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Fire performance and behvaiour of steel modular joints under tensile load- A numerical study

*Tattukolla Kiran[1,2], Huu-Tai Thai[1], Tuan Ngo[1], and Brian Uy[3]

[1] Department of Infrastructure Engineering, The University of Melbourne, Victoria 3010, Australia.
[2] Building 4.0 CRC, The University of Melbourne, Victoria 3010, Australia.

[3] School of Civil and Environmental Engineering, The University of New South Wales, Kensington, NSW 2052, Australia.
[1,2] tattukollak@student.unimelb.edu.au

ABSTRACT

The fire resistance of structures has become a fundamental consideration in the design of mid and high-rise modular buildings. Steel modular joints play a crucial role in structural performance in both ambient and elevated temperatures. When the steel modular joints are exposed to fire scenarios, the degradation of their strength properties makes them vulnerable to structural failure. However, studies on fire resistance (in terms of duration) and the behvaiour of inter-modular joints under non-uniform fire conditions remain unexplored. This research aims to develop a detailed non-linear three-dimensional finite element model to evaluate the fire resistance and behaviour of the inter-modular joint subjected to axial tensile load. The study employs a sequentially coupled thermal-stress analysis to predict the thermal and mechanical behaviour of the inter-modular joint. An internal modular joint connection is considered in the study. This paper presents detailed thermal and mechanical modelling and simulation procedures considering non-uniform fire scenarios. A comprehensive parametric analysis is conducted, including load ratios, different fire exposures, the diameter of the bolts, and gusset plate thickness. The results indicate that the internal modular joint connection showed two hours of fire resistance at a 30% load ratio. The findings of the study can be used to develop fire design guidelines for proposed inter-module connections.

[1,2] Doctoral candidate
[1] Professor
[1] Professor
[3] Professor

1. INTRODUCTION

Over the past decade, the Steel Composite Modular Prefabrication Construction System (SCMPCS) has emerged as a highly promising construction approach, owing to its advanced technological implementation, structural efficiency, sustainability, and cost-effectiveness. SCMPCS represents an innovative off-site construction technique wherein structural components are fabricated and assembled into volumetric or structural modules before on-site installation [Thai et al. 2020]. In the context of mid and high-rise modular construction, SCMPCS has gained significant attention for its potential to revolutionize conventional building methods by offering numerous advantages, including reduced construction time, enhanced quality control, and minimized environmental impact. Its applications span a broad range of building types, including mid- and high-rise residential complexes, industrial facilities, emergency shelters, disaster relief housing, and healthcare infrastructure such as hospitals [Liew et al. 2019].

The SCMPCS approach entails the off-site fabrication of structural modules, which typically include key internal components such as floor and ceiling beams, composite columns, walls, and integrated mechanical, electrical, and plumbing (MEP) systems. These prefabricated elements are subsequently assembled on-site, enabling significant benefits such as accelerated construction timelines, enhanced structural resilience, superior quality control, reduced environmental emissions, and overall cost efficiency. A critical aspect of modular construction lies in the connection system between adjacent modules. However, the development of modular connection systems that simultaneously provide ease of assembly, adaptability in manufacturing, material efficiency, and cost-effectiveness remains a significant challenge [Ferdoius et al. 2019].

Inter-module connections in modular construction systems are generally categorized into three primary types: bolted connections, post-tensioned systems, and self-locking mechanisms [Chen et al. 2017]. Among these, bolted connections are widely favored in structural steel applications due to their simplicity in fabrication and straightforward assembly using standard components such as nuts and washers. Several bolted connection strategies have been adopted in modular construction, including extended plate joints, bolted intermediate plates, overlaying extension plates, and cover plates incorporating blind bolts [Yang 2000]. In contrast, post-tensioned connections utilize high-strength rods that pass through the length of hollow steel columns, with continuity achieved through mechanical couplers, sleeve nuts, and shear keys—collectively forming what is known as the Post-Tensioned Rod (PTR) system [Sanches et al. 2021]. Additionally, a limited number of modular connection systems have been developed to facilitate both horizontal and vertical integration in steel and hybrid modular buildings [Kandel et al. 2023].

Fire hazards present a serious threat to structural integrity. In fire events, material degradation can lead to severe weakening of structural components, causing large-scale deformations or even full collapse [Jayakumar et al. 2023]. For instance, under elevated temperatures, beam-column connections in steel frames experience a rapid decline in mechanical strength and ductility. Such reductions in performance have been linked to catastrophic failures, including high-profile tower collapses. Experimental studies have evaluated thermal protection strategies for steel connections, comparing fire-exposed assemblies under standardized curves with numerical simulations. Findings showed that modified stub beam connections within column-tree configurations displayed superior resistance in terms of deflection control and overall deformation when compared to traditional bolted or welded joints [Chung et al. 2010].

[Peijun et al. 2020] conducted an experimental investigation on bolted T-stub connections under both ambient and elevated temperature conditions. The study revealed significant reductions in both yield and ultimate strengths of the connection, with decreases of 61.13% at 500 °C and 77.79% at 700 °C, respectively. The primary failure modes observed at high temperatures included backing plate deformation and bolt fracture. Similarly, [Hongxia et al. 2009] examined the tie capacity of web cleat connections exposed to elevated temperatures. Their tests involved applying combined tensile and shear loads to the web cleat connections. Results indicated a progressive reduction in the tie capacity as temperature increased, while the web cleat connections exhibited excellent rotational ductility under fire conditions.

Numerical investigations have also explored the fire performance of composite joints using both two-dimensional and three-dimensional finite element analyses. These simulations were validated against fire testing data and exhibited high predictive accuracy under thermal loads. Over the past two decades, extensive efforts by researchers [Wang et al. 2011; Akagwu et al. 2020; Al-Jabari et al. 2005] have led to a comprehensive understanding of steel and composite connection behaviours under elevated temperature conditions. Studies have explored various geometries and material combinations, resulting in improved numerical modelling techniques, analytical formulations, and practical recommendations that can now be incorporated into structural fire design standards.

A comprehensive review of existing research reveals that while extensive experimental and numerical investigations have been conducted on steel composite joints under fire conditions, there is a noticeable gap in the context of modular construction. Specifically, limited attention has been given to the behaviour of modular connection systems used in steel and steel composite modular assemblies when exposed to high temperatures. The lack of focused studies on the response and failure mechanisms of these modular interfaces highlights a critical research need. Addressing this gap, the current work undertakes a simulation-based analysis to evaluate both the thermal response and tensile load capacity of internal modular joint connections within modular steel structures under non-uniform fire scenarios with addressing key parametric studies.

2. DESIGN OF INTERNAL MODULAR JOINT

We have selected a recently proposed inter-module connection for steel and steel-composite buildings with an innovative profile (L shape), easy workability, ease of material availability in the market, and cost-effectiveness [Kandel et al. 2023]. The internal modular joint consists of two inter-modular connection the top module, bottom module, gusset plate, and high-strength bolts. Eight high-grade bolts are inserted through the top module, gusset plate, and bottom module tightened with nuts. The detailed sketch of the modular joint connection with dimension details used in the FE validation is presented in Fig. 1.

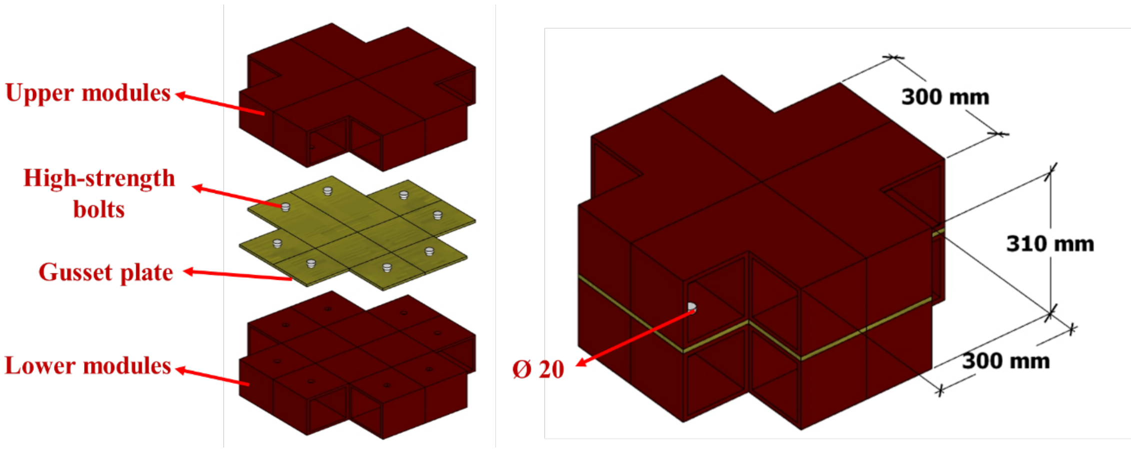

Fig. 1 Detailed view of internal modular joint and dimensions

The finite element (FE) model simulates realistic fire-induced structural behaviour, with axial tensile loading applied at the beam ends before fire exposure. This approach reflects the behaviour observed in fire-affected modular buildings, where beams subjected to elevated temperatures deflect and elongate. The resulting restraint—particularly from cooler adjacent modules or boundary conditions—leads to the development of catenary forces, which are transferred into the modular connections. Fire exposure is applied from the underside of the beams, simulating a compartment fire scenario where the heat source originates beneath the modular floor system. Both one-sided and two-sided fire exposure conditions are considered in the study, as illustrated in Fig. 2(a) and 2(b). In the FE model, the axial tensile load is applied at the beam ends using reference points coupled to the modular end nodes. The magnitude of the load corresponds to the ultimate tensile capacity of the inter-modular connector. This setup is intended to represent a worst-case loading condition under elevated temperature scenarios.

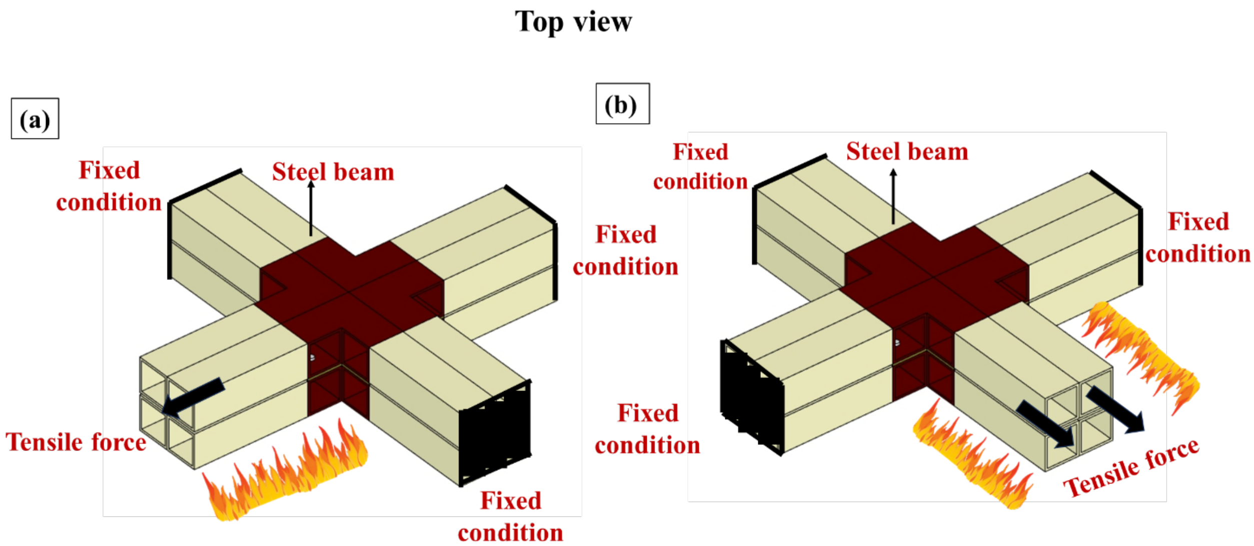

Fig. 2 View of applied axial tensile load on specimen (a) One-sided, (b) Two-sided exposure

3. FINITE ELEMENT MODELING AND SIMULATIONS

To analyse the thermal and mechanical performance of the internal-modular joint connection exposed to high temperatures. A 3D FE model is constructed in the study using Abaqus. Sequentially coupled thermal-mechanical analysis (SCTMA) is employed in the study. The procedure of this SCTMA consists of two steps: the first is applying the design mechanical loads on the test specimen, and in the second step, the temperature loads are applied within the test specimen by inputting the heat transfer results as a pre-defined load. During this simulation, the mechanical loads remain constant, and thermal loads are applied simultaneously until the specimen fails. Following this analysis, the nodal temperature, deflections related to fire time, and failure pattern of the specimen are established. The detailed explanations are discussed in the following sections.

In the FE model, the elastic-plastic models are taken from the Eurocode to simulate the thermal and mechanical behaviour of internal modular joints subject to high temperatures. A three-dimensional eight-node linear brick element, C3D86, was employed for steel module plates, gusset plates, and bolts in both the heat transfer and structural analyses. A 20 mm seeded mesh size is used in the study, and the same mesh size is kept constant in the thermal and structural models.

The thermal properties and temperature-dependent nonlinear properties of the steel material are taken from EN 1993-1-2:2004. Thermal characteristics such as specific heat, thermal expansion, and thermal conductivity were considered in the study. Mechanical characteristics such as yield stress, ultimate stress, stress-strain behaviour of structural steel, and elastic modulus concerning temperature are considered in the model. An E 350 grade of steel was used for steel components, and 12.9 grade of high-strength bolts was employed in the numerical simulation. A surface-to-surface contact is defined in the study, and hard contact is assumed as normal contact with a frictional coefficient of 0.3.

3.1 Heat transfer analysis

The FE model of the internal modular joint connection was developed for thermal analysis. To simulate the temperature exposure, the standard fire curve was preferred in the model. The non-uniform fire scenario is considered, such as the fire accident occurring at the bottom of the beams and composite columns and directly exposing to modular joint connection. The input fire loads were defined by gas temperature values of thermal radiation and convection. Constant heat transfer by convection was equal to 25 W/(m^2K), and the emissivity coefficient was taken as 0.7. For the unexposed side, heat convection of 9 W/(m^2K) was applied according to the Eurocode. The Stefan-Boltzmann constant was 5.67×10^{-8} W/m^2K^4 and the ambient temperature of 20 ºC was applied in the predefined loads. The simulation results in terms of nodal temperature were recorded for further validation.

3.2 Thermo-mechanical analysis

Three-dimensional stress analysis was considered following the heat transfer finite element model. For the stress analysis, the boundary conditions of the ends of the modules are considered fixed (all directions are restrained). The ultimate capacity of the modular connection at room temperature is found to be 1,160 kN. The tensile load was applied to the internal modular connection by varying the load ratio of 30%, 50% and 70%. The displacement behaviour of the modular joint connection and failure patterns under elevated temperatures was noted.

4. RESULTS AND DISCUSSION

4.1 Time-temperature response

The nodal temperatures were recorded at the surfaces and bolt locations. The thermal distribution within the internal modular connection and the corresponding time–temperature response is presented in Fig. 3 (a) and 3 (b), respectively. The specimen's temperature response was monitored until failure, at which point the simulation automatically terminated. The temperatures recorded on the exposed surfaces (Surface-1 and Surface-3) reached 654 °C, 884 °C, and 1081 °C at 60, 120, and 240 minutes of heating, respectively. In contrast, the unexposed surfaces (Surface-4 and Surface-5) exhibited significantly lower average temperatures of 267 °C, 445 °C, and 620 °C at the same time intervals. This difference is primarily due to Surface-4 and Surface-5 being exposed to ambient conditions, resulting in greater heat loss compared to Surfaces 1 and 3.

At the bolt locations (Surface-2 and Surface-4), temperatures of 722 °C and 356 °C were observed at 60 minutes, while 1021 °C and 679 °C were recorded at 240 minutes. A considerable reduction in temperature was noted at the inner bolt locations, indicating a pronounced non-uniform thermal distribution across the inter-modular connection. A significant temperature gradient was observed between the exposed and unexposed surfaces, attributed to the one-sided heating condition. The exposed surfaces showed a substantial rise in temperature over time, reaching 650 °C, 825 °C, and 1081 °C at 60, 120, and 240 minutes, respectively. In contrast, very low temperatures were recorded on the opposite side (Surfaces 3 and 5), with values of 112 °C and 55 °C at 60 minutes, 325 °C and 156 °C at 120 minutes, and 548 °C and 348 °C at 240 minutes of heating. At the bolt locations, a significant temperature difference was observed. From the measured time temperature response, it was found that the temperature gradient inside the steel modules and bolts of the two-sided exposure specimen is higher than the one-sided exposure specimen.

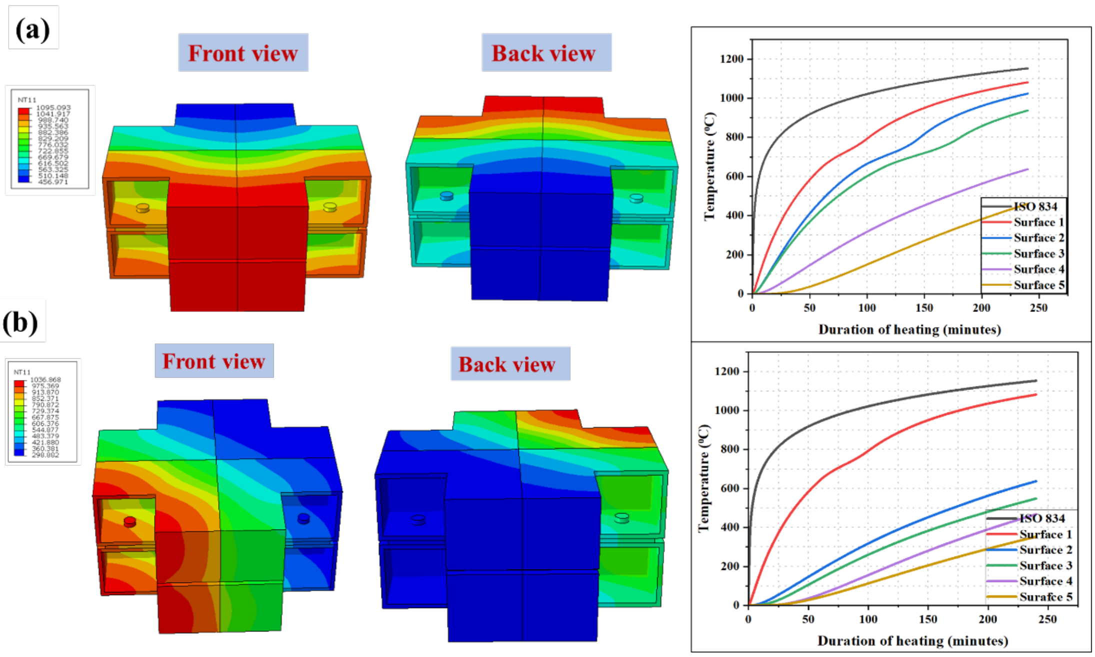

Fig. 3 View of thermal distribution and nodal time temperature response of internal modular connection (a) two side exposure, (b) one side exposure

4.2 Mechanical response under elevated temperature

The mechanical behaviour of the inter-modular joint was investigated under varying load ratios (30%, 50%, and 70%), different fire exposure scenarios (one-sided and two-sided), bolt diameters (20 mm and 30 mm), and gusset plate thicknesses (10 mm and 20 mm). These parameters were evaluated to assess their impact on the fire resistance performance of the inter-modular joint system.

Fig. 4 presents the vertical displacement response of inter-modular joints incorporating 20 mm and 30 mm diameter bolts under both one-sided and two-sided fire exposures. The results indicate that increasing the applied load ratio significantly reduces the fire resistance of the connection. For joints with 20 mm bolts under one-sided fire exposure, fire resistance times of approximately 130 minutes, 90 minutes, and 40 minutes were recorded at 30%, 50%, and 70% load ratios, respectively. In contrast, connections with 30 mm bolts demonstrated improved fire resistance, achieving 180 minutes, 120 minutes, and 60 minutes at the same load ratios. Under two-sided fire exposure conditions, joints with 20 mm diameter bolts exhibited fire resistance times of 120 minutes, 75 minutes, and 30 minutes at 30%, 50%, and 70% load ratios, respectively. Similarly, for joints with 30 mm diameter bolts, the corresponding fire resistance times were 170 minutes, 85 minutes, and 55 minutes.

This trend highlights the critical role of bolt diameter in enhancing the fire endurance of inter-modular joints. The larger bolt diameter provides a greater cross-sectional area, which improves thermal capacity and reduces stress concentration, thereby delaying failure. Additionally, one-sided fire exposure consistently resulted in higher fire resistance compared to two-sided exposure. This can be attributed to the asymmetric heating pattern, where one side remains relatively cooler, reducing the thermal degradation rate of the bolts and surrounding materials.

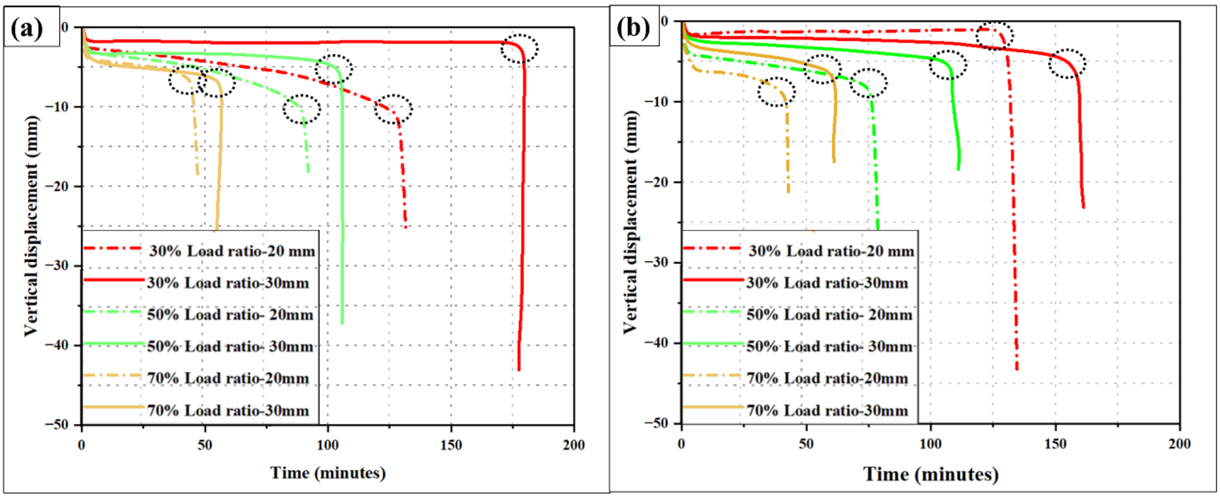

Fig. 4 Vertical displacement of the inter-modular joint system with 20 mm and 30 mm bolt diameters under (a) one-sided and (b) two-sided fire exposure

Fig. 5 illustrates the vertical displacement response of inter-modular joints with gusset plate thicknesses of 10 mm and 20 mm under both one-sided and two-sided fire exposure conditions. The results indicate that an increase in the applied load ratio significantly reduces the fire resistance of the connection. For joints with a 10 mm gusset plate subjected to one-sided fire exposure, fire resistance times of approximately 120 minutes, 90 minutes, and 40 minutes were observed at 30%, 50%, and 70% load ratios, respectively. In contrast, connections with a 20 mm gusset plate demonstrated enhanced fire performance, achieving 170 minutes, 100 minutes, and 70 minutes of fire resistance at the same load levels. In two-sided fire exposure conditions, the fire resistance times were notably lower. For joints with a 10 mm gusset plate, fire resistance durations of 110 minutes, 80 minutes, and 30 minutes were recorded at 30%, 50%, and 70% load ratios, respectively. Meanwhile, the use of a 20 mm gusset plate resulted in fire resistance times of 130 minutes, 90 minutes, and 75 minutes for the corresponding load ratios.

These results highlight the importance of gusset plate thickness in improving the thermal and structural stability of inter-modular joints exposed to fire. Thicker gusset plates offer greater thermal mass, delaying heat penetration and thermal softening. Moreover, the increased stiffness and load-bearing capacity of the thicker plates help distribute stress more effectively, reducing local deformations and delaying failure. The improved performance under one-sided fire exposure compared to two-sided exposure further highlights the role of asymmetric thermal gradients in preserving structural capacity. In one-sided fire conditions, the unexposed side retains a significant portion of its mechanical strength, which helps maintain joint integrity for a longer duration. Conversely, under two-sided fire exposure, uniform heating leads to more rapid degradation of material properties and earlier onset of failure.

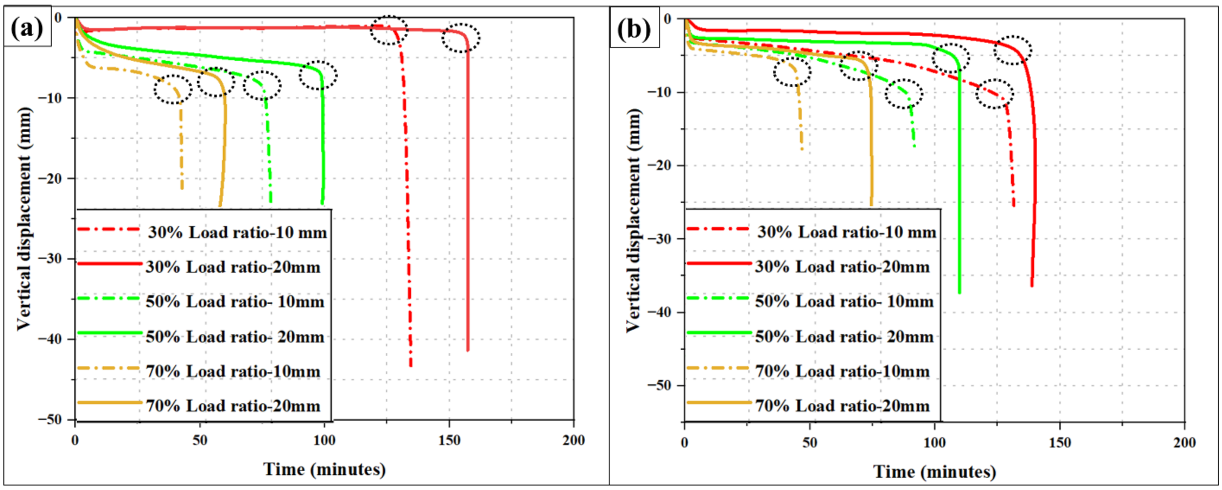

Fig. 5 Vertical displacement of inter-modular joints with different gusset plate thicknesses under (a) one-sided and (b) two-sided fire exposure

4.3 Failure behaviour

The failure modes of the inter-modular joint are illustrated in Fig. 6 (a) and 6 (b), representing one-sided and two-sided fire exposures, respectively. Two consistent failure modes were observed across all configurations in the FE analysis, regardless of bolt diameter (20 mm and 30 mm), gusset plate thickness (10 mm and 20 mm), and load ratio (30%, 50%, and 70%). The primary failure occurred at the bolts due to thermal degradation and stress concentration, leading to localized plastic deformation. The final failure mode in all cases was the separation between the two modules, indicating complete loss of structural integrity.

While higher bolt diameters and thicker gusset plates delayed the onset of failure and improved fire resistance, the overall failure mechanism remained unchanged. Similarly, higher load ratios led to earlier failure but followed the same sequence—bolt failure followed by joint separation. This consistent failure pattern highlights the bolts as the critical component in determining the fire performance of inter-modular joints.

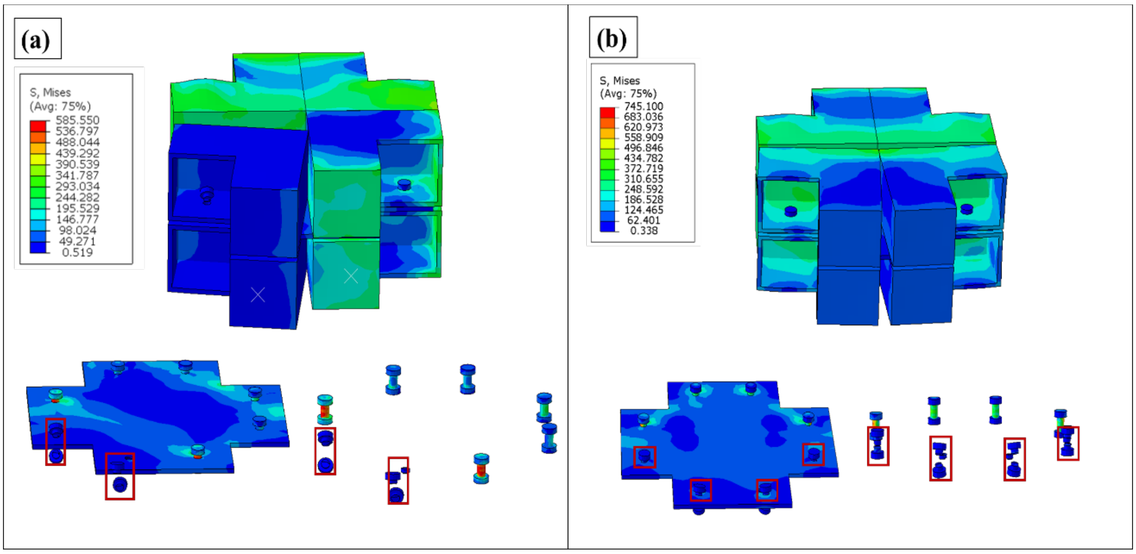

Fig. 6 Failure modes of the inter-modular joint connection under (a) one-sided fire exposure and (b) two-sided fire exposure

5. CONCLUSIONS

1. Thermal analysis showed a significant temperature gradient across the modular joint. In one-sided fire scenarios, bolts on the fire-exposed side reached temperatures exceeding 1000 °C, while those on the opposite (unexposed) side remained below 400 °C. This uneven heating influenced both the structural response and failure progression, highlighting the importance of localized thermal effects in joint design.

2. Inter-modular joints exposed to one-sided fire consistently exhibited longer fire resistance times than those under two-sided fire, due to the cooler unexposed side retaining structural capacity.

3. Increasing the bolt diameter from 20 mm to 30 mm significantly enhanced fire performance, delaying failure by up to 50 minutes under identical load conditions.

4. The use of 20 mm gusset plates resulted in longer fire resistance and lower displacement compared to 10 mm plates, due to improved thermal mass and load distribution.

5. All configurations failed through the same sequence: bolt weakening followed by complete module separation. This confirms that bolts are the critical component governing joint failure under elevated temperatures.

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