The 2025 World Congress on
Advances in Structural Engineering and Mechanics (ASEM25)
BEXCO, Busan, Korea, August 11-14, 2025

Analysis of thermal-structural performance of modular buildings under various compartment fire locations

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ABSTRACT

Modular construction is increasingly being adopted in the building industry due to its benefits over conventional construction, such as faster construction time, cost efficiency, ease of assembly, and a more sustainable approach to building. However, research on the behaviour of modular buildings under fire conditions remains limited. This study investigates the thermal and structural performance of composite modular buildings when exposed to fire. The numerical simulation of the fire response of concrete-filled steel tubular (CFST) columns, which are the key structural components in the modular buildings, is validated against experimental data. The agreement between numerical and experimental results confirming the accuracy of the modelling approach. A full three-dimensional model of a modular building is then developed using SAFIR software to simulate fire exposure. A parametric study is conducted by applying fire to different locations in the building, including a right bottom corner, a mid-bottom compartment, and a central compartment. Results indicate that fire exposure at corner locations leads to the most severe structural consequences, while fire in central areas results in comparatively lower impacts. This highlights the critical role of adjacent compartments and their contribution to load redistribution from fire-exposed zones.

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1. INTRODUCTION

Modular construction is an emerging method in which complete building units are prefabricated in a factory, transported to site, and assembled to form the final structure. This approach allows 70 to 95 percent of construction activities to be completed off-site in a controlled environment, resulting in improved quality, reduced schedules, and fewer on-site hazards Thai (2020). It also reduces environmental impacts by minimising material waste, dust, and noise. Compared to traditional methods, modular systems offer safer working conditions, greater productivity, and more consistent workmanship. These advantages have led to their growing use in residential, commercial, and institutional projects worldwide. Several notable buildings highlight the application of volumetric modular construction, including the La Trobe student tower in Melbourne, Croydon Tower in the United Kingdom, and the B2 Tower in the United States Thai (2020). While widely adopted for low- to mid-rise buildings, applying this method in high-rise structures introduces challenges such as inter-module load transfer, floor diaphragm action, connection detailing, and global stability under extreme conditions including fire.

Fire safety is a key concern, particularly as building height increases. In taller structures, the severity of fire exposure and the consequences of component failure become more critical. Past incidents, such as the First Interstate Bank fire (1988), Windsor Tower (2005), World Trade Center buildings (2001), and the Plasco Tower (2017), show the devastating human and economic impacts of uncontrolled fires Lama (2024). Prolonged heating can lead to thermal expansion, catenary action, strength degradation, and ultimately, progressive collapse. Therefore, achieving system-level fire resilience is essential in modular building design.

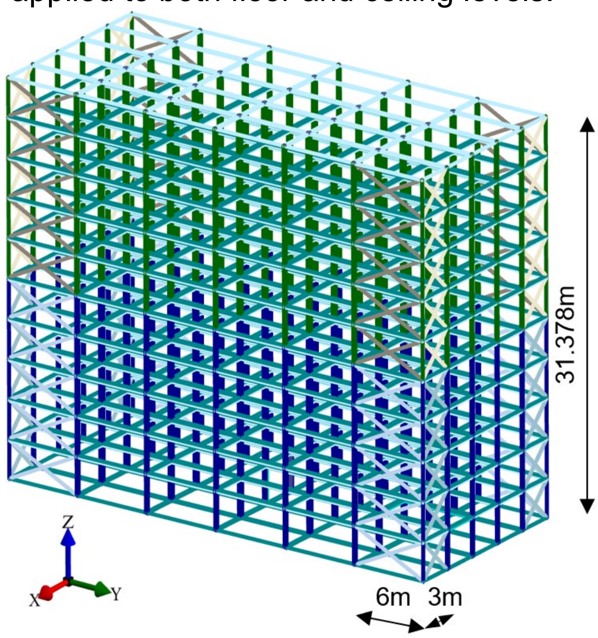
Most previous studies have focused on steel modular frames. However, bare steel has significant limitations under fire, including rapid strength loss, local buckling, and low thermal resistance. To overcome these issues, concrete-filled steel tubular (CFST) columns offer a promising solution. The concrete core absorbs heat and slows the temperature rise of the outer steel tube, while the tube restrains the concrete and delays spalling. Together, they enhance axial capacity and delay failure under fire conditions. Despite their advantages, composite modular systems remain underexplored. (Swami 2023) numerically studied a ten-storey CFST modular building and proposed dynamic amplification factors based on failure modes such as gusset plate shear and column buckling. (Peng 2022) analysed two- to twelve-storey composite modules under column removal scenarios.

Research on fire performance is more limited. (Agarwal 2014) examined ten-storey steel buildings under realistic compartment fires and emphasised the role of gravity columns and slab reinforcement in resisting collapse. (Thomas 2018) investigated progressive collapse in steel frames under localized fire, showing that thermal forces, especially during the cooling phase, can critically affect load redistribution and trigger collapse. (Venkatachari 2020) demonstrated that fire location and spread significantly influence the onset of collapse, suggesting current insulation guidelines may not be sufficient under severe fire conditions. (Shan 2022) found that while steel modular buildings could withstand isolated fires, travelling fires caused global collapse, especially in buildings with higher load ratios and slender members.

While composite modular buildings have the potential to perform well under fire conditions, their performance remains underexplored. Therefore, this study investigates the behaviour of a composite modular building under fire. It begins with the validation of CFST columns and then conducts a parametric analysis to examine the influence of fire location and the response of key structural elements, aiming to support the development of fire-resilient design strategies.

2. Building Geometry and design fire curve

The prototype building used in this study is based on the composite modular office building developed by (Morsy 2025). It is a ten-storey structure designed in accordance with Australian standards (AS/NZS 2327:2017) and (AS 4100:1998). Each floor consists of 30 volumetric modules arranged with corner-supported connections, as shown in Fig. 1. The center-to-center dimensions of each module are 6 m × 3 m × 3 m. A horizontal gap of 20 mm separates adjacent modules, while the vertical spacing between the ceiling beam of one module and the floor beam of the module above is governed by the thickness of the gusset plate, welding gap, and half the depth of the inter-module connector. Each module is framed using four corner CFST columns. Ceiling beams are fabricated from steel square hollow sections (SHS), while floor beams use steel rectangular hollow sections (RHS). Detailed section properties and dimensions are listed in Table 1. For the purposes of this research, the floor system is assumed to be a composite slab comprising a profiled steel deck with embedded reinforcement. The ceiling slab is modelled as a gypsum board system supported by ceiling beams, and partition walls are assumed to consist of double-layer gypsum boards. The imposed live load for the office occupancy is taken as 3.0 kN/m² for the floor slab and 0.75 kN/m² for the ceiling slab. In addition, a floor finish load of 1.0 kN/m² is applied to both floor and ceiling levels.



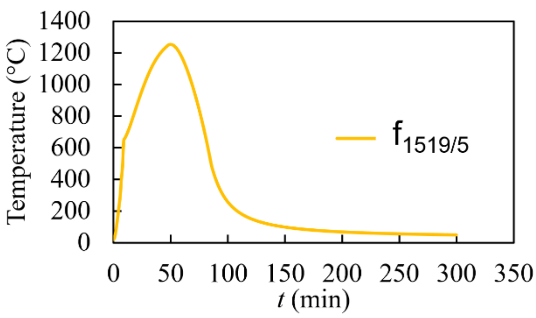


Fig. 1. 10-storey modular building

Fig. 2. Design fire curve

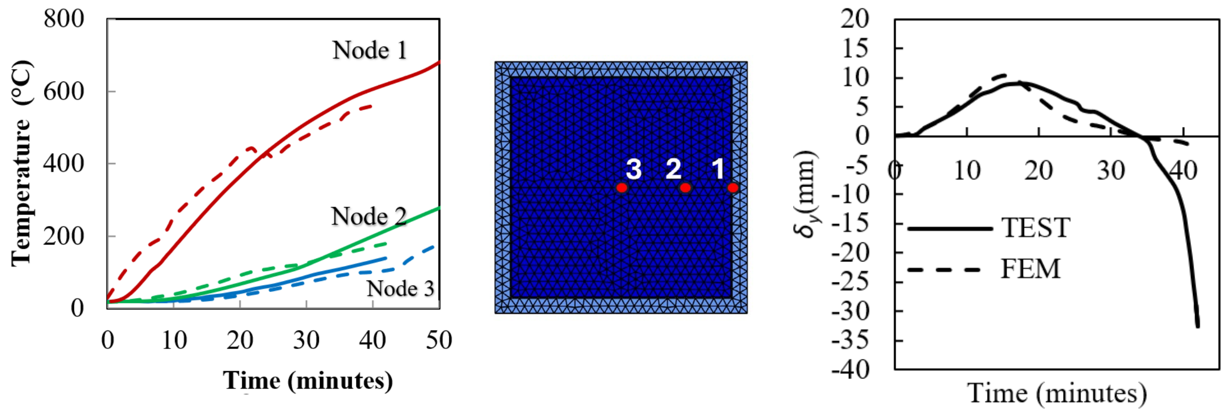
Table 1 Details

Components	Materials	Section size	
		1^{ST} to 5^{th} story	6^{th} to 10^{th} story
CFST columns	Concrete: 40 MPa Steel: 355 MPa	SHS 150×10	SHS 150×5
Floor beams (FB)	Steel: 355 Mpa	RHS 150×100×10	
Ceiling beams (CB)	Steel: 355 Mpa	SHS 80×4.5	
Braces (B)	Steel: 355 MPa	HSS 90×5.6	HSS 80×4.5
		HSS 90×7.1*	HSS 80×3.6*

A fuel load density of 1519 MJ/m² is adopted in this study, based on surveyed data from closed office compartments at the University of Buffalo, as reported by (Elhami-Khorasani 2021). This reference was chosen for its case-study-based approach, which provides realistic and building-specific assessments of fuel loads in university office environments. The design fire curve is developed using Ozone software Cadorin (2003), based on the fuel load of 1519 MJ/m² and the selected opening factor of 0.05. The resulting fire curve is illustrated in Fig. 2.

4. Validation of FE modelling

The accuracy of the numerical model was assessed by developing ten finite element (FE) models of CFST columns using SAFIR and validating them against experimental results from published studies Lama (2024). These columns were subjected to both uniform and non-uniform fire exposure conditions. The numerical results were compared with experimental data in terms of temperature distribution across the cross-section, axial and lateral displacements, failure modes, and fire resistance. The comparison showed good overall agreement, confirming that the model is capable of capturing the thermal and structural response of CFST columns under fire conditions. Fig. 3 presents a representative comparison of temperature distribution and vertical displacement demonstrating this agreement. Minor discrepancies were observed, such as slight differences in temperature and axial displacement and more abrupt failure in the numerical models compared to the experimental outcomes. These variations are likely due to idealised modelling assumptions, including simplified material properties and confinement effects, which may not fully represent the complex behaviour observed in physical tests.



(a) Time-temperature curves (b) Vertical displacement

Fig. 3. Predicted vs. measured results for column LSH1 Xiong (2021)

4. FE modelling of the building

The thermal-structural behaviour of the composite modular building is analysed using the nonlinear finite element software SAFIR Franssen (2017), which is specifically developed for structural fire analysis. A sequentially coupled approach is used: first, thermal analysis determines temperature distributions based on heat transfer mechanisms, which are then applied to structural analysis to evaluate fire-induced deformations and mechanical response. The material properties for thermal and structural analysis are based on Eurocode EN 1992-1-2, EN 1993-1-2 and EN 1994-1-2.

In the thermal model, columns, floor beams, ceiling beams, and connectors are developed using 2D thermal elements. For concrete, standard values for mass, moisture content, emissivity, and thermal conductivity are applied. Steel emissivity is taken as 0.7. A 1 mm air gap is assumed between the steel tube and concrete infill to account for thermal expansion differences. Fire exposure is applied only to the inner surfaces of columns and ceiling beams, with all other surfaces at 20°C. Floor beams are assumed to be protected within composite slabs and kept at ambient temperature.

The structural model is developed using 3D beam elements, comprising 45617 nodes and 20830 beam elements with 8 section types. Beam-to-column connections are modelled as rigid, and inter-module connections are represented as semi-rigid in the horizontal direction and pinned in the vertical direction. The applied loads include floor finishes, live loads, and wall loads, with the reduced fire load combination (DL + 0.3LL) used as EN 1991-1-2 for office occupancy scenarios.

5. Parametric Study

The parametric study examines the influence of fire location at the ground floor by analyzing three scenarios under the f1519/5 fire curve. Case I involves fire in the central compartment, fully surrounded by adjacent modules, as shown in Fig. 4. Case II represents a mid-bottom compartment with one side open due to the absence of an adjacent module. Case III is a corner compartment with two open sides, lacking adjacent modules on both the bottom and right. These configurations result in varying boundary conditions and levels of structural restraint, which significantly affect fire performance. Case III, with the least lateral support, fails earliest at 50 minutes. Case II, offering moderate restraint, fails at 136 minutes. In contrast, Case I benefits from full confinement and structural redundancy, withstanding the entire fire duration of 300 minutes.

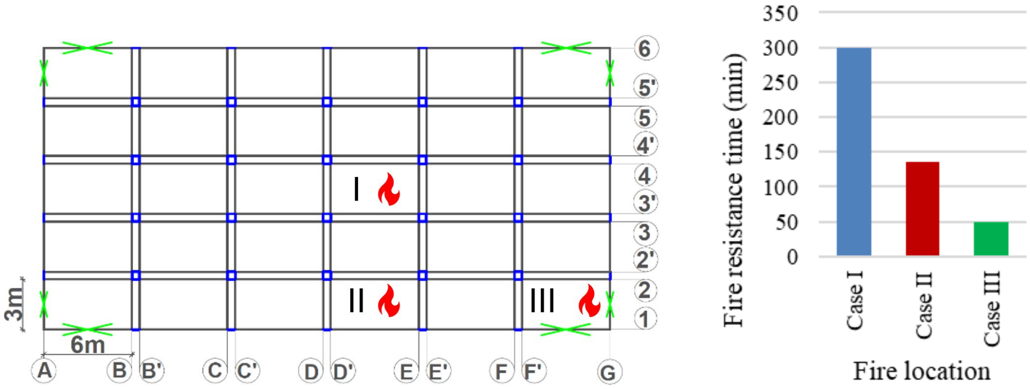


Fig. 4. Fire location and fire resistance time

5.1 Deformation Response

When exposed to fire, columns initially expand due to heat, enter a brief stabilization phase, and then shorten as materials degrade. The deformation behaviour varies notably with fire location. In Case I, where fire occurs in the mid compartment, all fire-exposed columns show similar patterns, with maximum vertical expansion of around 6.5 mm as shown in Fig. 5. This is due to symmetrical confinement from adjacent compartments and the presence of connectors that restrict thermal movement. In Case II, with fire in a mid bottom compartment, reduced restraint on the open side leads to greater expansion. Edge columns C_D'1 and C_E1 expand up to 8.6 mm, while more confined columns C_D'2 and C_E2 expand less, around 7.7 mm. This difference is due to lateral restraint conditions. The open side provides minimal resistance to thermal expansion, while the connected side offers additional confinement. In Case III, where fire occurs in a corner compartment, the absence of adjacent modules on two sides results in the largest vertical expansion. Column C_G1 expands up to 9.5 mm, followed by C_F'1 and C_G2 at 9.2 mm, whereas the more confined column C_F'2 expands only 7.7 mm. Horizontal displacement follows a similar trend. Top displacements of the columns increase with the reduction in surrounding restraint, reaching 5.7 mm in Case I, 6.6 mm in Case II, and 7.7 mm in Case III as shown in Fig. 6,. This increasing displacement can lead to misalignment of axial loads from upper modules, introducing eccentricity and additional bending, which reduce column stability.

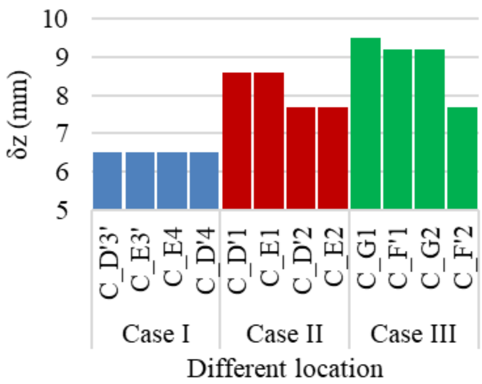


Fig. 5. Axial displacement at column top

Fig. 6. Lateral displacement at column top

5.2 Axial load transfer mechanism

In Case I, fire-exposed columns initially expand, generating compressive forces that stabilize and later decrease as the columns contract. Tensile forces then develop due to restraint from the surrounding structure and inter-module connectors, reaching about 400 kN, as shown in Fig. 7. All columns show a similar load–deformation response due to uniform boundary conditions. In Case II, with one side open, deformation becomes asymmetric. Edge columns develop lower compressive forces, around 400 kN, while more restrained corner columns reach up to 450 kN. Although the overall trend is similar to Case I, failure occurs earlier at which corner columns enter the tensile stage, and edge columns provide minimal resistance. In Case III, with fire in a corner compartment, an initial drop in compression is observed, as illustrated in Fig. 8 due to unrestrained early expansion. As restraint from connected components develops, the columns follow a typical pattern. Column C_F’2 shows the highest compressive force, followed by C_G2, C_G1, and C_F’1. After peak compression, the corner column sheds load earlier, likely due to the presence of cooler adjacent columns, whereas others retain load longer due to limited support.

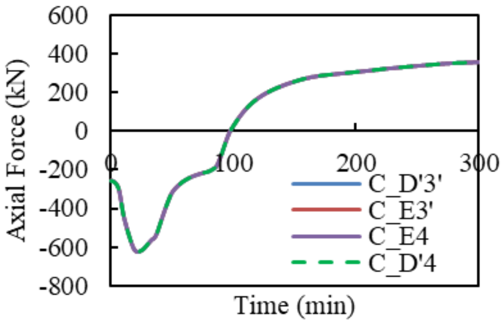


Fig. 7. Axial force in columns -Case I

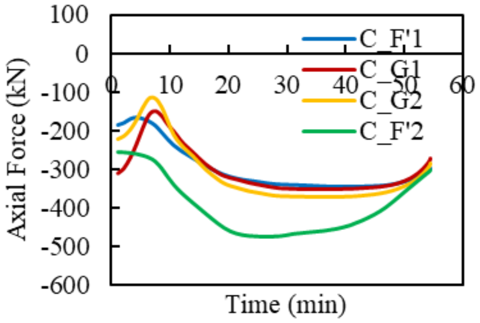


Fig. 8. Axial force in columns-Case III

The ceiling beams exhibit variation in axial forces during fire exposure. As they expand due to heating, compressive forces increase, reach a peak, and then gradually decrease, as shown in Fig. 9. This general trend is observed in all cases, with the surrounding structure, particularly the upper floor beams and adjacent ceiling beams, helping to maintain force equilibrium. In Case I, the upper floor beams share the increased forces in a relatively uniform manner. In Case II, the ceiling beam CB_D’E1 lacks an adjacent compartment and corresponding beams, resulting in an imbalance. Its axial load is largely transferred to the upper floor beam UFB_D'E1, which carries up to 230 kN, while the opposite beams support only 90 kN, as shown in Fig. 10. This difference is due to uneven boundary restraint. In Case III, the imbalance is more pronounced due to fire in a corner compartment, where two sides lack adjacent modules. Ceiling beams CB_G12 and CB_FG1 have no neighboring components to assist with load sharing. As a result, the short upper floor beam UFB_G12 carries approximately 500 kN, while UFB_F'12 carries 280 kN. On the longer side, UFB_F'G1 bears 290 kN, whereas UFB_F'G2 carries only 100 kN. These differences reflect the significant impact of fire location and boundary conditions on axial force redistribution in modular structures.

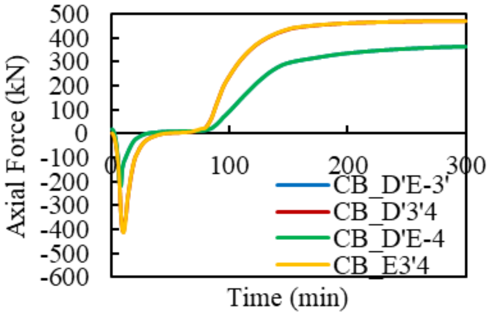


Fig. 9. Axial force in ceiling beam-Case I

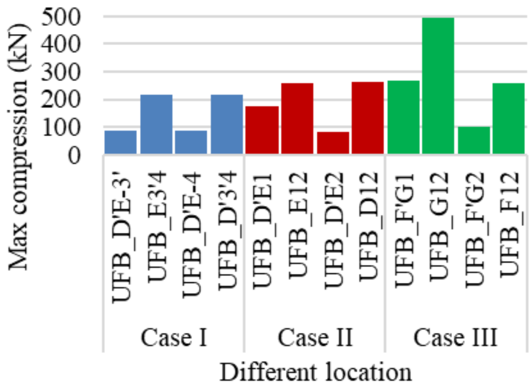


Fig. 10. Maximum compressive force in upper floor beams

3. CONCLUSIONS

This study investigates the structural behaviour of a modular building under fire exposure. The analysis begins with the validation of a key structural component, the CFST columns. Following this, a parametric study is conducted by varying the fire exposure locations. The key conclusions drawn from the research are outlined below.

- A FE model was developed which captures the behavior of CFST columns, connectors and the overall building response effectively.
- Fire location significantly affects structural performance. Corner fires lead to earlier failure due to limited restraint, while central fires provide greater fire resistance through full confinement.
- Boundary conditions strongly influence deformation. Columns in corner compartments show greater vertical and lateral expansion than those in central areas.
- Axial force redistribution is more effective in well-confined regions. Edge columns carry higher loads under rising temperatures due to reduced support, increasing failure risk.
- Lack of adjacent compartments leads to imbalanced axial forces, with edge-connected upper floor beams carrying much higher loads during fire.

ACKNOWLEDGMENT

This research was supported by the Australian Research Council (ARC) under its Future Fellowship (FT200100024) and Discovery Project (DP230100018). In addition, the first author would like to acknowledge The University of Melbourne, the Melbourne Research Scholarship and the Building 4.0 CRC top-up scholarship for doctoral degree research support.

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