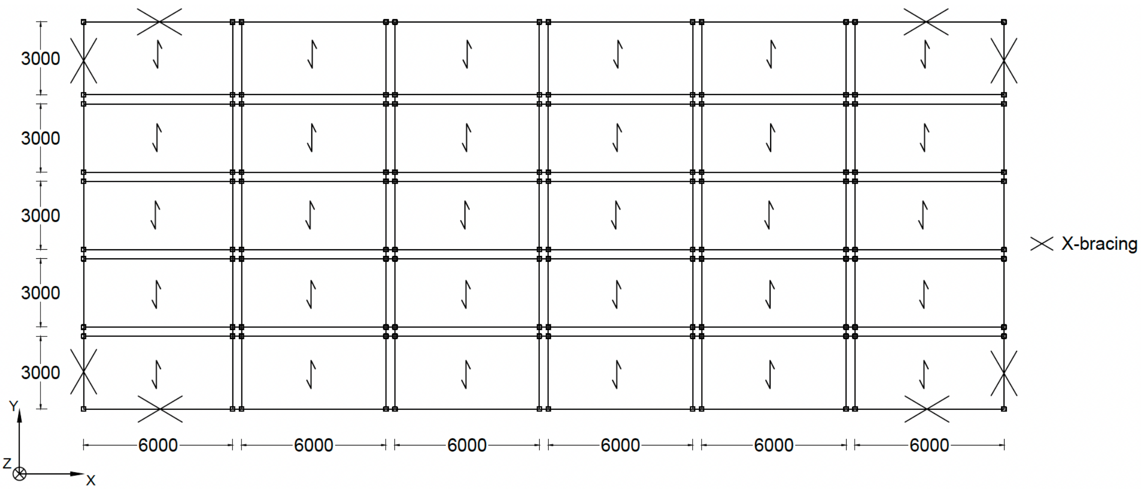


Fig. 2 Plan view of the 10-storey CMB. (Morsy et al., 2024)

Table 1. Structural member section sizes and materials used in the analysis model. (Morsy et al., 2024)

Element	Material	Section size: 1st to 5th storey	Section size: 6th to 10th storey	Notes
Floor beams	Steel	RHS 150x100x10		S355
Ceiling beams	Steel	SHS 80x6.3		S355
CFST columns	Steel	SHS 150x10	SHS 150x5	S355
	Concrete			$f_{ck} = 40\ MPa$
Braces	Steel	HSS 90x5.6 HSS 90x7.1*	HSS 80x4.5 HSS 80x3.6*	S355
Tie plate	Steel	14 mm		S460

* In the Y-direction

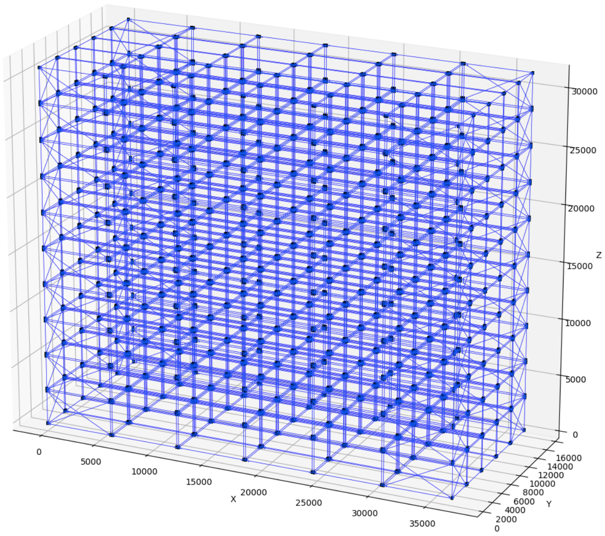


Fig. 3 CMB 3D model.

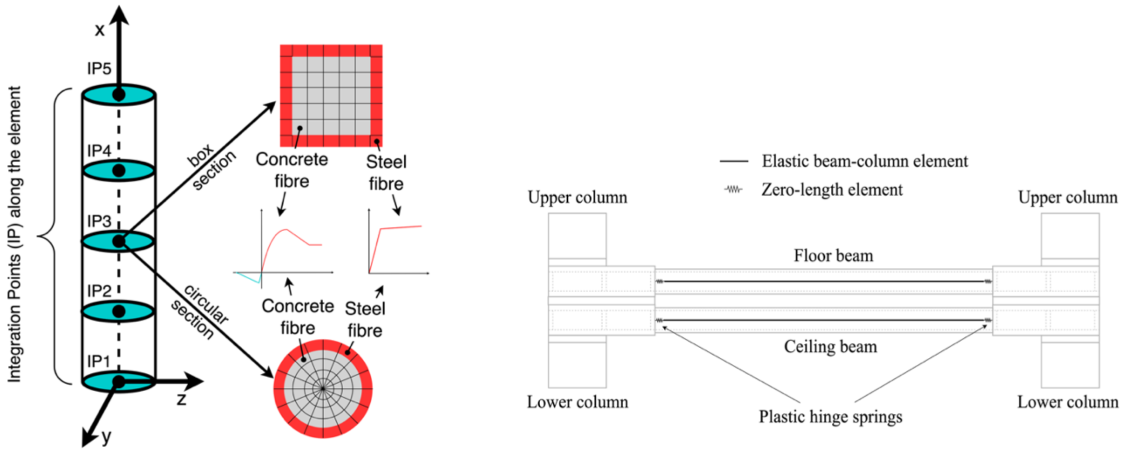


Fig. 4 CFST columns fibre section model (left) and beams concentrated plasticity model. (Morsy et al., 2024)

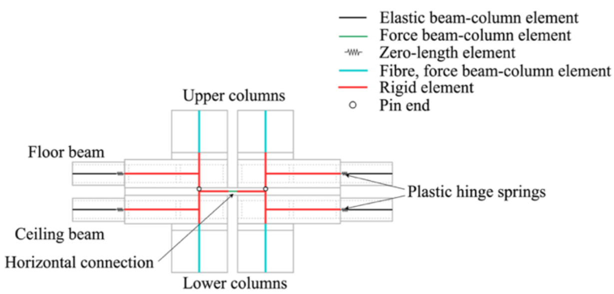
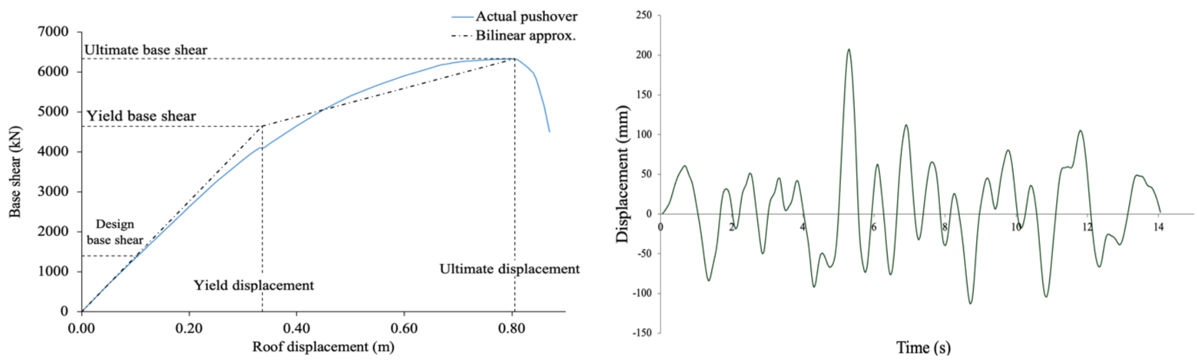


Fig. 5 Connections modelling approach. (Morsy et al., 2024)

2.2 Results

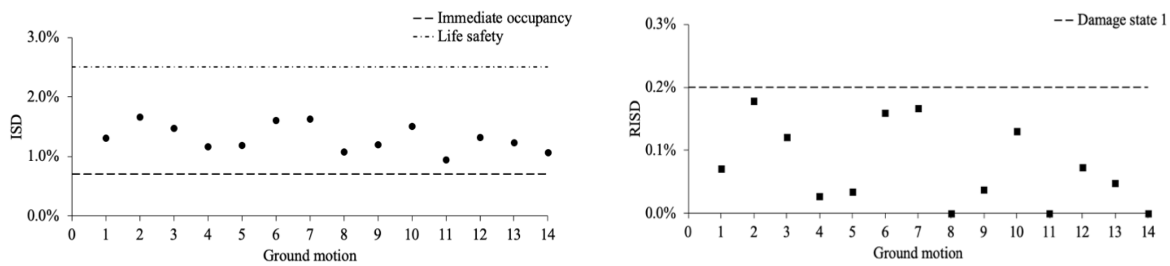
The nonlinear analyses carried out in this study include nonlinear static pushover and nonlinear time history analysis. The pushover analysis was carried out to obtain the ductility and overstrength of the building by laterally displacing the structure incrementally. The pushover curve was idealized as bilinear while ensuring the area beneath both curves, up to the ultimate displacement, remained approximately equal (Sanches et al., 2021). The actual pushover curve, which illustrates the building's lateral behaviour in the Y-direction, and the bilinear approximation can be seen in Fig. 6(a). In general, the results from the pushover analysis showed that the current Standards significantly underestimated the overstrength of the building. The overstrength factor was determined as the ratio of the ultimate base shear to the design base shear. Similarly, the ductility was calculated as the ratio of the ultimate displacement over the yield displacement (Sanches et al., 2021). In the Y-direction, the structure exhibits an overstrength factor of 4.53, significantly exceeding the Standard's (*AS 1170.4*, 2007) value of 1.30. Similarly, the ductility factor of 2.40 surpasses the Standard's value of 2. Nonlinear time history analysis evaluated the seismic performance for a suite of 14 ground motions at different hazard levels: baseline seismicity earthquake and an amplitude scaled version to simulate high seismicity regions. Ground motions used in this study were derived by (Hu et al., 2022, 2023) using a conditional mean spectrum matched to the Standard (*AS 1170.4,* 2007) spectrum for bedrock conditions. The bedrock ground motions were then used as input for site analysis to generate ground motions for class D_e. To shorten nonlinear time history analyses, record durations were shortened using the strong motion duration approach, defined as the time interval between 5% and 95% cumulative Arias Intensity (Sanches et al., 2021). Several key metrics were recorded, including inter-storey drift (ISD), and the residual inter-storey drift (RISD) to assess the structural performance, where RISD was calculated following (*FEMA P58-1*, 2018). Fig. 6(b) shows the roof displacement against the shortened time for one of the ground motions.

The composite modular building showed robust seismic performance for the two hazard levels. Although the ISD for the baseline seismicity earthquake hazard level was within the acceptable limit for immediate occupancy. The ISDs exceeded the immediate occupancy limit for higher hazard level ground motions but remained within the life safety limit, as shown in Fig. 7(a). The results suggests that the building will suffer minor damage during moderate seismic events, while maintaining structural integrity under more severe events. The RISD were almost zero for baseline seismicity earthquake hazard level and only minor residual deformations, not exceeding damage state 1, were observed for the scaled ground motions, as shown in Fig. 7(b). These results suggests that the building that would require minimum repair cost after an earthquake event, lowering repair costs and downtime.



(a) *(b)*

Fig. 6 (a) Pushover results in the Y-direction and (b) the displacement-time history from the nonlinear time history analysis.



(a) *(b)*

Fig. 7 Nonlinear time history results for (a) the ISD and (b) the RISD for the scaled ground motions.

3 Preparation of small-scale model for shake table testing

Currently, a small-scaled model is under development to perform a shake table test that will serve to validate the modelling approaches used and provide a benchmark for corner-supported modular buildings. Since it will be a small-scaled test, steel hollow columns are going to be used instead of CFST columns. Validation of the models of modular buildings is crucial for future research.

The small-scale model will be made up of modules whose dimensions are provided in Section 2.1. The scaled model will consist of two modules in the X-direction and three modules in the Y-direction with a height of four stories, as shown in Fig. 8. A scale of 15 will be used for the test, resulting in a total length of 0.8m in the X-direction, 0.6m in the Y-direction, and a height of 0.9m. For each module, in order to represent the diaphragm effect of floor slabs, cross-bracing was added. Beams will be welded to the columns in order to form intra-module connections. A plate shall be welded on top corners for each module for inter-module connections. During assembly, an additional plate will be added to represent the horizontal inter-module connections. These plates are then bolted together to form the vertical inter-module connection.

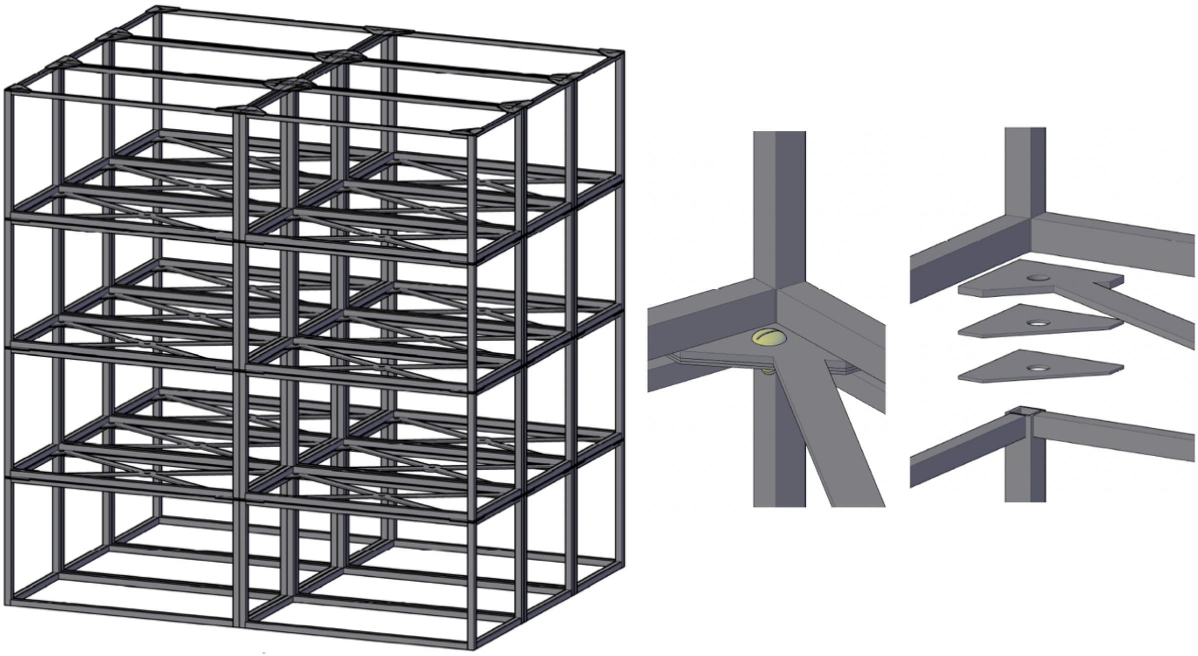


Fig. 8 3D view of the scaled-down prototype (left) and the corner connections details (right).

4 Conclusions

In this paper, advanced modelling techniques were utilised, implementing OpenSees software in order to study the seismic performance of a 10-storey CMB with CFST columns. The nonlinear analyses, including pushover and nonlinear time history, show that current Australian Standards significantly underestimate overstrength and ductility of the building. Results of the pushover analysis demonstrated the favourable seismic performance of the CMB, while nonlinear time-history analyses showed that during the baseline seismic event, ISD remained below life safety limits. During strong and very strong seismic events, these exceed life safety threshold but remain within immediate occupancy drifts.

In the case of moderate seismic events, the RISD, were negligible, while in the case of more intensive ground motions, these remained minimal. As a result, CMB systems will sustain only minor, repairable permanent damage, this will contribute to reducing time and cost to restore the building after a seismic event. These findings confirm the efficiency in CFST-based modular construction for seismic risk mitigation in the case of mid-rise buildings. A small-scale shake table test is currently underway to validate the modelling approaches used and provide a benchmark for corner-supported modular buildings, further advancing our understanding and supporting the integration of modular construction into current seismic design Standards.

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