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A review of recent developments in structural elements of modular steel building systems

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ABSTRACT

Modular steel building (MSB) development provides an innovative approach to modern construction, offering enhanced construction speed, quality, cost-effectiveness and promoting sustainable development. As rapid population growth and urban land scarcity drive the need for high-rise construction, advancing MSBs is essential, but overcoming key challenges, like insufficient design guidelines, limited understanding of seismic and connection behaviour, and transportation constraints is crucial to fully realise the potential of MSBs. This paper critically examines recent research advancements and highlights future research needs. It provides an in-depth review of structural forms and lateral load-resisting systems, as well as the structural performance of modular floor beams, columns, and connection systems. Optimised novel beam sections with enhanced structural performance which can be utilised to reduce weights of modular floors are presented. The review also focusses on inter-modular connections, which play a vital role to ensure integrity of assembled MSB. Herein, these connections are categorised as bolted, grouted, self-locking, and tie-rod connections. A brief description, classification, ductility, and failure modes of these inter-modular connections are summarised in tables, including the most recent studies, to facilitate an effective comparison. While the structural performance of inter-modular connections at local level under gravity and seismic loading has been examined, their impact on global lateral stability of MSB requires further investigations. This review will act as a comprehensive reference for engineers, researchers, and technical experts in the industry.

1. Introduction

1.1. Background

The recent outbreak of covid-19 has brought immense pressure on existing health-care facilities worldwide and the growing requirements outstrips their infrastructure and space capacity. For example, the Nuffield trust in the UK has projected that due to the growing population and the increasing number of elderly individuals, there will be a requirement for approximately 22 new hospitals of 800 beds each by 2027. Currently several national health service (NHS) buildings are quite old and require a massive spend of around £5 billion for refurbishments [1]. Additionally, new housing supply in UK is currently lower than the government's ambition of 300,000 new homes per year [2]. New housing supply is also a challenge in Australia and according to an estimate commissioned by

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the national housing finance and investment corporation (NHFIC), there will be a shortage of around 106,000 homes across the country by 2027 due to high interest rates, expensive construction costs and community opposition to development. Also, more than 1.8 million new households are expected to form across Australia from 2023 to 2033 [3].

In parallel, building construction is a key driver of natural resource consumption and carbon dioxide emissions to the environment. The aim to achieve net zero carbon target can only be achieved by minimising the carbon footprint of the construction sector. Over 1/4 of steel produced annually is used in the construction of buildings. However, often the average material utilization ratio for typical steel structural members is below 50 % of their capacity [4]. In these cases, the design configuration could be optimised to reduce material and energy consumption, whilst supporting the loads safely.

1.2. Benefits of modular steel building

The issues stated above can be addressed by utilizing Modular Steel Building (MSB). In modular building construction the pre-assembled volumetric (3D) modular units or panelized (2D) systems are prefabricated off-site and then transported to the construction site and assembled to develop an entire building [5,6]. Volumetric units are fully-fitted, room-sized modules that include mechanical, electrical, and plumbing (MEP) fittings as well as interior finishes, making them suitable for medium-to high-rise buildings of 12 or more storeys [7,8], due to speedy construction [9]. In contrast, panelized systems consist of lightweight 2D wall and floor panels with partial MEP fittings [10], requiring more on-site labor and assembly work, and are generally limited to low-to medium-rise buildings of 4–8 floors.

MSBs are flexible to architectural design due to their open-frame structures and increased module sizes, owing to large beam spans [5]. MSBs can be used with any type of façade with a variety of features to meet aesthetics requirements. A high-quality interior design and tailor-made integrated furniture manufacturing can be ensured in the factory. This integration helps avoid mismatch in the size or style of interior finishes [11]. Owing to these advantages, modular building construction is mostly used for structures with repetitive architectural layouts including schools, hospitals, residential and hotel buildings, and possesses many advantages over conventional construction. These include improved quality [12] as modules are assembled in a factory-controlled environment with high precision and minimal involvement of on-site labor, enhanced speed of construction (20–70 %) [13], reduced project budget (20 %), lightweight, less sound pollution (30–50 %), less use of water and skilled labour-force, less wastage of material due to precise working off-site (up to 90 %), better compliance to health and safety regulations due to less work involved on-site (reduction in injuries by 80 %), reduced transportation of materials (70 %) and improved architecture and interior design of the buildings [14–17]. Also, modular building modules can be disassembled in most cases and reused, thereby effectively maintaining their asset value [18]. Furthermore, Cao et al. [19] conducted a comparative study to investigate environmental performance of modular and conventional construction in terms of natural resources and energy usage, as well as material wastage, and found that modular construction is more environmentally friendly. Due to these exceptional benefits, MSBs are gaining increasing popularity in modern construction practices worldwide.

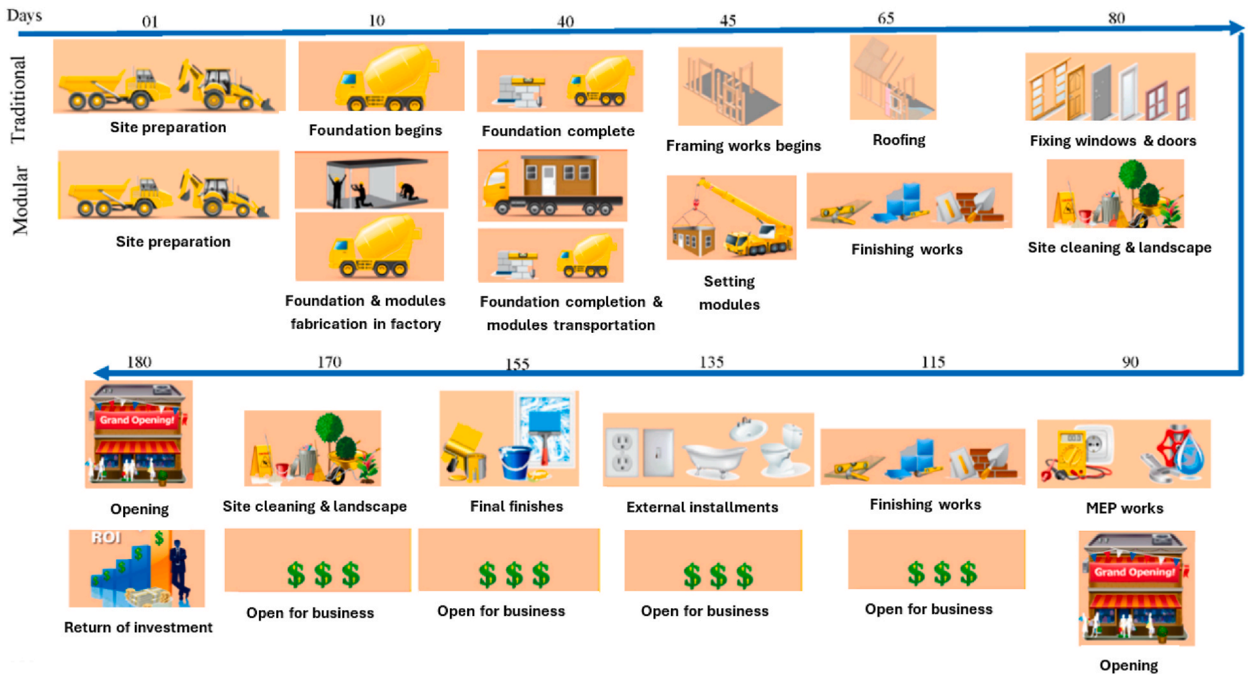


Fig. 1. Comparison of modular and conventional construction in terms of timeline [17].

Modular buildings can be produced using aluminum, timber, steel and pre-cast concrete depending on functionality requirements. Aluminum modules are light-weight and recyclable but are still in the initial research stage, whereas timber modules are primarily limited to low-rise buildings. In contrast, steel and pre-cast concrete modules are commonly employed for medium to high-rise buildings by the industry. In comparison to concrete-modules, steel modules are relatively light-weight, sustainable and allow more flexibility in architecture and interior design [5]. A typical steel-module weighs around 15–20 t and is 20–35 % lighter than typical concrete-module, which weighs approximately 20–35 t [20]. Aye et al. [21] investigated the life-cycle energy needs of modular-steel, modular-timber and conventional concrete residential buildings to evaluate their environmental performance. The study demonstrated that modular-steel has substantial potential of reusability after the lifespan of a structure and can save up to 81 % of embodied energy and 51 % of material mass, whereas modular-timber can save up to 69 % of embodied energy and 36 % of material mass, and concrete can save up to 32 % of embodied energy and 2 % of material mass. Both modular-timber and concrete materials showed relatively lower environmental benefits.

Furthermore, a comparison of the physical progress of modular and conventional construction is illustrated in Fig. 1 [17]. In MSBs, many activities are performed simultaneously in both the manufacturing plant and on-site, enabling faster project completion and an earlier business opening for operations as compared to traditional construction methods. Additionally, the fabrication of fully-fitted modules in a controlled factory environment is unaffected by weather conditions, thereby preventing delays and ensuring consistent productivity with high quality. After project inception, factory production of fully-fitted modules begins in parallel with on-site foundation construction. Once the foundation work is completed, the modules are delivered and assembled on-site. Afterwards, site cleaning and landscaping are carried out, and the project is handed over to the client for business operations. On the contrary, conventional construction follows a sequential schedule, where foundation is first constructed before commencing structural framing, MEP installations, exterior finishes, and interior fit-outs. These activities are executed entirely on-site, making them highly prone to weather conditions and labor productivity fluctuations, often resulting in extended project timelines.

1.3. Constraints of MSB

Despite the extensive recognition of MSB to tackle some of the most critical construction challenges in healthcare and housing sector, it is imperative to understand and overcome key constraints hindering the effective utilization of MSB by industry. Currently, there is lack of specific design guidelines, limited understanding of structural and connections systems, and inadequate understanding of the seismic performance of MSB. In comparison to conventional construction, MSB have more connections with complex behaviour. For instance, a typical internal connection of MSB consists of eight columns and sixteen beams [22]. Key challenges faced by designers, clients and contractors are listed below in Table 1 [23–26]. Due to dense city populations, limited availability of land and uncompromising construction regulations in major cities around the world there is need to extend modular construction to high-rise buildings, which requires extensive research and development works, as medium-to-high rise MSBs are relatively new to

Table 1
Summary of key challenges faced by MSB industry as reported by past research [23–26]

C.1. Skilled workforce	Shortage of skilled designers, installers and labors can adversely affect the project in terms of cost, time and quality.
C.2. Industry and market perception	The market perspective is that MSB has limited capabilities to make alterations and satisfy customer desires.
C.3. Higher initial costs	MSB requires massive initial investments to set-up a modern automated manufacturing plant. In order to become a profitable business it requires a substantial production rate of replicable module and components [27].
C.4. Transportation limitations	There are many challenges associated with transportation of partially or fully fitted volumetric modules on site including road regulations, load capacities of roads, maximum height restrictions and vehicle load limitations. Transportation costs can vary between 10 % and 18 % of overall project cost. Also due to limited space and unloading areas on construction sites, a continuous and uninterrupted delivery of modules is required on-site during construction. However, trailers with special permits are mostly allowed to access main roads only on weekends, further complicating logistics.
C.5. Lifting limits of tower cranes	Lifting capacity of tower cranes has major impact on project costs of MSB. Cranes commonly available in market have lifting capacities under 20 t, and increasing the lifting weight above 20 t can substantially increase the cost of crane by 60 % [20].
C.6. Research and development (R&D)	Inadequate industry investment in R&D to overcome technical challenges in MSB. Due to limited awareness of MSBs within the industry, clients and designers hesitate to adopt modular construction in their projects. A study by Schoenborn et al. [28] emphasised the need for manufacturers to invest in R&D, engage with architects and clients, and educate them about the manufacturing process, benefits, and limitations of MSBs.
C.7. Design constrains	Design of MSB is locked at preliminary stage of project allowing minimal changes for flexibility. Initially, the designers are required to spend significant time developing accurate shop drawings due to the increased extent of detailing. Alterations in design at later stage are difficult and costly to implement due to standardized geometry of modules. Also, size and weight restrictions during transportation, module tolerances, and site-layout can significantly impact the architectural design.
C.8. Standard design guidelines	Due to unavailability of standard design guidelines for MSBs, designers primarily rely on conventional design codes which are mostly based on limit state design criteria [29]. This often leads to an overestimated design due to limited understanding and reliability of inter-modular connections. Conversely, the design may also fail to account for more critical load scenarios specific to MSBs, including the formation of additional stresses at joint locations and short-term loads induced during assembling, both of which can potentially influence the load transfer behaviour [30]. When combined with seismic forces, these stresses can adversely affect the safety and performance of MSBs. Recently Dan-Adrian and Tsavdaridis [31] have proposed a nomenclature to standardise different categories of inter-modular connections, paving a way for further studies to develop a unified approach for the classification and development of comprehensive design standard for inter-modular connections. Also, Yuan et al. [32] proposed a parametric design for modular structures based on Building information modeling (BIM), which considers both manufacturing and assembly aspects in the design stage to overcome coordination errors and reduce project costs.

construction industry and therefore deeper understanding of their behaviour is warranted.

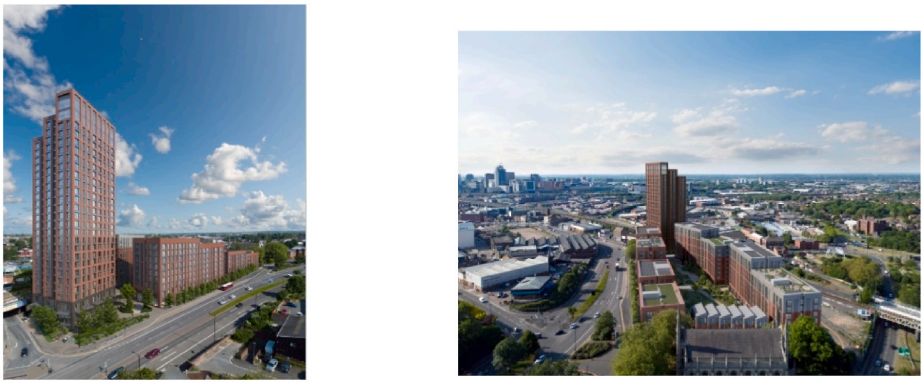
1.4. Review significance and scope

Contributing to a better understanding of the structural performance and design of MSBs, this paper reviews recent and important research developments of structural components for MSBs. An in-depth review is necessary due to the rapid emergence of recent developments in MSBs, and therefore this review is anticipated to advance the future growth and applications of medium-to-high rise MSBs and act as a comprehensive reference for engineers, researchers, and technical experts in the industry.

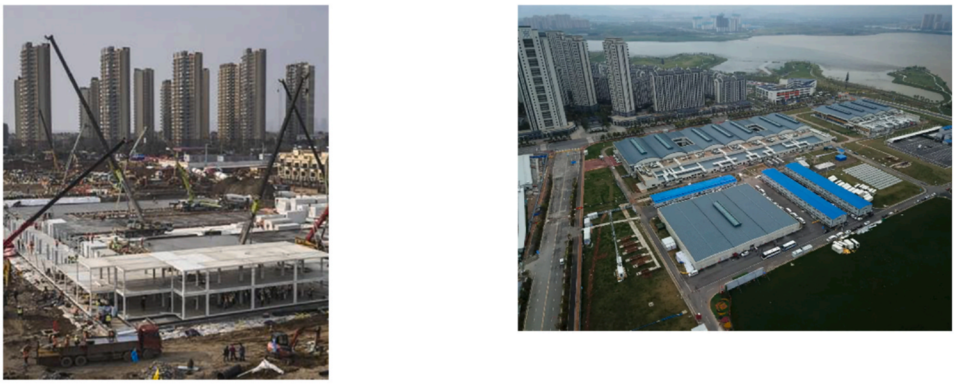
Although MSBs have gained significant importance, only a few review studies have been conducted previously by researchers. Past reviews, such as those by Thai et al. [33] and Ferdous et al. [34], focus on modular construction for high-rise and multi-storey buildings, whilst others, like by Rajanayagam et al. [35], Nadeem et al. [36], and Dan-Adrian and Tsavdaridis [31] have specifically addressed modular connections. However, these studies do not provide a comprehensive analysis of the overall performance of the structural system, including all key components such as modular floor beams, modular floors, modular columns, and all connection types. Our study aims to bridge this gap by providing a comprehensive review of all structural components and the research advancements and proposed systems relevant to modular steel structural systems. This makes it a valuable reference for structural engineers, researchers, and technical experts in the industry.

The review starts with presenting some examples of applications of MSBs in Section 2. Sections 3 and 4 present the structural forms and lateral load resisting systems of MSB, respectively. Section 5 reviews the research that has been conducted to investigate and optimise the structural performance of modular floor beams. Sections 6 and 7 focus on modular floor systems and modular columns, whilst Section 8 comprises a comprehensive review of research developments on the connections system, which is a critical component of modular structures. Afterwards, the main conclusions are summarised in Section 9.

The review focused exclusively on modular steel buildings, excluding studies on concrete and timber modules. Specific attention was given to study the performance of modular floor beams, steel columns, and various connection types, including inter-modular,



(a) Smith's Garden, Birmingham UK, currently under construction (Courtesy of DAA Ltd., 2024)



(b) Huoshenshan hospital, China (Gatheeshgar et al., 2021b) (c) Leishenshan hospital, China (Gatheeshgar et al., 2021b)

Fig. 2. Examples of MSB applications in the UK and worldwide.
(a) Smith's Garden, Birmingham UK, currently under construction (Courtesy of DAA Ltd., 2024)
(b) Huoshenshan hospital, China [40]
(c) Leishenshan hospital, China [40].

intra-modular, foundation connections, and connections to concrete cores. Studies addressing lateral stability and hazard resilience were also prioritised. A key area of interest was inter-modular connections, a rapidly developing field where researchers are conducting both experimental and numerical investigations into bolted, grouted, self-locking, and tie-rod connections. The analysis of the reviewed papers in the following sections focuses on the most recent research advancements from the past few years, while also recognising significant earlier developments to provide a comprehensive overview.

2. Applications of MSB

Mid to high-rise building projects have showcased numerous advantages of prefabricated modular technologies. The history of using non-conventional and lightweight MSB for housing buildings trace back to mid-20th century. To overcome housing crisis after post world wars period, the UK government approved the programme to produce pre-fabricated transportable modular houses. During 1946–1949 more than 150,000 volumetric modular houses were manufactured and erected across UK. Both steel and aluminium were used in the construction of modular houses since all available timber resources were allocated for mine propping [37].

Towards the close of the 20th century, the shortage of affordable urban homes led numerous housing suppliers to consider cold-formed steel (CFS) frame volumetric modules for the construction of dwellings. In the UK, MSB experienced a boost in 2004 when the Housing Corporation made restrictions that a minimum of 25 % of the new social housing projects it finances must utilise advance construction methods [24]. For example, Paragon West London UK, which was constructed in 2006 and consists of several buildings ranging from 11 to 17 stories, primarily built using corner-supported modules and integral corridors. The modules only resist vertical loading whereas lateral stability was achieved by connecting the modules with concrete core. Cluster modules are connected to core by attaching ties to cast in place (CIP) anchored plates in the core. In total, the project consisted of 600 student rooms with attached bath, 114 rooms with private kitchen and bath, and 44 one-bedroom and 63 two-bedroom essential worker apartments. Module size was mostly restricted to 12m × 2.8m based on motorway transport limits [18,38].

Also, a 12-storey Student residence at Bond Street, Bristol UK was constructed using modular technology. The modules are designed to resist only gravity loading whereas lateral stability is achieved through four braced steel cores. The 6 to 10 stories of volumetric modules are supported on a 2-story steel framed podium to provide flexible open space beneath. The project included 400-bedroom modules with a width of 2.7m and around 100 paired modules to build studio apartments. The cladding system is comprised of lightweight rain screens and its dead load is supported by modules [18].

Nowadays, there is even a higher increase of MSB applications. Mapleton Crescent in London UK, a 25-storey domestic project, which was constructed using partially open-sided modules. After completion in 2018, it was the tallest modular structure in Europe. The modules only resist gravity loading whereas lateral stability is achieved through triangular slip-formed concrete core. In total the project consists of 53 one-bedroom, 26 two-bedroom and 10 three-bedroom apartments. Modules were typically 6.5m long by 3.2–3.5m wide. The 22–24 floors of volumetric modules sits on 1.8m thick reinforced podium at 1st floor. In total the project comprised of approximately 252 modules which were installed at a fast pace and at average 8 modules were installed every day [38]. Fig. 2a shows Smith's Garden in Birmingham UK, a residential project currently under-construction, which consists of six separate blocks, including a 26-storey MSB. A total of 1143 modules will be produced off-site, and the project is expected to be completed in January 2026 [39].

In addition, it is noteworthy that MSB can be used to build healthcare facilities to overcome patient capacity and maintenance backlogs in national health systems [41]. Modular construction can be used to develop new healthcare units, adoptable clinical spaces, and isolation facilities. Modules can also be used for roof-top vertical extension of existing hospital building as they cause minimum disruptions to operational functioning of medical facilities due to their sustainability advantages [38]. Fig. 2b and Fig. 2c shows the 1000 bed Huoshenshan hospital and a 1600 bed Leishenshan hospital in China, both built as emergency filed facilities to provide much-needed medical care during the Covid-19 pandemic. The hospitals were constructed in approximately two weeks times by assembling steel modules on RC foundations. Also in 2024, a 26 floor Jindu residential building in Xiangyin, China was assembled on-site in just five days. Stainless steel was used to manufacture 264 modules in the factory [42]. China is experiencing a rapid growth in modular construction industry due to increasing urban and industrial developments. In 2024, China's modular construction sector exceeded $18 billion and is expected to surpass $19.5 billion by 2025 [43]. Recently, a 50-story College Road tower was constructed in South London, UK. It is currently the tallest MSB in Europe, consisting of 1725 modules [42]. Additional examples of applications of MSBs in various countries are listed in Table 2.

Table 2
Examples of applications of MSBs in different countries [38,42]

Project name	Location	No. of floors	No. of modules
Cheatham Street Flats	San Marcos, TX, USA	4 modular floors above podium	589
Seattle South Lake Union Hotel	Seattle, WA, USA	6 modular floors above conventional basement and grade level	264
BoniFaCio SPA & Sport Resort	Sochocin, Poland	Extension of existing building	34
Creekside Wharf	London, UK	2 building blocks of 22 and 12 floors	653
United Court Transitional Housing	Hong Kong	8 building blocks, each having 4 floors	2076
Wolverhampton student residence	Wolverhampton, UK	25-floor building	820
Apex house	London, UK	25-floor building	679

3. Structural forms of MSB

Based on geometrical and load transfer mechanism, modules in steel structures are generally categorised into four generic forms: (a) load bearing four-side modules, (b) partially open-side modules, (c) corner-supported modules and (d) non-load bearing modules (pods). All four types are utilised in field based on architectural and structural requirements [18,44–46].

In four-side closed modules (see Fig. 3a), the vertical load is transferred through the longitudinal walls and therefore the walls of upper floor modules rest directly above the lower floor modules. The side walls consist of CFS C-sections spaced at 300–600 mm and openings are provided on need basis at ends to install windows and doors. Modules are fabricated from 2D structural panels in factory starting from 150 to 200 mm thick floor joists to which side walls and ceiling panels are connected. This form of modular construction is mostly limited to eight storeys heights and is highly dependent on the compressive resistance of wall structural elements and lateral stability system [7]. These modules are mostly used in hotels, houses and student accommodation buildings.

In partially open-side modules (see Fig. 3b) more open spaces are created by adding small size square hollow section (SHS) corner and interior posts in walls and stiff edge beams in floor joists. Ample interior spaces and corridors can therefore be designed by placing two or more modules together. These modules can also be used in hotels with in-built corridor and balconies.

In case of corner-supported modules (see Fig. 3c), complete open spaces can be designed in both longitudinal sides by transferring the load from bending action of edge beams to corner posts. The module frames are mostly constructed of stiff SHS corner posts and LCS edge beams. SHS are used as posts due to their excellent buckling capacity. The maximum height of buildings is constrained solely by the dimensions of the SHS to resist compressive load for a specific module size. Maximum size of SHS for corner posts is limited to 150x150 × 12.5 mm in MSB.

Pods (see Fig. 3d) are light steel structures, designed to support only their self-weight and any additional forces applied during lifting and installation. They are incapable to transfer loads and rests directly above the floor or supported by an independent structure. Pods are mostly used as kitchen, washroom or plant room.

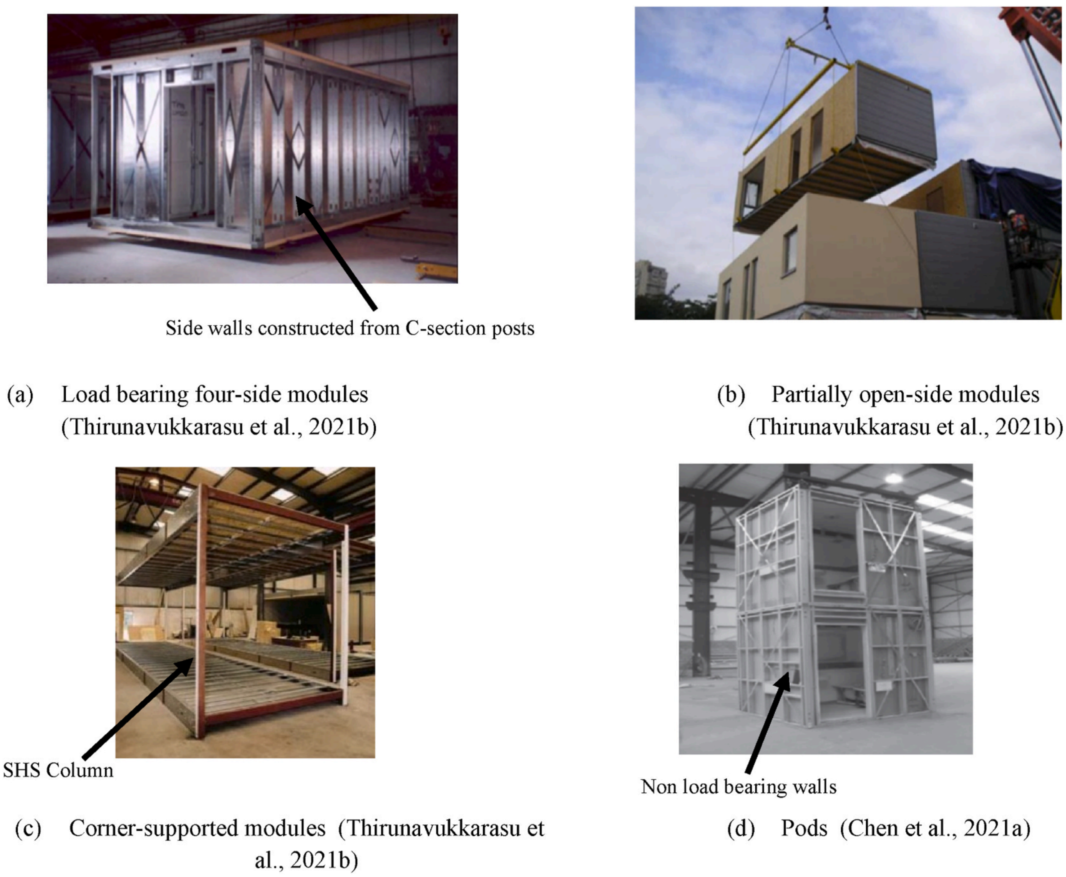


Fig. 3. Forms of modular steel structures.
(a) Load bearing four-side modules [17]
(b) Partially open-side modules [17]
(c) Corner-supported modules [17]
(d) Pods [47].

4. Lateral stability systems and seismic performance of MSB

A well-designed structural mechanism is necessary to ensure the lateral stability of MSB against seismic and wind forces. For low-rise buildings, stacked-module structures are capable of transferring both gravity and lateral loads through inter-modular connections in corner-supported MSBs, and via side walls in continuously supported MSBs. In this form of structures, individual modules are placed vertically above existing modules and side-by-side and are connected on-site to form the complete building. Their use is generally limited to three floor buildings with regular plans [8]. Stacked-module structures can function as moment-resisting frames (MRFs), with their performance largely dependent on the behaviour of inter-modular connections. Research has shown that these connections can range from pinned to full-strength and rigid classifications. By incorporating rigid inter-modular connections, MRF systems can become suitable for the construction of medium-rise buildings, providing the necessary lateral strength and stiffness [48].

To ensure lateral stability under seismic loading of MSBs, the design process begins by identifying the site's seismic hazard parameters, soil classification, and the building's importance class to determine the appropriate design spectra and amplification factors. Based on the selected lateral force-resisting system, the building mass, fundamental period and ductility requirements are then defined to calculate seismic forces and ensure compliance with code-specific resistance and detailing provisions. In the case of MRFs, robust inter-modular connections capable of transferring seismic forces and providing adequate lateral strength and stiffness are essential. If these joints are pinned or overly flexible, they may result in large inter-storey drifts, increasing the risk of structural instability or even

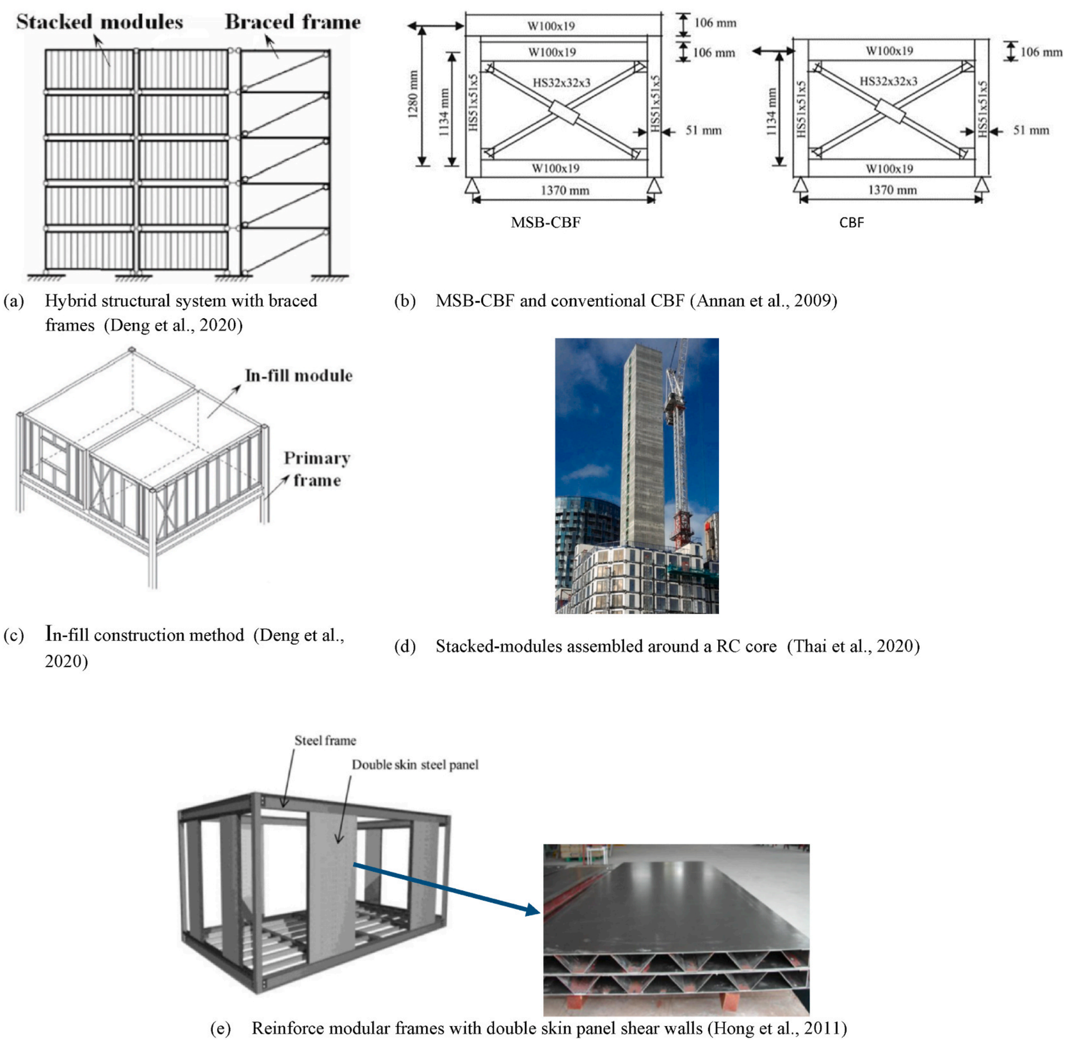


Fig. 4. Lateral stability enhancement of MSB.
(a) Hybrid structural system with braced frames [8]
(b) MSB-CBF and conventional CBF [50,51]
(c) In-fill construction method [8]
(d) Stacked-modules assembled around a RC core [33]
(e) Reinforce modular frames with double skin panel shear walls [52].

progressive collapse. The characteristics of these joints, including their classification based on stiffness and strength, ductility capacity, failure modes, and overall seismic performance, must be thoroughly assessed. The performance of 28 different inter-modular connections, as examined through experimental and numerical investigations, is discussed in Section 8.4.

As the height of MSBs increases, the risk of overturning due to seismic activity becomes critical. Inter-modular connections alone cannot resist lateral loads, as the risk of connection failure is a major concern [49], necessitating additional lateral stability technologies. To address this challenge for high-rise modular-construction, hybrid structural systems with conventional moment frames, braced frames, modular in-fills, reinforced-concrete (RC) cores, shear walls and base isolation are utilised in combination with MSB.

In a hybrid moment frame structure (see Fig. 4a), stacked-modules are combined with a primary moment-resisting steel or RC frame to resist lateral loads [8]. Additionally, braced frames can be used to enhance lateral capacity of stacked-modules. To investigate this concept, Annan et al. [50], Annan et al. [51] performed two tests to examine the performance of MSB with concentrically braced frame (CBF) and compared the results with conventional CBF (see Fig. 4b). The findings revealed ductile behaviour for both specimens up to certain high drift-levels. MSB-CBF specimen failed due to extensive bending deformation of columns, while the conventional-CBF specimen shown extensive out-of-plane buckling of bracing member at the mid-section. Initial lateral stiffness of MSB-CBF was around 93 % compared to the conventional-CBF specimen. At a ductility level both below 2 and above 6, the conventional-CBF specimen exhibited enhanced lateral stiffness. Between these ductility levels both specimens performed similarly.

Another method for securing lateral stability is by infilling the modules within the primary frame structure, known as unit modular in-fill construction method (see Fig. 4c). The feasibility of this idea was verified by Park and Ock [53] in terms of cost optimisation and project timeline of a pilot project. It was found that this method is more economical compared to conventional construction, however no significant benefits were observed in terms of project duration. The spacing of the primary frame columns was selected to ensure that two to three modules can be recessed in between.

Alternatively, stacked-modules can be assembled around a RC core to ensure lateral stability through module to core connections (see Fig. 4d). The RC core mainly resists lateral loads, whereas modules only resist gravity loading. This technique is commonly employed worldwide for construction of high-rise MSB. To study the robustness of MSB with core wall under different progressive collapse cases due to removal of corner-module, Hajirezaei et al. [54] performed numerical investigations with variable building heights and locations of RC core in building plan. A parametric analysis was also conducted to examine the impact of the stiffness of inter-modular connection springs, the rigidity of intra-modular connections, and the formation of plastic hinges on the robustness of the MSB. The results showed that for low-to-mid height MSB, core walls can provide significant robustness, due to enhanced load distribution and reduced lateral displacements. However, for high-rise MSB, the immediate collapse of multiple columns was observed. Additionally, preventing plastic hinge formation in beams can help avoid this collapse.

Furthermore, steel shear walls are also employed as a lateral stability system in the industry to avoid RC CIP cores. Hong et al. [52] proposed to reinforce modular frames with double skin panel shear walls, and investigated its behaviour through cyclic tests (see Fig. 4e). To avoid premature local buckling of outer steel plates, a corrugated steel plate was welded in between. The test results revealed that lateral stiffness of frames with double skin panels was significantly increased by four times as compared to frame specimen without panels. Also, the shear walls yielded before the yielding started for module structural members, thus avoiding excessive damage of module frame. Similarly, Wang et al. [55] investigated the seismic performance of a module frame with infilled CFS stud walls, both with and without openings, using cyclic load tests. Openings were provided to fit-in windows and doors. The findings showed reduced initial lateral stiffness of about 24.4 %–28.7 % and shear capacity of about 3.8 %–15.5 % for CFS stud walls with openings, in comparison to walls without openings.

All approaches discussed above can significantly enhance the lateral stability of MSB, but they also reduce the pace of construction and increase environmental impact, which are key advantages of modular construction. Another technique is the use of base isolation, which allows rocking motions in the MSB, adequately prolongs the natural period, dissipates energy through the lifting of modular-structure, and also upholds the benefits of MSB. Li et al. [56] performed dynamic load shake table test on 19-floor reduced scale MSB with pre-stressed super-elastic strings and rocking surface at podium level. The results revealed that in comparison to fixed support conditions, the specimen had about 50 % reduced overturning moment at base and the tension forces in connections were also significantly reduced. The rotational angle at base was also substantially reduced by about 30 %–60 % when boundary conditions were changed from free-rocking to super-elastic strings restrained building.

5. Floor beams of MSB

5.1. Optimisation of modular beam profiles

Cold-formed steel (CFS) structures, made by bending flat steel sheets at ambient temperature, have been in use for over a century, but the development of higher-strength materials and broader structural applications has led to their increased adoption over traditional hot-rolled steel members [57–59]. The behaviour of cold-formed steel structures is complex due to the thin-walled nature of their sections. Over the past decades, extensive research using experimental, numerical, and analytical approaches has led to the development of various design methods, such as the Direct Strength Method (DSM) [60], enabling accurate predictions of structural performance. The lightweight nature of CFS offers significant benefits for MSB buildings, making the modules easier to handle, transport, and assemble. CFS is currently opted in MSB floor panels, due to its advantages of high strength to weight ratio and light weight characteristics [17].

However, recent studies conducted to investigate the behaviour of structural elements of modular buildings concluded that there are still challenges associated with transportation and lifting of modules due to its weight and size [61,62]. Despite their advantages, CFS sections presently available in the market for industrial use are somewhat inefficient in terms of structural performance and material usage due to limitations of forming and press braking machinery used by different production facilities. Typical floor panels account for 30 % of the weight of steel modular unit [20], and this can be reduced by using optimised lightweight and novel metal sections that consume less material. Optimisation techniques can be employed to enhance the capacity of structural members for a given quantity of material and this effective utilization of material can also benefit the manufacturers due to decreased raw material usage and environmental footprint. Recent developments in the roll forming procedures made it possible to manufacture low-cost novel and optimised cross-sectional shapes with variable sizes in bulk by adjusting the rollers [62,63]. Similarly, aluminium can also be utilised in MSB owing to its benefits including excellent corrosion resistance, light weight and recyclability, however research on aluminium sections is in initial stage and its structural behaviour and performance has to be extensively investigated to ensure its effective usage in modular floor panels [47,64].

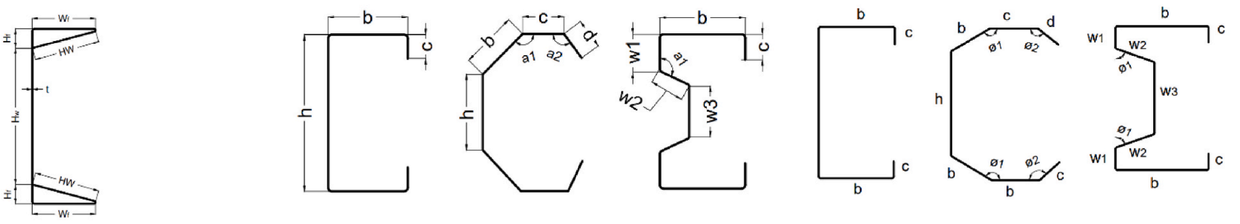
Recently research work has been conducted to investigate and optimise the performance and design of modular beam profiles. A summary of the proposed cross-sectional shapes by researchers over the last 5 years is shown in Fig. 5. Novel sustainable and optimised CFS sections have been explored through optimisation techniques and numerical modelling of composite and built-up sections, hollow flange beams, sigma sections, lipped channel sections and few more. Several optimisation techniques have been used, including particle swarm optimissation (PSO), genetic algorithm (GA) and whale optimisation algorithm (WOA). Relevant research work on MSB floor panel beams is summarised in Table 3. The table includes information on the material of the steel beam profile, the optimisation technique applied, the proposed cross-sectional shape and the percentage improvement achieved in terms of enhanced capacity or reduced weight. The studies have focused on the investigation of the flexural and shear capacity, as well as on the resistance to web crippling phenomenon, as will be further explained in Sections 5.2 and 5.3, respectively. Based on the results of these investigations, new design techniques, improvements in existing design equations and novel cross sections were suggested for application in modular floors. It is noteworthy that these studies were mainly numerical, through finite element (FE) analysis, revealing the research need for future experimental investigations.

5.2. Flexural and shear capacity

Gatheeshgar et al. [65] explored the flexural performance of modular construction optimised (MCO) beams through parametric FEM study and proposed improved DSM design equations to calculate their bending moment capacity. MCO beams have inbuilt structural advantages with enhanced bending moment capacity due to improved distortional buckling capacity, as there are no free edges in the cross section. On another study, WOA and numerical modelling techniques were employed to develop efficient CFS beam sections with reduced weights without impacting the flexural capacity [40]. A market available lipped channel section (LCS) was initially considered as benchmark. The optimisation technique focused to reduce the coil length of optimised LCS, folded-flange and sigma sections and resulted in 15 %, 20 % and 24 % weight reduction per unit length. Using PSO and FEM techniques, Gatheeshgar et al. [62] studied the enhanced flexural strength of solid and slotted perforated web CFS sections with reference to same material weight of commercially available LCS. PSO was used instead of GA, as it can easily incorporate theoretical constraints [71]. The optimisation resulted in 30 %, 60 % and 65 % enhanced flexural strength for solid optimised LCS, folded-flange and super-sigma CFS sections respectively and 57 % increase for slotted perforated web super-sigma sections. The use of super-sigma sections was recommended in MSB due to improved bending capacity and closer flexural center. Similarly Ye et al. [71], used PSO and FE modelling to study the increased flexural capacity of six different braced and unbraced CFS channel beams. The Optimisation process resulted in a 25 % enhanced flexural capacity for laterally braced beams and 75 % increased capacity for unbraced beam sections, using the same material quantity.

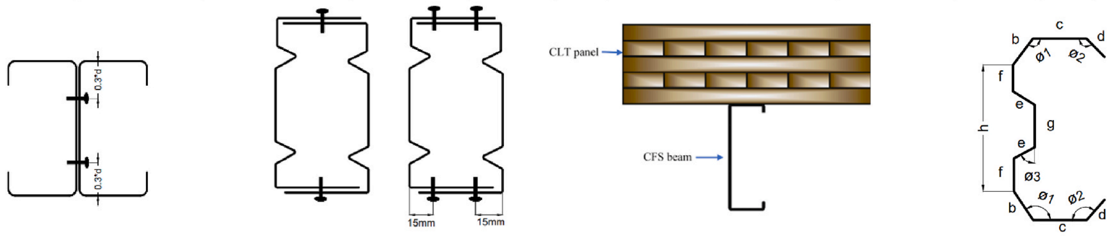
Long span lightweight beams are required to enlarge the interior space and enhance the aesthetic ambiance inside the MSB. To overcome this challenge, Thirunavukkarasu et al. [17] performed parametric numerical analysis to investigate the bending performance of open and closed built-up sections with different screw arrangements and spacing. The researchers investigated both LCS open built-up sections and closed unlipped channel sections with intermediate web stiffeners. The study revealed 156 % enhancement in flexural strength for built-up sections compared to conventional single sections. In addition, closed built-up sections have shown better performance as compared to open sections. On another study involving composite beams for modular applications, Navaratnam et al. [66] employed FE analysis to investigate the flexural performance of cross-laminated timber (CLT) and CFS composite beam. In FE model, the CLT panel was created with five layers of uniform thickness and CFS beam was modelled as commercially available LCS. The results have shown approximately 20 % increase in bending capacity of CLT-CFS composite modular floor beam compared to the sum of individual flexural capacities of CLT panel and CFS beam.

Similarly, Perampalam et al. [67] concluded that optimisation resulted in 30 % increased flexural capacity for novel CFS smart beam section with reference to standard LCS section for same material quantity, although significant reduction in shear and web crippling capacity was observed. The researcher claimed that smart beam sections have improved flexural and torsional strength as the flexural center of these beams aligns with the web axis. Moreover, Perampalam et al. [68] investigated the structural performance of CFS hollow flange sections (HFS) beams using GA and numerical modelling techniques and compared results with benchmark LCS for constant material weight. To study the bending behaviour, 4-point loading finite element model was developed, whereas for shear loading three-point loading case was considered. The length of the modelled beams was based on the clear web height with aspect ratio of 1. The optimisation resulted in 65 %–90 % enhancement of bending capacity of HFS beams without any reduction in shear and web crippling strengths. Gatheeshgar et al. [72] used PSO and non-linear FE analysis to optimise CFS LCS beams under combined action of flexure, shear and web crippling. The optimised beam sections were than compared with market available LCS of same weight. The combined optimisation comparison results have shown 12 % enhanced bending capacity without any loss in shear and web crippling capacities.



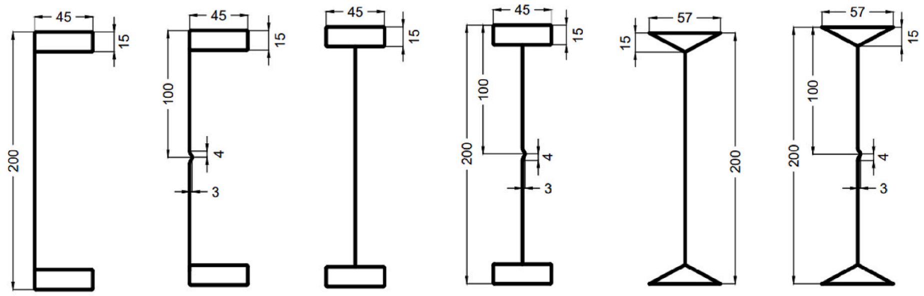
MCO LCS Folded-flange Sigma LCS Folded-flange Super-sigma

a) (Gatheeshgar et al., 2021a) b) Gatheeshgar et al., (2021b) c) Gatheeshgar et al., (2020b)



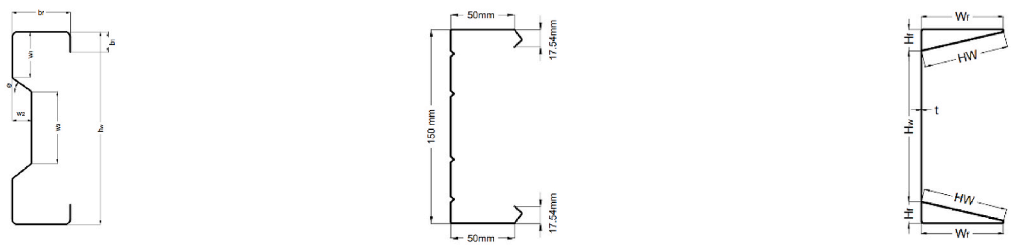
LCS open built-up sections | Closed unlipped channel sections | Cross-laminated timber (CLT) and CFS composite beam | Smart beam

d) Thirunavukkarasu et al., (2021b) e) Navaratnam et al., (2021) f) Perampalam et al., (2019b)



Hollow flange sections

g) Perampalam et al. (2019a)



Sigma section | Supacee section | MCO

h) Thirunavukkarasu et al. (2023a) i) Thirunavukkarasu et al. (2023b) j) Thirunavukkarasu et al. (2021a)

(caption on next page)

Fig. 5. Cross-sectional shapes of proposed modular beams.
(a) [65]
(b) Gatheeshgar et al. [40]
(c) Gatheeshgar et al. [62]
(d) Thirunavukkarasu et al. [17]
(e) Navaratnam et al. [66]
(f) Perampalam et al. [67]
(g) Perampalam et al. [68]
(h) Thirunavukkarasu et al. [64]
(i) Thirunavukkarasu et al. [69]
(j) Thirunavukkarasu et al. [70].

Table 3
Recent numerical research on modular beam profiles - considered types and shapes.

Reference and structure type	Material Yield strength f_y (MPa)	Type of analysis	Optimisation technique	% change in capacity: Flexural capacity (FC) Web crippling capacity (WCC) Increase (+) Reduction (−)	% reduction in weight	Depictions in Fig. 5
Gatheeshgar et al. [65] MSB	CFS: 300, 450 and 600	FC: 4-point	–	FC: 25 % (+)	–	a
Gatheeshgar et al. [40] MSB	CFS: 450	FC: 4-point	WOA	–	15 % for optimised LCS 20 % for folded-flange 24 % for sigma sections	b
Gatheeshgar et al. [62] MSB	CFS: 450	FC: 4-point	PSO	FC: 30 % for optimised LCS (+) 60 % for folded-flange (+) 65 % for sigma sections (+) 57 % for perforated web super-sigma sections (+)	–	c
Thirunavukkarasu et al. [17]	CFS: 450 and 600	FC: 4-point	–	FC: 156 % (+)	–	d
Navaratnam et al. [66]	CFS: 450	FC: 4-point	–	FC: 20 % (+)	–	e
Perampalam et al. [67]	CFS: 450	FC: 4-point	PSO	FC: 30 % (+)	–	f
Perampalam et al. [68]	CFS: 450	FC: 4-point WCC: ITF load-case	GA	Fc: 65 %–90 % (+)	–	g
Thirunavukkarasu et al. [64]	Aluminium: 180 and 220	WCC: ITF load-case	–	WCC: 20 % (−)	–	h
Thirunavukkarasu et al. [69]	Aluminium: 180 and 220	WCC: ETF load-case	–	WCC: 4 % (+)	–	i
Thirunavukkarasu et al. [70]	CFS: 300, 450 and 600	WCC: ETF load-case	–	WCC: Up to 50 % (−)	–	j

5.3. Web crippling capacity

In order to investigate the web crippling capacity of aluminium sigma sections for MSB, Thirunavukkarasu et al. [64] performed FEM to study the ultimate capacity under interior two-flange (ITF) loading case. The results discussed key parameters, including radius, yield strength, web thickness and bearing length, and their impact on the web crippling capacity of section. Moreover, comparison of results with conventional aluminium LCS under ITF load case illustrated that the web crippling capacity of sigma sections is about 20 % lower than that of LCSs. On an accompanying study, Thirunavukkarasu et al. [69] investigated the web crippling capacity of aluminium SupaCee sections under end two-flange (ETF) loading case. The parametric investigation results have shown that an increase in the material yield strength, the web thickness and the bearing length has a positive impact the web crippling capacity, whereas an increase in the radius and the depth of section have detrimental effects. Also, a comparison of the web crippling capacity of aluminium SupaCee and similar LCS revealed that SupaCee sections have enhanced capacity. Additionally, Thirunavukkarasu et al. [70] used validated FEM technique to perform detailed parametric study to study the web crippling performance of MCO beams under ETF loading condition with unfastened flanges case. In total, 162 models were developed for parametric analysis, out of which 81 excluded corner radius. The results indicated that web crippling capacity of MCO beams reduces about 15 %–50 % with inclusion of corner radii. Also, the AISI S100 codified equation to calculate web crippling capacity have shown contradictions with FE parametric analysis results and therefore a new equation was developed.

Also, Alsanat et al. [73] experimentally and numerically investigated the web crippling performance of roll-formed aluminium LCS with web holes under ETF load case. After validation of the FE models, a parametric study was conducted and the results have shown that web openings can substantially reduce the web crippling strength for both fastened (not exceeding 47 %) and unfastened (not exceeding 53 %) conditions. Also, design equations were developed with revised strength reduction factors to accurately predict the reduction in strength.

6. Floor system of MSB

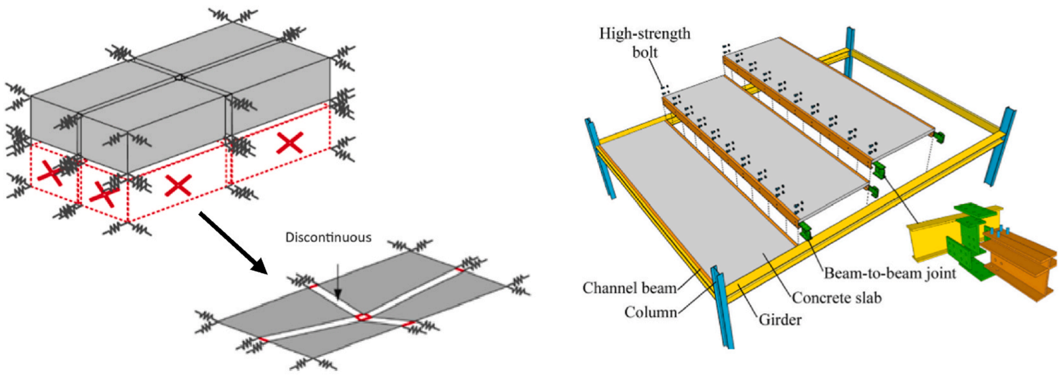
In MSB, solid RC slabs, hollow RC slabs, and floor joists are commonly used as floor system. Unlike conventional steel building (SB), the MSB features an intermediate cavity between floor beams (FB) and ceiling beams (CB). This cavity is typically filled with insulation layers to improve thermal and acoustical performance of the building. Gatheeshgar et al. [74] performed parametric FEM study to investigate the fire behaviour of conventional SB and MSB floor panels, formed of variable beam sections including optimised CFS folded-flange, super-sigma and LCS. Type and thickness of sheathing boards, lining layers of ceiling boards, and load-ratios were also varied in the study. The results have shown that MSB floor panels have enhanced fire resistance rating (FRR) compared to conventional SB. Also 75 % enhanced fire capacity of optimised beams was observed in comparison to benchmark LCS. Additionally, based on validated FEM, Perera et al. [75] found that adding an extra layer of gypsum-board sheathing on the fire face can increase the fire resistance level of floor system by at least 30 min.

In comparison to conventional steel buildings, the adjacent module slabs in MSB are only connected at four corners through inter-modular connection, which adversely affects the performance of floor system (see Fig. 6a). Zhang et al. [76] numerically investigated the collapse capacity of MSB RC floor-system under four interior-modules removal, two edge-modules removal and one corner-module removal scenarios. The results revealed better performance of floor-system with interior-modules loss and weakest performance with one corner-module loss. Furthermore, the MSB floor-system collapse performance was compared to the SB, demonstrating significantly higher robustness in the SB system. To avoid on-site wet RC slabs, Fang et al. [77] proposed a modular parallel flange channel-reinforced concrete (PFC-RC) composite floor-system, connected to FBs via beam-to-beam joints (see Fig. 6b). The repeating segments of modular-slabs are interconnected through webs of PFCs, using high-strength bolts, significantly enhancing the structural stability and robustness of MSB.

7. Steel columns of MSB

Limited research work has been conducted on the structural performance of corner-supported modular-steel columns. Park et al. [78] investigated the enhanced capacity of unsymmetrical steel-concrete composite columns through pure-axial (PAL) and combined compression-bending tests (CL), considering variable slenderness-ratios and eccentricity. The impact of through-bars was also studied during the CL tests, and relevant design equations were proposed. Under PAL tests, the columns failed under local-buckling and concrete crushing. For CL tests, significant lateral deformation was noted followed by local-buckling and concrete crushing. The proposed column is not economically feasible, as concrete is filled in factory which can substantially increase the weight of module, making it difficult to transport. To overcome this challenge, Chen et al. [79] proposed SHS steel-concrete composite columns, in which concrete is filled on site through pouring holes after assembling the adjacent modules vertically.

On another research examining the performance of modular steel columns, Deng et al. [80] used parametric FE analysis with variable parameters to determine the enhanced capacity of columns in contact with tenons of a novel inter-modular connection. The frictional-coefficient between columns and tenons, tenons-length, and tenon-thickness were varied. The findings revealed that increasing the tenons-length and tenons-thickness significantly enhances the ultimate capacity of columns by reducing the buckling



(a) Boundary condition of MSB floor-system (Zhang et al., (2024)

(b) Modular PFC-RC composite floor-system (Fang et al., 2024)

Fig. 6. Forms of floor systems in MSB.
(a) Boundary condition of MSB floor-system (Zhang et al. [76]
(b) Modular PFC-RC composite floor-system [77].

length, while the frictional-coefficient had minimum effects on column capacity. Similarly, Li et al. [81] and Farajian et al. [82] used numerical and analytical methods to propose effective-length factors (K-factors) for sway and non-sway MSB columns, considering boundary constraints of FB and CB as well as inter-modular connections. The findings have shown that using direct K-factors of conventional may lead to unrealistic results.

Perforations are sometimes introduced in columns to assemble inter-modular connections which can reduce the ultimate load-bearing capacities of columns. Singh and Chan [83] numerically investigated the effects of perforations with variable location, shape, size, depth, and column-thickness, on the buckling strength of columns. The results revealed that increase in perforation size can significantly reduce the column capacity, whereas location and shape of openings had minimum effects. However, among different shapes, square-shaped openings caused a greater reduction in column capacity compared to hexagonal and circular openings.

To improve the fire rating of columns to 2.5h, Zhang et al. [84] performed axial-load tests on full-scale SHS column specimens in furnace and proposed using two layers of 12 mm fiber-reinforced-calcium-silicate boards with 50 mm thick rock-wool insulation underneath. Also, Yu et al. [85] studied the fire performance of insulated wall-system and group modular-columns through tests and numerical investigations and concluded that three-layers of gypsum-boards protection can ensure 180 min fire rating of group-columns, however use of mineral-wool insulation beneath gypsum-boards was not recommended.

8. Connections of MSB

The structural behaviour and robustness of a modular building is highly dependent on the load resistance mechanism, structural integrity, ductility, energy dissipation and rotational strength of the connections between structural elements and modules. Connections shall be designed to transfer forces in a clear path to ensure reliable performance of the structure against vertical, wind and seismic loading [36]. In comparison to conventional cast in place structures, there are more joints and connections in MSB because of the necessity to connect structural members to develop individual modular units and also to connect modular units to form complete building. Connections in MSB can be classified into four groups as illustrated in Fig. 7: Intra-modular connections (see Section 8.1), module to foundation connections (see Section 8.2), module to frame/core connections (see Section 8.3) and inter-modular connections (see Section 8.4) [8,47]. Inter-modular connections connect different modules with one another, while all the connections within the module including CB and FB to ceiling and floor stringers, beams to columns and CB and FB to ceiling and floor panels are intra-module connections. Module to frame/core connections are used in medium to high rise MSB to ensure lateral stability by forming a hybrid system between stacked modules and MRF or core. Ideally connections should be simple, easy to install on-site with minimal welding, and detachable [35].

8.1. Intra-modular connections

Intra-modular connections are similar to conventional building joints and connect the structural members within a module. They transfer loads to columns and to inter-modular connections. Both bolted and welded connections are employed as intra-modular connections in MSB. A series of research studies have been performed and new connections have been proposed in order to improve the performance and reduce the weight of these connections. Examples of recent research proposals are presented in Fig. 8.

Lawson et al. [5] proposed a fin plate shear connection for beam to column joints. Due to relatively low ductility, flexural and rotational capacity, this type of connection is limited to only three storey MSBs. The applications of these connections might cause progressive collapse of stacked modules [88] which could be avoided by flexural strengthening the fin plate connections. For beam to

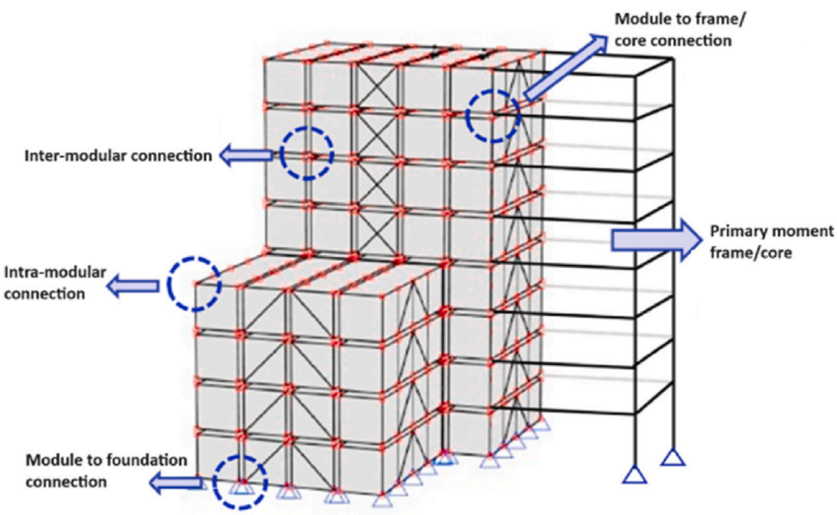
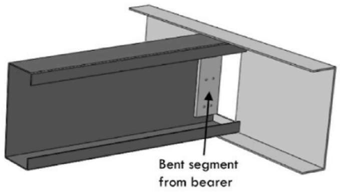
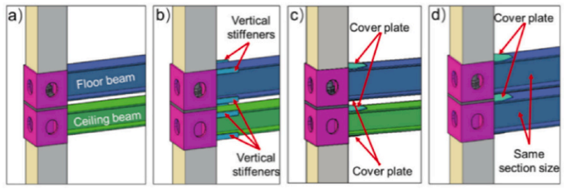


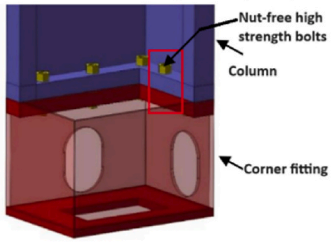
Fig. 7. Types of connections in MSB [8].



(a) Cut and bend bolted connection (Gateshead et al., 2021)



(b) Welded beam to column connections reinforced with cover plates (Liu et al., 2022)



(c) Corner-fitting connection (Zhang et al., 2020a; b)

Fig. 8. Examples from recent research proposals on intra-modular connections.
(a) Cut and bend bolted connection (Gateshead et al., 2021)
(b) Welded beam to column connections reinforced with cover plates [86]
(c) Corner-fitting connection [51,87]

stringer joints, Gatheeshgar et al. [40], developed a new cut and bend bolted connection to replace conventional cleat plate connection. The proposed connection is made by introducing rectangular shape cuts at three edges in the web of bearer which are then bent transversely to connect joist beam web through bolts. These connections can, however, detrimentally impact the structural capacity of bearer (see Fig. 8a).

Luo et al. [89] performed experimental and numerical investigations to study the structural behaviour of three different forms of beam to column connections, including welded connection (W), end plate connection (EP) and end plate connection with rib stiffeners (ST). Results have shown that both EP and ST connections exhibited ductile failure, while relatively brittle failure was observed for W connections. Also, ST connections demonstrated relatively higher flexural and rotational capacity in comparison to EP connections due to considerable plastic deformation of the stiffeners and end plate. Nevertheless, rib stiffeners in beam to column connections might conflict with the interior finishes and wall panel faces of corner supported modules.

Additional research on intra-modular connections was carried out by Innella et al. [90] who studied the load bearing capacity of carbon steel self-drilling screw connections between CFS stud and plasterboard-panels in MSBs. Annan et al. [91] and Annan et al. [50], Annan et al. [51] numerically investigated the effects of direct welded stringer-to-floor beam connections on the structural performance of typical floor joist in MSB. This is unlike traditional SB construction, which mostly use cleat or clip angle shear connections. The FEM results concluded that welded connections partially restrict the rotation and develop hogging moments and tensile axial forces in floor stringers, which should be considered in the design. Styles et al. [92] used comprehensive FE model to numerically investigate the effect of beam to column connection rotational capacity on the structural performance of MSBs. A conventional double cleat angle was considered as beam-column connection, and it was shown that an increase in stiffness of intra-modular connections can significantly improve the structural behaviour and lateral stability of MSBs.

The seismic behaviour of intra-modular connections has been studied by Liu et al. [86] (see Fig. 8b), who examined the seismic performance of different welded beam to column connections reinforced with cover plates, vertical stiffeners and enlarged section of ceiling beam. The cyclic load tests and numerical studies results showed that reinforcing details improved the seismic performance of connections by enhancing plastic deformation and effectively shifting the plastic hinge outward from the beam ends. Zhang et al. [45, 87] (see Fig. 8c) studied the seismic behaviour and failure modes of three connection specimens between open section column and bottom frame corner-fitting, using both experimental and numerical investigations, with variable magnitude of axial load. High strength, nut free bolts were used to connect the L-shaped end plates of column and corner fitting. The results showed improved energy dissipation, lateral stiffness and ductility capacities compared to conventional connections. However, it is evident that research on the seismic behaviour of intra-modular connections is limited, and further investigation is necessary.

8.2. Module to foundation connections

A module to foundation connection effectively distributes the load from superstructure of MSB to foundation underneath. This type of connection is more critical in medium to high rise MSBs, especially in locations exposed to significant wind or seismic loading, which might fail due to overturning or sliding if not properly restrained. Similar to conventional structures, MSBs may use precast or CIP isolated, combine, mat or pile foundations. Park et al. [93] used experimental and non-linear FEM investigations to examine the behaviour of embedded corner-supported-module-columns to foundation connection with variable embedment depths, shapes of end plates, and effects of shear studs between mortar and module columns (Fig. 9a). They reported that the embedment depth of columns has significant positive effects on the connection performance and development of maximum column strength under seismic loading, and pull-out failure might occur in case of insufficient depth. In contrary, shear studs result in relatively brittle failure. Annan et al. [91] proposed an untraditional floor-to-foundation rigid connection, on which the columns rest on floor beams, which are than connected to foundation through anchor bolts. Moreover, Fig. 9b depicts a more conventional connection proposed by Ref. [94], between the module corner fitting and precast foundation, utilizing anchor bolts.

8.3. Module to frame/core connections

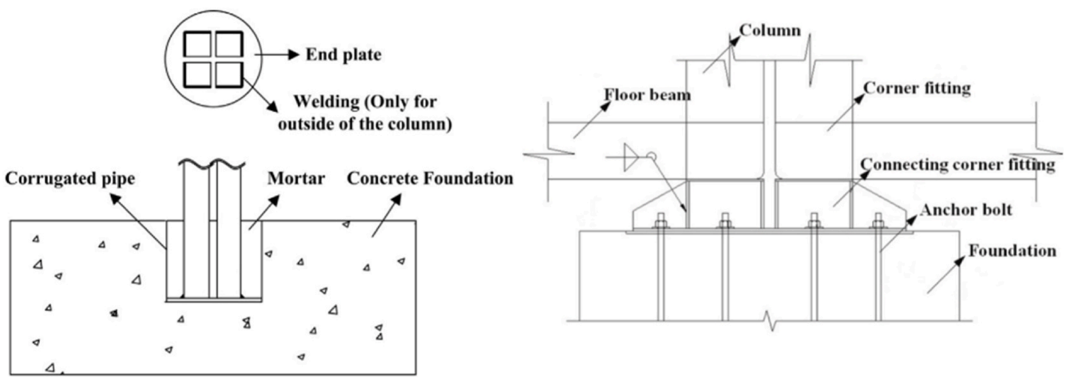
In a hybrid building system, a module to frame/core connection should be rigid to effectively transfer the lateral forces from stacked modules to MRF or core. The Chinese standard [94] suggested stiffened cover plates and high-strength bolts connection between the module corner fittings and columns of MRF (see Fig. 10a). Mark Lawson and Richards [7] proposed an extended plate connection between modules and corridors, through which the shear forces from modules to core are transferred by corridor structural members. Choi et al [95] proposed a connection between modular beams and a RC core by incorporating CIP stud bolts and a steel plate embedded in the core (see Fig. 10b). This steel plate is further welded to a gusset plate, which is finally bolted to the module beam. To simplify the connection, the modular structural members could also be directly welded to the embedded steel plate at the face of the core. Furthermore, Shan and Mou [96] developed a novel module to core connection and investigated its structural performance through numerical investigations under cyclic and extreme loads. The connection consists of a steel-plate with shear boxes embedded in core, and a connector with a shear-key rod inserted between adjacent modules connection boxes (see Fig. 10c). Four high-strength bolts are fastened to develop the connection. The results revealed that the proposed connection has sufficient resisting capacity in the elastic range, with a ductility factor of 2.

8.4. Inter-modular connections

Inter-modular joints develop vertical-connection (VC), horizontal-connection (HC) or combined vertical and horizontal connections between stacked modules. They effectively transfer load amongst modular-units and provide a clear-path to transmit forces to the foundation. These connections are critical to ensure lateral stability of MSBs [31]. A gap is mostly provided between the FBs and CBs to create external access for assembling inter-modular connections and to provide sufficient space to install building services. Welded connections are mostly avoided on-site. due to limited workspace, quality control issues and time constraints. To develop high-performance joints, extensive research has been conducted to investigate this type of connections. Herein, there are categorised into four categories, bolted, grouted, self-locking and tie-rod connections, respectively. A total of 28 different inter-modular connections are included in this review and presented hereafter.

8.4.1. Bolted inter-modular connections

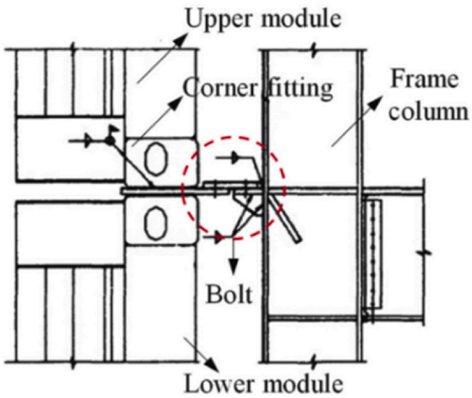
Bolted connections are widely used in industry as they require less site work and are demountable, however tolerance accumulations in high-rise MSBs may cause misalignment and the structure becomes vulnerable to slip failure under lateral loading. Additionally, their installation requires adequate on-site access openings in the joint regions, potentially causing damage to the interior finishes and reducing the strength of structural members. Furthermore, bolted joints are susceptible to corrosion in moisture-prone environments. Table 4 presents a review on recent and important research studies on 14 bolted inter-modular connections (see



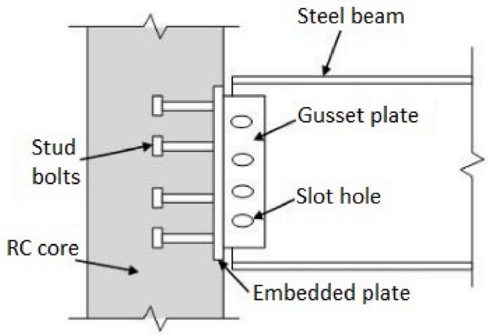
(a) Embedded corner-supported-module-columns to foundation connection (Park et al., 2016)

(b) Module corner fitting and precast foundation connection (CECS 334-2013)

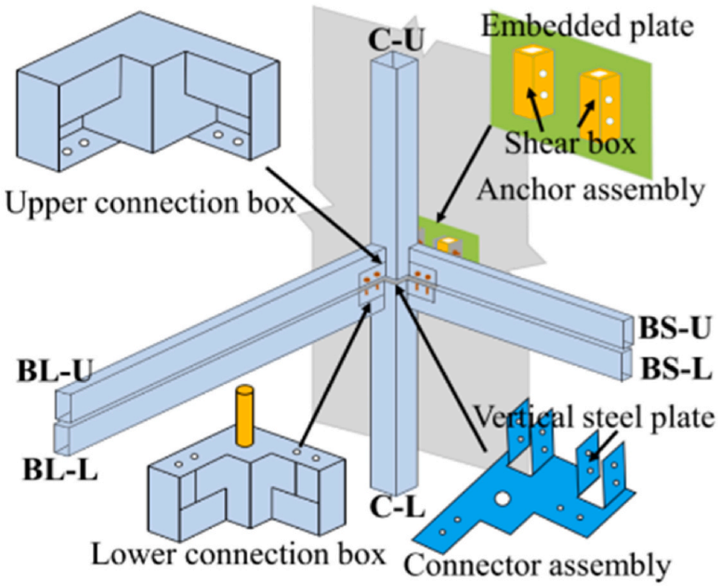
Fig. 9. Module to foundation connections.
(a) Embedded corner-supported-module-columns to foundation connection [93]
(b) Module corner fitting and precast foundation connection [94].



(a) Module to MRF connection (CECS 334-2013)



(b) Module to core wall connection (Choi et al., 2017)



(c) Module to core wall connection with shear boxes (Shan and Mou, 2024)

Fig. 10. Module to frame/core connections.
(a) Module to MRF connection [94]
(b) Module to core wall connection [95]
(c) Module to core wall connection with shear boxes [96].

Fig. 11), including a description and classification of the connection, the type of research performance and the main findings. Most of the studies focus on column-to-column and FB-to-CB bolted connections, with and without tenons and gusset plates. Both blind and high-strength bolts were employed to develop connections.

Similarly, Bazarchi et al. [103] studied axial and shear-force performance of side-to-side modules bolted connection. The connection is un-restrained against uplift, suitable only for gravity-force-resisting modules with separate LFRS, and consists of cap-plates welded to top of bottom modules-columns, cruciform plug-in tenons bolted to cap-plates, and a tie-plate with openings to pass through tenons. The tie-plate develops the HC between side-to-side modules and is bolted at ends of cap-plates. VC is developed through plug-in tenons and interior faces of upper-module columns. Six full-size exterior connection specimens were tested under cyclic and monotonic loading with variable sizes of cruciform tenons and tie-plates. The results revealed no unfavorable behaviour, however initial sliding of columns before interacting with tenons is a serviceability design concern.

The seismic load behaviour of blind bolted connection with tenons was investigated in a recent study by Yang et al. [97]. The connection is achieved by placing the tenon (bolted to beam) between adjacent module columns. Cyclic-load tests were performed on four T-shaped exterior connections with variable parameters. Connections with and without cover plates, internal diaphragm and combined bolted CB and FB were tested. Blind bolts were used to install cover plates. The results showed that connections with cover

Table 4
Review of research studies on bolted inter-modular connections (presented in reverse chronological order).

Reference	Connection description	Connection classification	Experiments investigations	Numerical investigations-Parameters	Design standards	Ductility factor	Failure modes
Yang et al. [97] Fig. 11a	Tenon between adjacent module-columns (MC).	Full and partial strength connections based on parameters.	4 cyclic-load tests on T-shaped exterior connections (CMS1-CMS4).	Plastic-deformation Failure-modes.	Material properties: [98] SMFR criteria: [99] . Classification: [100]	1.86–2.74	CMS1: Column and connection zone failure. CMS2: Gap opening between at joissnt and column failure. CMS3: Yielding of beams and connection zone failure CMS4: Column failure.
Liu et al. [101] Fig. 11b	VC: Tapered-head bolts between the corner-fittings. HC: Gusset plate.	–	4 T-shaped cyclic-load tests, with variable beam sizes and axial compression ratio.	Variable load ratio. Cover-plate thickness. Gap between beams.	Material properties: [98] . Ductility: [102] .	2.79–3.32	Buckling of unreinforced beam end.
Bazarchi et al. [103] Fig. 11c	VC: Plug-in tenons and interior faces of upper columns. HC: Tie-plate between side-to-side modules.	–	6 cyclic and monotonic load tests with axial load applied through beams.	In-plane shear performance of tie-plate.	Cyclic loading: [104].	–	C1-C4: Net-section of tie-plate yielded. C5-C6: Slippage between tenons and cap-plate observed followed by yielding of tie-plate.
Rajanayagam et al. [105] Fig. 11d	Extended end plates of top-right and bottom-left MC to provide additional intermediate layer of steel plate.	–	monotonic lateral-load tests (parameters: variable bolts diameter, holes size and configuration)	Validation with test results.	Shear strength and slip capacity: [106].	–	The connection is prone to slip failure and therefore large bolt holes shall be avoided.
Sendanayake et al. [107] Fig. 11e	C1: Additional steel-plate inserted between column base plates and gap was ensured. C2: Damping rubber-layers inserted in gap.	Full strength connection.	4 monotonic and 4 cyclic lateral-load tests (parameters: connecting-plate and rubber-layer thickness)	Validation with test results.	Material properties: (AS 1 [108] Loading setup: [108]. SMRF criteria: [108].	21.82–88.88 (energy balance approach)	Column plates yielded and plastic deformation was observed. Connector-plate also deformed. Ultimately weld fractured.
Zhang et al. [109] Fig. 11f	The cruciform plate with plug-in tenons is inserted between adjacent MC and beams are bolted. Finally cover-plates are installed.	–	–	Two exterior connections under cyclic-load. One connection had four diagonal haunch-braces.	Design limits: [110].	–	Plastic deformation.
Dhanapal et al. [111] Fig. 11g	Consist of upper and lower blocs. During assembling, blocs are connected through high-strength screws. HC: Gusset plate.	–	6 full-size beam-column and column-to-column specimens were tested.	Variable blocs-weight Screw locations.	Material properties: [112].	–	Under axial-compression: Global-buckling (Ductile). Under axial-tension: Rupture of screws (brittle).
Wang et al. [113] Fig. 11h	VC: The giant-bolt is placed inside locating-	Equivalent to semi-rigid connection for	2 monotonic static-loading tests were performed two	–	Classification: [100].	–	Excessive deformation of

(continued on next page)

Table 4 (*continued*)

Reference	Connection description	Connection classification	Experiments investigations	Numerical investigations-Parameters	Design standards	Ductility factor	Failure modes
	tube and end-plates are welded at adjacent MC. HC: Base plate.	un-braced and rigid for braced-frame system.	exterior specimens with variable diagonal stiffeners.				beam end at joint location.
Cho et al. [114] Fig. 11i	VC: Blind bolts between adjacent MC. HC: Irregular bolted plate between beams.	–	2 cyclic-load tests; 1 specimen with 4 knee-bracings.	–	Material properties: [115]. Design strengths: [116].	–	Shear failure of 1st blind bolts was initiated at 7 % drift, when other structural members had already failed.
Lee et al. [117] Fig. 11j	FB is strengthened with web-stiffeners and CB ends are reinforced with stiffened-bracket. A connection plate is bolted to beams.	Full-strength and rigid joint.	5 full-scale exterior specimens with variable PFC size and number of stiffeners in bracket. Benchmark weld joint was also tested.	Initial-stiffness values.	Material properties: [118]. Loading and classification: [119].	–	Yielding of FB, followed by development of plastic hinge.
Deng et al. [120] Fig. 11k	Cruciform plate is inserted between adjacent MC and bolts are installed. Cover plates are finally welded to restore the cut parts of column webs.	Connections with stiffeners: Semi-rigid and full-strength.	4 exterior specimens, with and without stiffeners, were tested under combined axial-compression and cyclic-loading.	–	Material properties: [121,122,123]. Design: [121,122,123]. Classification: [100].	2.82–3.41	Development of plastic hinges in CB and fracture of weld at joint ends.
Chen et al. [124] Fig. 11l	VC: High strength stay bolts. HC: Plug-in tube device.	Unstiffened-connection: pin-joint assumption is valid.	2 monotonic-static and 4 cyclic-load tests	Internal stress-distribution.	–	2.35–3.42	Gap opening between adjacent MC at plastic stage. Local-buckling of MC ends and fracture of joint.
Hwan Doh et al. [125] Fig. 11m	Two sides consist of bolt-holes and access openings. Openings are also provided on other two sides for installation tools.	–	2 shear load tests Simply-supported on set of brackets, loaded at mid joint.	Validation with test results.	Design capacities: [126].	–	Bolts failed in tension in a ductile mode. No failure of bracket observed.
Styles et al. [92] Fig. 11n	VC: Bolting the end plates of adjacent modules columns. HC: Bolting the end plates of side-to-side MC.	–	–	Load-displacement and rotational capacities of VC and HC.		–	–

plate and internal diaphragm significantly improve the ductility and energy dissipation characteristics, satisfying special moment resisting frame (SMRF) criteria. Yang et al. [127] also investigated corner T-shaped connections with similar details.

8.4.2. Grouted inter-modular connections

The tolerance alignment issues present in bolted connections can be resolved by use of grouted connections (see Fig. 12), with enhanced lateral stiffness. These connections facilitate speedy module assembly by eliminating the need for on-site welding and bolting. However, disassembling the modules require additional effort, as grouted connections are not easily demountable. Connection integrity is maintained through the bond strength at the interface between the steel tube and grout, along with the mechanical interlock provided through the shear transfer mechanism. Grouted connections have been recently adopted in MSB industry by researchers and are based on the concept of circular hollow section (CHS) grouted-sleeve connections from the offshore and wind turbine industries [128]. Table 5 presents a review on recent research studies on 6 grouted inter-modular connections, including a description and classification of the connection, the type of research performed and the main findings. Researchers have employed high strength

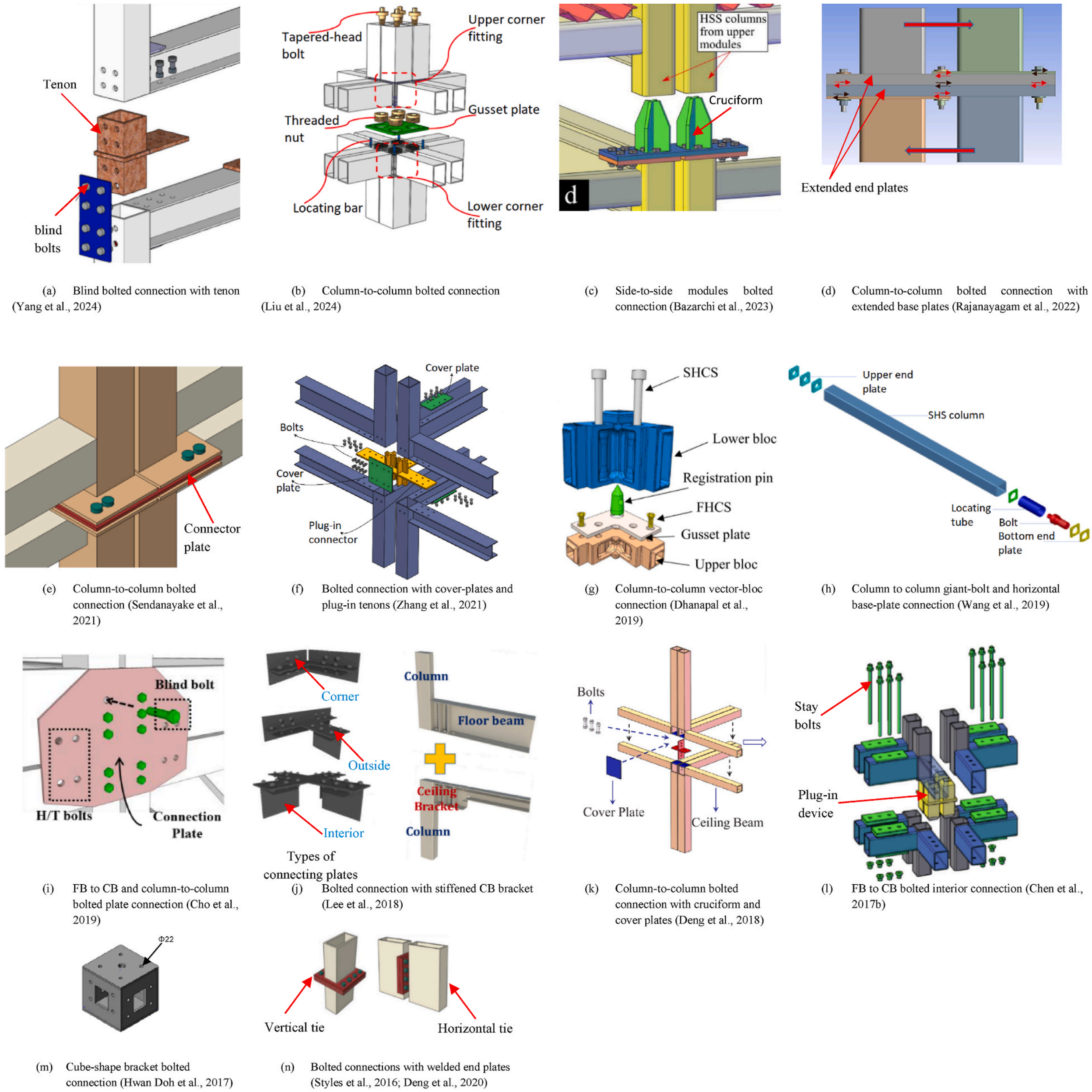


Fig. 11. Bolted inter-modular connections.
(a) Blind bolted connection with tenon [97]
(b) Column-to-column bolted connection [101]
(c) Side-to-side modules bolted connection [103]
(d) Column-to-column bolted connection with extended base plates [105]
(e) Column-to-column bolted connection [107]
(f) Bolted connection with cover-plates and plug-in tenons [109]
(g) Column-to-column vector-bloc connection [111]
(h) Column to column giant-bolt and horizontal base-plate connection [113]
(i) FB to CB and column-to-column bolted plate connection [114]
(j) Bolted connection with stiffened CB bracket [117]
(k) Column-to-column bolted connection with cruciform and cover plates [120]
(l) FB to CB bolted interior connection [124]
(m) Cube-shape bracket bolted connection [125]
(n) Bolted connections with welded end plates [8,92]

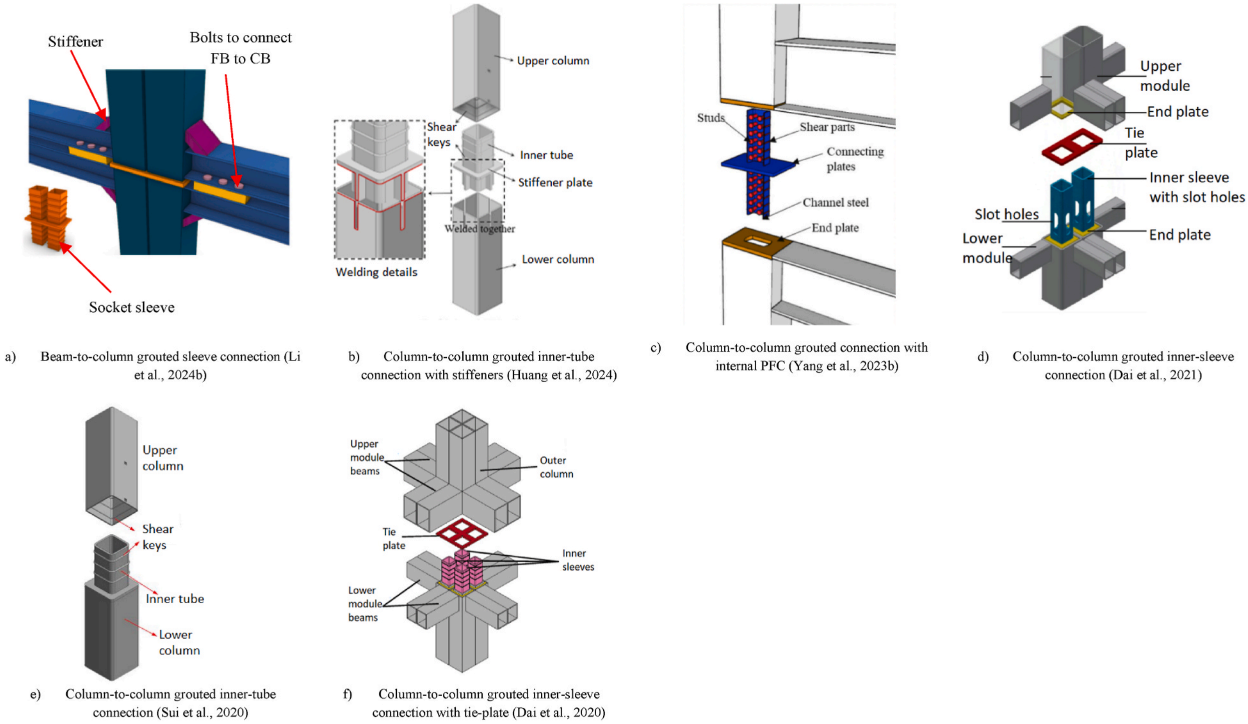


Fig. 12. Grouted inter-modular connections.
(a) Beam-to-column grouted sleeve connection [129]
(b) Column-to-column grouted inner-tube connection with stiffeners [128]
(c) Column-to-column grouted connection with internal PFC [130]
(d) Column-to-column grouted inner-sleeve connection [131]
(e) Column-to-column grouted inner-tube connection [132]
(f) Column-to-column grouted inner-sleeve connection with tie-plate [133].

grout (HSG) with and without steel-fibres to develop these novel connections. The grout is filled on-site during assembling process.

The seismic behaviour of grouted inter-modular connection has been presented in the recent work of Li et al. [129] who investigated the seismic performance of an exterior connection. The connection is developed by placing the grouted socket-sleeve between adjacent modules columns. Both monotonic and cyclic-load tests were performed on four types of connections. Specimens with and without diagonal stiffeners, and bolted FB to CB beams, were tested. Based on results the grouted connection with bolted FBs to CBs can be classified as full-strength and semi-rigid. This type of connection can also improve buckling load capacity of columns, which requires future investigations. Furthermore, Yang et al. [130] investigated seismic performance of a corner connection. The connection consists of an internal PFC with welded shear-studs and shear-parts, intermediate connecting-plate, inner-diaphragms, and perforated end-plates welded to the column ends. During assembling, the PFC is placed between adjoining modules end-plates in proper sequence, and the gap between module columns and PFC is filled with non-shrinkage HSG. Cyclic-load tests were performed on four full-scale T-shaped specimens with variable axial-load ratios, and with and without diagonal stiffeners. Based on results the grouted connection be classified as full-strength. Also, stiffeners significantly enhanced the load-bearing capacity and ductility of connection by 12.60 % and 27.20 % respectively.

8.4.3. Self-locking inter-modular connections

Some researchers have also investigated the performance of self-locking connections (see Fig. 13) that depend on self-weight of upper-modules to develop joint with mechanical behaviour comparable to bolted connections, however these connections require high-accuracy manufacturing and installation. Table 6 presents a review on research studies on 4 self-locking inter-modular connections, including a description and classification of the connection, the type of research performed and the main findings. Chen et al. [49] proposed self-locking rotary connection with upper and lower module columns corner-fittings and can be classified as equivalent to semi-rigid connection. Dai et al. [141] proposed column-to-column self-locking connector with joint boxes and is classified as full-strength and semi-rigid connection. Moreover, Sharafi et al. [142] proposed modular-integrating system comprising of strips with integrating-connections featuring geometrical grooves and tongues to enhance stability of modular buildings against severe and accidental loading. The seismic performance of a corner connection has been studied by Chen et al. [143]. The connection consists of lower and upper module corner-fitting with chamfered endplate and horizontal gusset-plate and can be classified as full-strength and semi-rigid. The proposed connection has better performance as compared to other self-locking connections, shown in Table 5.

Table 5
Review of research studies on grouted inter-modular connections (presented in reverse chronological order).

Reference	Connection description	Connection classification	Experiments investigations	Numerical investigations-Parameters	Design standards	Ductility factor	Failure modes
Li et al. [129] Fig. 12a	Consists of grouted socket-sleeve between adjacent MC.	Type-2 and Type-3: Full-strength and semi-rigid. Type-4: Partial-strength and semi-rigid.	4 monotonic and cyclic-load tests were performed on four types of connections. Type-1: Un-grouted. Type-1, 2 had stiffeners. Only Type-4 is without bolted-plate connection between beams.	–	Material testing: [134]. Grout testing: [135]. Classification: [100].	4.38–5.36 (monotonic) and 2.82–4.04 (cyclic)	Gap opening: Only observed in Type-1 connection. Weld failure between beam-column ends.
Huang et al. [128] Fig. 12b	Inner-tube with shear keys (SKs) and stiffener plate welded to lower MC.	Full-strength and rigid.	8 three-point bending on specimens with variable spacing of SKs, length and steel-fibres in grout and inner-tube size.	Grout and inner-tube performance. Lateral capacity. Effects of shear-spans ratio.	Material testing: [136] . Grout testing: [137]. Classification: [100].	1.5–7.1	With HSG: Fracture of inner-tube. With low strength grout: Grout-slippage. Failure mode changed from shear to flexural, as shear-span ratio increased.
Yang et al. [130] Fig. 12c	PFC with welded shear-studs and shear-parts, placed between adjoining modules end-plates, and the gap is filled with HSG.	Full-strength.	4 cyclic-load tests variable axial-load ratios, and with and without diagonal stiffeners.	Validation with test results.	Material testing: [98]. Loading setup: [99] . Classification: [121,122, 123].	1.37–2.44	Weld cracking of beam-column intra-modular connection and tearing of adjacent column walls.
Dai et al. [131] Fig. 12d	SK-GSC: Inner-sleeve with SKs welded to the top end-plate of lower column. SH-GSC: Comprises of an inner-sleeve with slots.	Partial-strength and rigid in braced MSB.	3 three-point tests 3 four-point tests	–	Material: [138]. Classification: [100].	–	SH-GSC failure: Ductile due to tensile failure of the narrowed section of inner-sleeve. SK-GSC failure: Less ductile due to weld failure.
Sui et al. [132] Fig. 12e	SKs are provided in both inner-tube and upper-module column. Inner-tube is welded to the top of lower MC.	–	8 full-size specimens, including partial and fully HSG specimens, and benchmark grouted and non-grouted column specimens.	Failure-modes. Validation with test results.	Material testing: [136] . Grout testing: [139].	–	Tensile loading: Shear-cracks in HSG, punching failure due to unstiffened end-plate and yielding of SHS tube. Compression: Local-buckling and yielding of SHS tube and grout-cracking.
Dai et al. [133] Fig. 12f	SKs are provided in both inner-sleeves and module columns. HC: Through Tie-plate.	Partial-strength connection.	15 tests on pull-out capacity with variable inner-sleeve sizes, steel-fibres percentage in HSG, and spacing of SKs.	Failure-modes. Validation with test results.	Material testing: [140].	Above 4.0	The grout at central portion was crushed.

To compare the performance of different types of connections in terms of strength and stiffness, Dai et al. [133] conducted a comparative study between three different categories of column-to column connections: vector-bloc connection [111] (see Section 8.4.1 - Fig. 11g), grouted inner-sleeve connection [133] (see Section 8.4.2 - Fig. 12f), self-locking connector with joint boxes [141] (see Section 8.4.3 - Fig. 13c). The load-displacement curves of all three connections are shown in Fig. 14. To compare the initial axial-stiffness, the load on y-axis is normalised by dividing it with plastic capacity of the connected modular columns. The curves indicate that the initial axial-stiffness, strength and ductility of grouted inner-sleeve connection is greater than the other two connections.

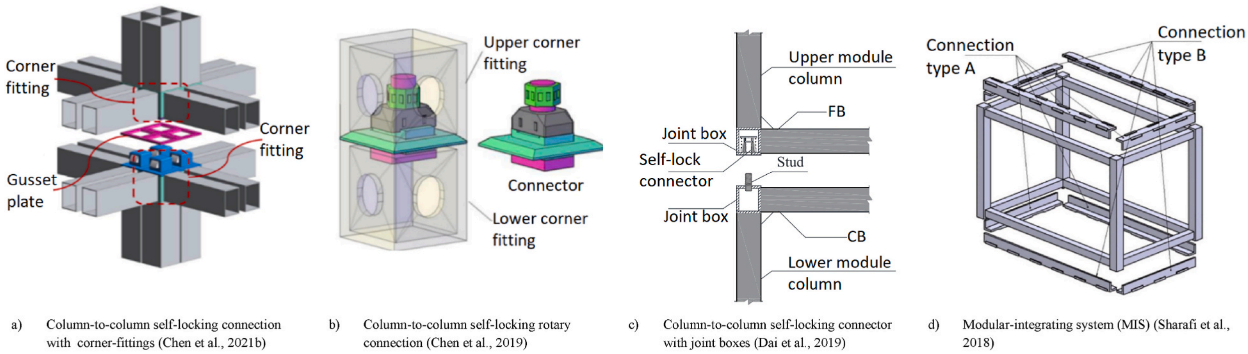


Fig. 13. Self-locking inter-modular connections.
(a) Column-to-column self-locking connection with corner-fittings [143]
(b) Column-to-column self-locking rotary connection [49]
(c) Column-to-column self-locking connector with joint boxes [141]
(d) Modular-integrating system (MIS) [142].

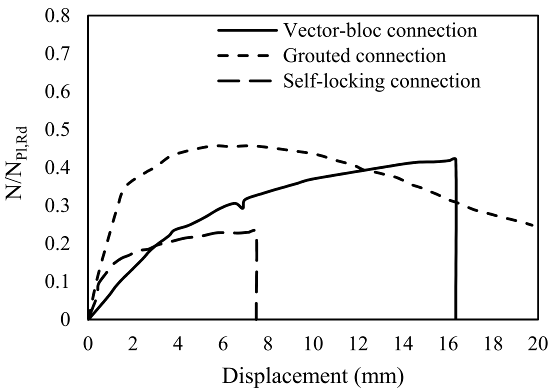


Fig. 14. Load-displacement curves of connections for a comparative study (adopted from Dai et al. [133]).

8.4.4. *Tie-rod inter-modular connections*

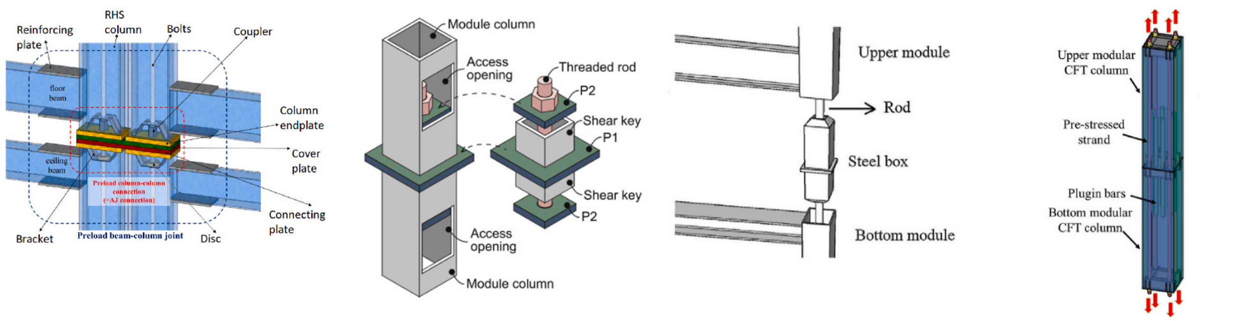
Tie-rod connections (see Fig. 15) have also been introduced by researchers, but they require more site-work and mostly utilise hydraulic-jacks for assembling. Table 7 presents a review on research studies on 4 tie-rod inter-modular connections, including a description and classification of the connection, the type of research performed and the main finding. Recently Lee et al. [144] investigated the structural behaviour of connection. The modules are connected vertically using brackets, couplers and steel-rod bolts (SRBs), pre-installed in SHS columns within factory. The horizontal connection is achieved through steel plates. To avoid gap-opening and slip failure, a design method is developed to estimate minimum pre-load to avoid gap-opening and slip, addressing an area not previously explored by researchers. The results revealed that the proposed connection with sufficient induced pre-load behaves as rigid. Additionally, Lacey et al. [145] proposed a column-to-column post-tensioned connection featuring a shear-key and access opening, which is classified as semi-rigid connection. Furthermore, Sanches et al. [146] proposed a column-to-column post-tensioned connection with a threaded-rod that extends along the entire height of columns and a steel-box. Moreover, Chen et al. [79] studied the performance of column-to-column pre-stressed strands connection with plugin-bars. Concrete is poured on-site after pre-stressing strands to enhance connection stiffness, and can be classified as weak semi-rigid connection.

9. Conclusions

This review paper examines the key aspects, advancements, and research developments in MSB construction. It offers an in-depth review of structural forms and lateral load-resisting systems, along with the structural performance of modular floor beams, floor system, columns, and connection systems. MSBs are predominantly utilised for structures with consistent usage offering several benefits over conventional construction. However, it is crucial to address key constraints including the lack of design guidelines, limited R&D, and logistical challenges, which restrict the industry's ability to fully utilise MSB. Based on this comprehensive review, the main findings and recommendations for future studies are outlined below. Also, Table 8 briefly presents the key findings and future recommendations.

Table 6
Review of research studies on self-locking inter-modular connections (presented in reverse chronological order).

Reference	Connection description	Connection classification	Experiments investigations	Numerical investigations	Design standards	Ductility factor	Failure modes
Chen et al. [143] Fig. 13a	VC: Upper module corner-fitting squeezes the locking-tabs of lower module corner fitting. Locking-tabs are later ejected during slow downward movement of upper-module. HC: Gusset-plate.	Full-strength and semi-rigid.	4 cyclic-load tests on corner T-shaped specimens with variable shapes, sizes and gap between beams.	Validation with test results.	Material testing: [98] Classification: [100].	2.50–3.20	Plastic hinges produced at the root of FB and CB.
Chen et al. [49] Fig. 13b	Upper and lower corner-fittings with access-holes to rotate the connector.	Equivalent to semi-rigid connection.	Bending-capacity test. The specimen included connection as well as portions of adjacent modules columns.	Validation with test results.	–	–	Local buckling of upper plate of lower corner-fitting.
Dai et al. [141] Fig. 13c	The stud is fixed to lower-module joint-box, whereas other components of connector are located inside the upper- joint-box. The stud is fixed into connector during slow downward movement of upper-module.	Full-strength and semi-rigid connection.	7 cyclic-loading test on seven T-shaped full-size joints with variable beam sections. 1 monotonic-load test.	–	Material testing: [98] Loading setup: [99]. Classification: [100].	2.7–3.1	Buckling or fracture of FB and CB.
Sharafi et al. [142] Fig. 13d	MIS consists of strips with integrating-connections featuring geometrical grooves and tongues, which are joined to perimeter beams of adjacent modules.	–	Static and dynamic shake-table tests. Integrity of system was checked against lateral loads and removal of modular supports.	Performance of MIS.	–	–	–



a. Column-to-column post-tensioned connection with couplers (Lee et al., 2024)
b. Column-to-column post-tensioned connection with shear-key (Lacey et al., 2019)
c. Column-to-column post-tensioned connection with steel-box (Sanches et al., 2018)
d. Column-to-column pre-stressed strands connection with plugin-bars (Chen et al., 2017a)

Fig. 15. Tie-rod inter-modular connections.
(a) Column-to-column post-tensioned connection with couplers [144]
(b) Column-to-column post-tensioned connection with shear-key [145]
(c) Column-to-column post-tensioned connection with steel-box [146]
(d) Column-to-column pre-stressed strands connection with plugin-bars [79].

- *Lateral Stability systems for high-rise MSBs:*
  Limited studies have been conducted to enhance the overall lateral stability of MSBs. Additionally, research conducted to improve lateral stability by incorporating hybrid systems, RC cores and steel shear walls have shown effectiveness, but they can reduce the advantages of modular construction by increasing the construction time and the carbon footprint. The addition of base isolation could be beneficial, as this technique can increase the natural period and energy dissipation of MSBs by allowing rocking motions, thereby eliminating the need for additional lateral stability structures. However, further research is required on this subject.

Table 7
Review of research studies on tie-rod inter-modular connections (presented in reverse chronological order).

Reference	Connection description	Connection classification	Experiments investigations	Numerical investigations - Parameters	Design standards	Ductility factor	Failure modes
Lee et al. [144] Fig. 15a	VC: Through brackets, couplers and steel-rod bolts (SRB), pre-installed in columns. HC: Steel plates. The couplers apply the pre-load in SRB using impact or torque wrench.	Rigid connection at sufficient design pre-load.	–	Pre-load to avoid gap-opening and slip. Variable beam sizes. Impact of gap-opening.	Design limits: [147]	–	Gap-opening and slip at insufficient pre-load.
Lacey et al. [145] Fig. 15b	Consists of post-tensioned tie-rod and a SHS SK with an intermediate steel-plate, inserted between two adjoining MC. Access-openings are provided in MC to induce initial pre-load to the tie-rod.	Semi-rigid connection.	6 tests to study shear-force and initial-slip behaviour. Examined variable interior finish surfaces, contact-area and initial torque magnitude in tie-rods.	Variable slip-factors tie-rod pre-load.	Slip test: [148].	–	Weld failure between SHS and intermediate plate. Deformation of exterior SHS. Bearing of exterior and interior SHS.
Sanches et al. [146] Fig. 15c	VC: Developed by post-tensioned threaded-rod which passes through complete height of column and is tied to steel-plates at columns ends. HC: Through steel-box which is inserted between adjoining modules.	–	8 cyclic-load tests on T-shaped specimens with variable steel-box thickness and initial pre-load. 2 specimens with standard weld connections were also tested.	–	Material testing: [149]. Loading setup: [150]. Design limits: [151].	–	Certain gap-opening and slippage was observed.
Chen et al. [79] Fig. 15d	VC: Through the stretching of pre-stressed strands before pouring concrete in columns. Strands are joined together via strand-connectors. HC: Through shear-block welded to seal-plate. Plugin-bars prevent concrete failure and enhance stiffness.	Weak semi-rigid connection [46].	2 cyclic-load tests on two story corner-supported modular frame with propped connections. Diagonal braces were used to provide in-plane stiffness.	Validation with test results. Internal-force distribution modular-frame compared with conventional frame.	Loading setup: [102] Design limits: [152].	–	Concrete-cracking, debonding of strands and plug-in bars and gap opening between columns.

- *Optimisation of modular floor beam profiles:*
  Numerical investigations conducted on optimised novel beam sections have demonstrated increased structural capacities and reduced weights of modular floors in comparison to conventional LCS beams. The use of optimised novel beams can substantially reduce the challenges related to transporting and lifting modules. Nevertheless, since these studies were only numerical, there is a clear need for future experimental investigations. Further research is also needed on fire and collapse performance of MSB floor-system.
- *Categories of inter-modular connections:*
  In this study, connections are categorised into four categories, bolted, grouted, self-locking and tie-rod connections. Bolted connections are more efficient to install and can be easily detached, however their tolerance accumulations in high-rise MSBs may result in significant misalignment, making the structure more susceptible to slip failure under seismic loading. Grouted connections, on the other hand can offer a high level of assembling tolerances with improved lateral strength and stiffness. Self-locking connections, consists of complex parts and require precise manufacturing and on-site assembly. Finally, tie-rod connections typically require hydraulic-jacks for assembly, making on-site work difficult.
- *Inter-modular connections global performance (seismic, wind, fire):*
  Significant research has been devoted to investigating the structural performance of inter-modular connections under both gravity and seismic loading. Nevertheless, further studies are essential to fully understand their impact on the global seismic

Table 8
Key findings and future recommendations.

Key findings	• **Lateral stability** of high-rise MSBs relies on hybrid systems, increasing project timelines and carbon footprint. • **Base isolation** can enhance the time period and energy dissipation of MSB by enabling rocking motions without incorporating extra systems. • **Optimised beam sections** provide increased structural strength and reduced weight for modular floors, however no tests have been conducted to validate these results. • **Inter-modular connections** can be categorised as bolted, grouted, self-locking and tie-rod. Significant research has been reported on their structural performance under both gravity and seismic loading. • **Grouted inter-modular connections**, a newer approach, can address challenges in other connection categories. These connections can be classified within a range from semi-rigid and partial strength to rigid and full strength and can increase lateral stability of MSB without need of hybrid system. • **No standard design guidelines** exist for MSBs and therefore industry relies on conventional limit state design criteria which may not fully address critical load scenarios specific to MSBs.
Recommendations for future research	• Given the limited studies conducted on **utilization of base isolation**, further research is recommended. • Experimental studies are needed to investigate the structural performance of **novel beam optimised sections for MSB applications**. • Studies on **global seismic performance of MSBs** with different inter-modular connections and the performance of connections **under fire and wind loading conditions** is recommended. • Future studies should focus on enhancing **the performance of grouted connections** by incorporating various bond strengths and interlocking schemes to develop rigid and full-strength connections in MSBs. • Further studies are also required to **develop unified design guidelines.**

behaviour of MSBs. Additional research is also needed to evaluate the performance of inter-modular connections under fire and wind loading conditions.

- *Grouted inter-modular connections performance:*

  These connections are relatively new in MSB industry, and therefore further research is needed to enhance their seismic performance by incorporating different mechanical interlocking schemes and to improve their cost and quality control. Additionally, these connections can also increase the load-bearing capacity of columns by reducing their effective buckling length, an area which also requires further research.
- *Design guidelines:*

  As has been reported, past research efforts have sought to refine design guidelines, yet a singular, well-defined recommendation remains absent. Recently Dan-Adrian and Tsavdaridis [31] proposed nomenclature to categorize inter-modular connections, Yuan et al. [32] introduced a parametric design based on BIM, Murray-Parkes et al. [30] developed a handbook to design modular buildings, Isaac et al. [153] developed a graph based method to enhance modular design by improving flexibility and reducing repetitiveness, resulting in more efficient designs for clients. The existing references provide some technical guidance, however further studies are still required to prepare design guidelines suitable for industrial application of MSBs and consideration for future. The design guidelines should account for all adverse load scenarios, including additional stresses developed due to misalignment and tolerance accumulation, as well as stresses induced during transportation and installation. The BIM process can significantly reduce coordination discrepancies by integrating the design, manufacturing, and installation stages. However, current BIM products lack certain features specifically related to modular construction, and further research is warranted to advance BIM technology to meet these requirements.

CRediT authorship contribution statement

Farhan Ahmed: Writing – original draft, Investigation, Conceptualization. **Michaela Gkantou:** Writing – review & editing, Supervision, Conceptualization. **Georgios Nikitas:** Writing – review & editing, Supervision. **Maria Ferentinou:** Writing – review & editing, Supervision. **Ana Bras:** Writing – review & editing, Supervision. **Mike Riley:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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