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Review

Seismic performance of mid-to-high rise modular steel construction - A critical review

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ABSTRACT

Modular steel construction (MSC) comprises off-site manufactured volumetric modules and on-site assembly, leading to reduced construction periods, improved quality, and reduced waste of resources. This environmentally friendly solution has been extensively used for low-rise buildings as an alternative to traditional on-site construction. The popularity of MSC has now spread to mid-to-high rise applications in seismic regions to meet the increasing urban construction demand, owing to its significant technical advantages. The influence of earthquake becomes critical as the height of the building increases. Hence, this paper presents a state-of-the-art review of the seismic performance of mid-to-high MSC and articulates the key technical issues. The module classification is presented as a brief introduction of MSC, followed by discussion of the structural system. Afterwards, the seismic performance of the lateral force resisting system and recent innovations on the connection system are reviewed in detail, on which the seismic performance of MSC highly depend. The global seismic response analysis methodology, characteristics, failure mode as well as the current design criteria are evaluated, providing a more comprehensive understanding of the seismic performance of MSC. Finally, the recently developed isolation systems for MSC are introduced. As a currently developing area, there is great potential for innovation in mid-to-high rise MSC. Despite progressively increasing research exploring the seismic performance of MSC, a comprehensive understanding of this topic has not been achieved, hindering the further prevalence of mid-to-high rise MSC in areas with potential seismic hazards. Given this situation, several key research areas are suggested thereupon at last, aiming to promote the further extended application of MSC in seismic regions.

1. Introduction

The modularized production of buildings has attracted extensive interest from engineers in recent years with the growing environmental impact and increasing labor costs for the traditional on-site construction [1–4]. Modular construction has, therefore, become increasingly popular and promoted across the construction industry, especially for buildings with repetitive architectural plans and structural layouts, such as hospitals, hotels, classrooms and dormitories [5–7]. Modular construction permits a large portion of the building to be manufactured in factory condition, making it environmentally friendly and highly efficient. The fully finished volumetric modular unit is therefore prefabricated in the factory, and it is transported to the construction site and assembled to form a complete building. This construction method is an excellent alternative to traditional on-site construction because of its significant technical advantages, including faster construction speed, better quality, reduced environmental disturbance around the construction site and convenience in demounting and recycling. It allows the building to be handed over and put into use as soon as possible.

Among the various module types for modular construction, the steel-based module is the ideal structural form, owing to its flexibility in architectural design, long span, lightweight, and convenience in connection as compared to concrete and timber framed modules [8,9]. Reinforced concrete slabs and partition walls are usually integrated in the steel module to ensure good acoustic and thermal insulation, providing a complete building system for modular steel construction

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(MSC). It has been demonstrated that MSC can fully exploit the advantages of modular construction, especially with regard to speed of construction [10]. In a very recent example, a post-disaster hospital that could accommodate 1000 patients was successfully built in just 10 days by employing MSC in Wuhan, China, aiding in the fight against the virus COVID-19 [11].

Three generic forms of modules exist in MSC, depending on the load transferring mechanism: the continuously supported module, frame supported module, and non-load bearing module [12,13], as illustrated in Fig. 1. For the continuously supported module, the loads are transferred through the side walls, which provide continuous support. Steel studs spaced at intervals of 300–600 mm form the four-sided walls. The compressive resistance of the side walls is crucial, and this type of MSC is mainly limited to buildings that are approximately four storeys high [12]. Frame supported modules have columns at their corners, and sometimes at intermediate points. The edge beams span between the posts and transfer loads from the edge beams to the posts. The corner posts require high compression resistance and are generally in the form of structural hollow sections (SHS), to obtain a smooth building elevation and excellent compression, torsion, and bending behavior [14,15]. The frame supported module is popularly used in current practice. Non-load bearing modules, or pod-like modules, are unable to transfer loads and are supported by a floor. Modules in this category usually have a certain building function, such as acting as a staircase, bathroom, or kitchen.

Despite the popularity of MSC in low-rise buildings worldwide, expanding city populations and strict requirements for construction environment in urban areas have called for mid-to-high rise modular construction [16–20]. Its feasibility has been proven by the successful launching of various projects in various regions, e.g., a five-story dormitory in Tianjin, China (Fig. 2(a)) [21], a 13-story hostel in NTU, Singapore (Fig. 2(b)) [22], and a 17-story residence in the UK (Fig. 2(c)) [23]. These projects have provided confidence to the construction industry, governments and investors in the applicability of MSC for mid-to-high rise buildings. However, the majority of the current applications of mid-to-high rise MSC are limited to non-seismic zones, and the influence of the lateral load such as earthquake becomes critical with the increase of the building height. The seismic performance of MSC, especially mid-to-high rise MSC, is not adequately understood, as it is a relatively new structural form.

This paper aims to provide a critical review and systematic investigation on the seismic performance of mid-to-high rise MSC, including the structural system, lateral force resisting system (LFRS), and innovations on connections, followed by an examination of the global response and design criteria. Challenges for the seismic design and analysis of mid-to-high rise MSC are pointed out and emphasized. The outcomes of this paper are expected to promote the future development and application of mid-to-high rise MSC in seismic regions.

2. Structural system of modular steel construction

The structural system is vital to ensuring the structural stability and safety of MSC. Several types of structural systems have been proposed for MSC in previous practice. Structural systems can be categorized into three types, according to the lateral-force transferring mechanism: the stacked module structure, module-moment frame hybrid structure, and module-concrete core hybrid structure. They are designed to satisfy various height requirements for buildings [10,12,24–27].

2.1. Stacked module structure

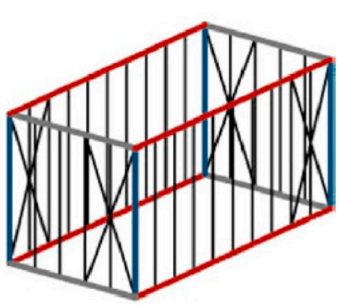
Recent studies have mainly focused on the stacked module structure. The individual module units are connected with each other on-site to form the entire building, as shown in Fig. 3. The gravity and lateral loads caused by wind and earthquake are transferred by the side walls for the continuously supported module, or by the inter-module connection for the frame supported module. The layout of the module may be varied to obtain reasonable mechanical properties for the MSC. The stacked module structure is suitable for low-rise buildings comprising no more than three stories and with a regular plane layout [24–26]. However, the stacked module structure can be built higher by using an incorporated lateral force resistant component and rigid module-to-module connections.

2.2. Module-moment frame hybrid structure

Unlike the stacked module structure containing exclusively module units, the module-moment frame hybrid structure combines stacked modules with a primary steel or concrete moment frame, to improve the lateral force resistance of MSC. The stacked modules can be supported by a braced frame to thereby resist the lateral force together, as displayed in Fig. 4(a). The stacked modules can also be supported by a podium frame, thereby forming a podium structure (Fig. 4(b)). The podium structure is often used to provide a commercial or communal space, such as supermarket or car park in the bottom one or two floors of the building. In addition, the modules can be recessed in the primary frame, as shown in Fig. 4(c). This structural form is also called the "modular in-fill construction method", and its applicability and construction feasibility were verified by Park et al. [13] and Andrade et al. [28]. The columns are placed at two or three times the width of the module, i.e., approximately 6 m or 9 m, to ensure two or three paratactic modules can be recessed in the primary frame.

2.3. Module-concrete core hybrid structure

Similar to the module-moment frame hybrid structure, the module-concrete core hybrid structure comprises a concrete core, around which modules are arranged (as shown in Fig. 2(c)). The concrete core



(a) Continuously supported module [10]

(b) Frame supported module [13]

(c) Non-load bearing module [12]

Fig. 1. Classification of the modules in modular steel construction (MSC).

(a) Five-story dormitory in China [21]

(b) 13-story hostel in Singapore [22]

(c) 17-story residence in the UK [23]

Fig. 2. Mid-to-high rise modular construction.

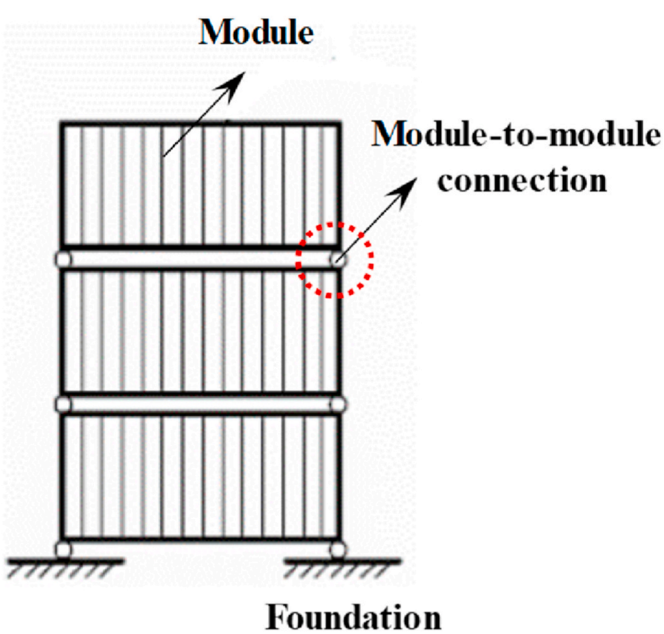


Fig. 3. Stacked module structure (Adapted from Ref. [24]).

efficiently resists the lateral force, and has been widely adopted for high-rise modular construction worldwide, such as a 17-story residence in London, England [23], 18-story residence in Zhenjiang, China [29], and Atlantic Yards B2 projects in New York, America [18]. However, the manufacturing, transportation, and assembly of modules needs to be properly scheduled for the hybrid structure to ensure that the primary moment frame and concrete core are constructed first, thereby guaranteeing the efficiency of modular construction.

Mid-to-high rise MSC requires not only adequately stiffened modules to form the LFRS, but also requires a high-performance connection system to ensure efficient load transfer systems both horizontally and vertically. This makes these two objectives, i.e., in regards to, the LFRS and connection system, the most essential issues affecting the seismic performance of MSC for all types of structural systems [30]. However, it is challenging for mid-to-high rise MSC to resist lateral force efficiently, owing to the discontinuities in the lateral-force resistant component, and the fact that the connection system for MSC should meet structural demands along with the manufacturing and construction considerations. Numerous studies have focused on the above challenges to reveal the seismic performance of MSC, and are summarized as follows.

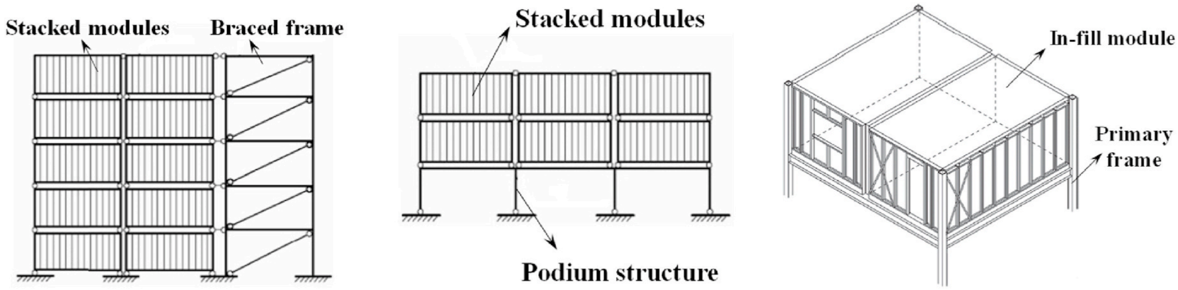
3. Seismic performance of the lateral force resisting system

Traditional lateral-force resistant components such as a steel plate shear wall or, brace have been considered for inclusion in modules. The seismic performance of these lateral-force resistant components has been explored and verified.

3.1. Steel plate shear wall

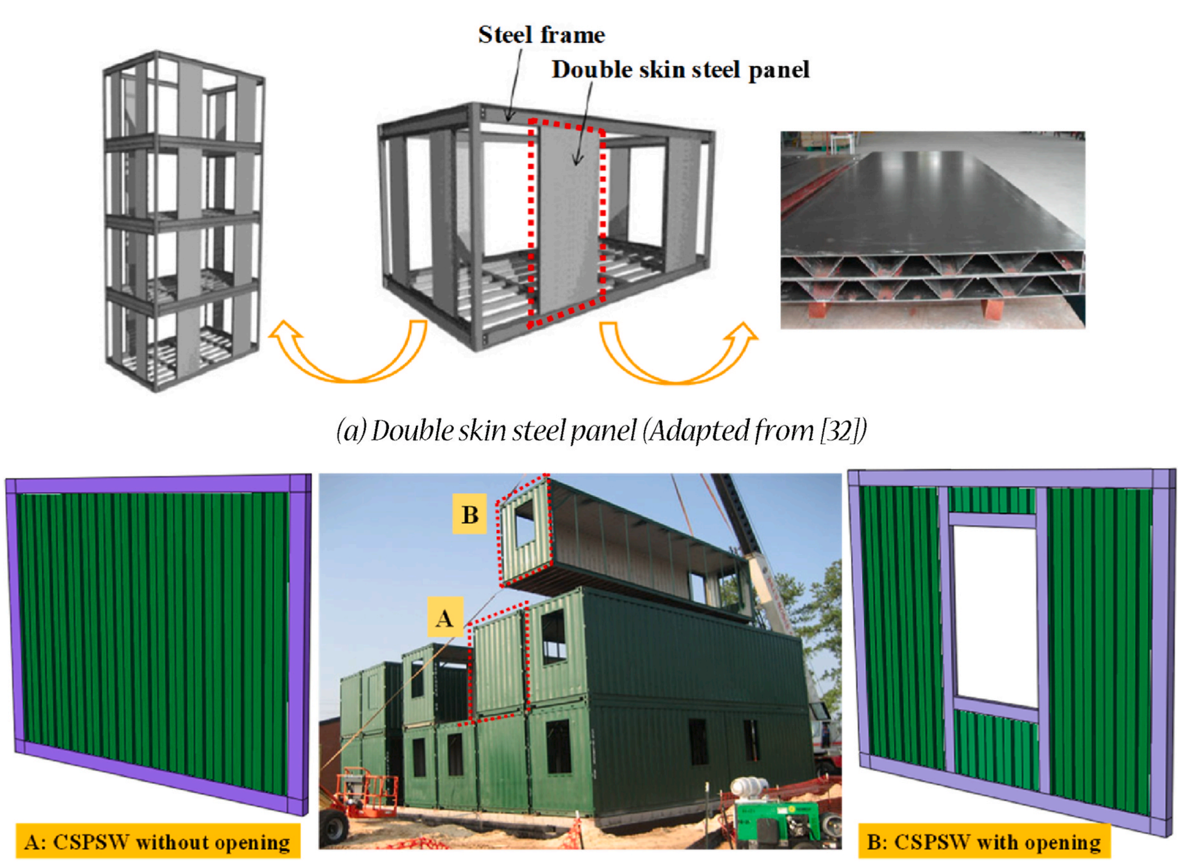
The steel plate shear wall has been widely utilized for tall buildings in high seismic hazard areas, owing to its high initial stiffness, significant strength and good ductility. However, the flat steel panel is prone to elastic buckling under lateral force, accompanied by loud noise. Although adding stiffeners can prevent the global buckling of the steel plate, this approach is time-consuming and costly [31]. This situation has prompted engineers to explore modified types of infill panels, especially for the civilian construction. Hong et al. [32] proposed a double skin steel panel system (Fig. 5(a)) for MSC. Corrugated steel plates were welded to double skin steel plates, to prevent the premature buckling of the steel plates. The cyclic test was conducted, and it indicated that the double skin steel panel could increase the initial stiffness of the frame without buckling caused by the lateral force. In addition, the steel panel reached the yield point before the yielding of the frame. Therefore, this system exhibited favorable seismic performance.

Recently, the container-like module, as a typical type of steel module, has been increasingly adopted in MSC, making full use of its superiority in lifting and disassembly (Fig. 5(b)) [33]. The enclosed corrugated steel plate has been demonstrated via numerical simulation to be an important lateral-force resistant component for the module [34]. Corrugated steel plate shear walls (CSPSWs) have been verified to provide better seismic performance over flat plates, with advantages including a higher initial stiffness, improved buckling strength, and higher energy dissipation capacity [35–38]. However, the CSPSWs in MSC are very different from traditional shear walls in the following aspects: 1) boundary condition: the individual module units are



(a) Stacked modules braced by primary moment frame *(b) Stacked modules supported by podium structure* *(c) Recessed modules supported by primary frame structure*

Fig. 4. Module-moment frame hybrid structure (Adapted from Refs. [24]).



(a) Double skin steel panel (Adapted from [32])

(b) Corrugated steel panel (Adapted from [33])

Fig. 5. Steel plate shear walls in the module.

connected merely in the corner region by inter-module connection, resulting in a discontinuity of the lateral-force resistant component; and 2) openings for building function: openings serving as doors or windows are commonplace in MSC. Consequently, many studies have been conducted to investigate the seismic performance of CSPSWs in MSC.

Ding et al. [33,39] conducted cyclic tests to investigate the seismic performance of CSPSWs in MSC. The seismic mechanisms of CSPSWs with and without openings were revealed. It was indicated that the initial stiffness of CSPSWs was reduced by the opening or slit in the infill panel, whereas the energy dissipation capacity improved significantly. Furthermore, Deng et al. and Wang [40–42] studied the seismic performance of CSPSWs numerically and theoretically. Formulas for predicting the initial stiffness of CSPSWs were proposed, and a high efficiency analysis model for CSPSWs was developed based on the general finite element software ABAQUS. Boundary conditions and openings were considered for CSPSWs in MSC. Similar investigations conducted by Yu et al. [43] and Zuo et al. [44] also demonstrated that the opening was a critical factor influencing the seismic performance of CSPSWs in MSC and accordingly should be properly considered in the seismic design. Recently, the steel strip has been proposed for strengthening the openings in CSPSWs by Dai et al. [45]. Although the quantified design method needs to be further explored, the primary experimental results indicated that the steel strip was favorable for strengthening the CSPSWs with openings, and that the seismic performance in regards to, e.g., the initial stiffness, ductility and energy dissipation capacity was evidently improved.

3.2. Brace

Annan et al. [46,47] conducted an experimental study on the seismic performance of a modular steel-braced frame, as shown in Fig. 6(a). A regular concentrically braced frame with similar geometric and material properties was also tested for comparison. The different lateral force distribution patterns were revealed and discussed. The test results indicated that the braced steel module was vulnerable to the bending of the column segment between the ceiling beam and floor beam, whereas the regular frame was vulnerable to the out-of-plane buckling of the brace. Both specimens demonstrated stable and ductile behavior up to a drift ratio of 3.1%. Sultana et al. [48,49] extended the work of Annan et al. by adopting shape memory alloy (SMA) braces in the steel module, as shown in Fig. 6(b). Super-elastic SMA have the ability to undergo large plastic deformations and then to restore to the center while unloading. The simulation results indicated that the maximum residual inter-story drift was reduced by up to 98%, which was attributable to the re-centering capability of the super-elastic SMA braces, resulting in a reparable module unit. This characteristic is especially desired for MSC, where module units are expected to be recycled if necessary. In the future, other seismic damping components, such as buckling-resistant braces, may be incorporated in the module to obtain a more economical scheme and better seismic performance of MSC [22].

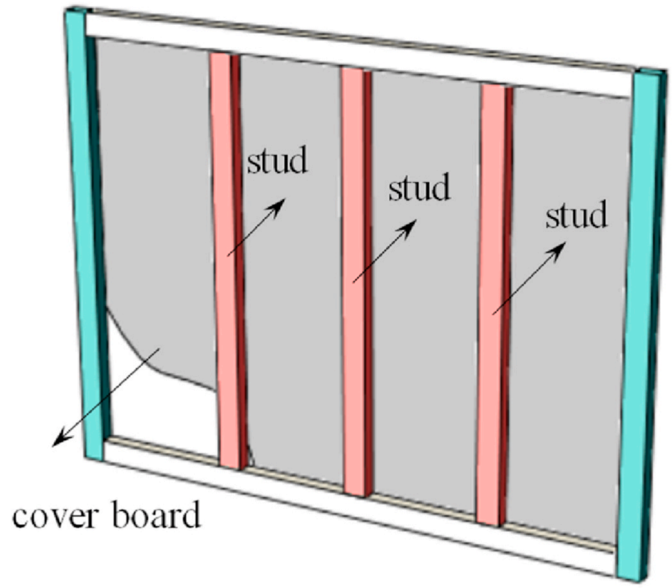


Fig. 7. Steel stud wall in the module.

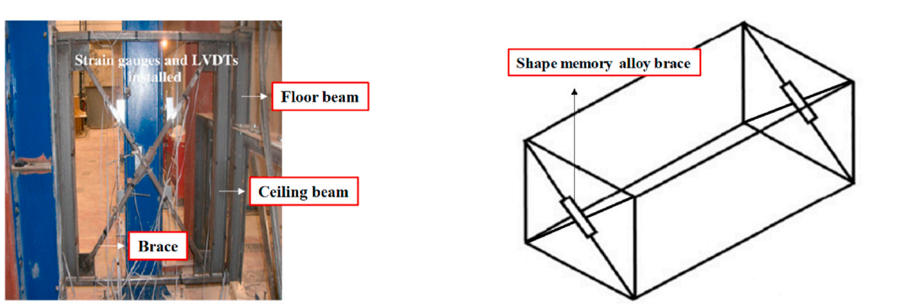
3.3. Steel stud wall and group columns

The steel stud wall (Fig. 7) is the crucial component for transferring the vertical and horizontal force for the continuously supported module. The steel stud wall is usually made of cold-formed steel (CFS) tubes or channels sheathed by, e.g., the oriented strand board, cement particle board, calcium silicate board, gypsum board. Previous studies have mainly focused on the axial compression behavior of steel stud walls [50–52] as well as their fire performance [53–55]. The seismic performance of steel stud walls with various configurations, cover boards, steel stud tube spacings, and openings have been investigated by Restrepo et al. [56], Moghimi et al. [57], Wang et al. [58], Bao et al. [59], Fulop et al. [60], Macillo et al. [61], Fiorino et al. [62], Ye et al. [63] and Wang et al. [64] by series of cyclic tests and the shake table tests conducted by Fiorino et al. [65]. It has been recognized that the cover board makes a considerable contribution to the load bearing capacity and stiffness of the steel stud wall. The steel stud wall is prone to weld tearing fracture owing to its relatively thin cold-formed steel member, making it difficult to guarantee the quality of the weld. In addition, series of numerical and theoretical studies have been carried out to further explore the seismic performance and design methods of the steel stud walls [63,66–69]. Despite the complex configurations and the connection between the cover board and the stud, several simplified numerical models have been developed for the sheathed steel stud walls [68,70–73].

For the unbraced frame supported module, the group columns serve as the lateral-force resistant component. Three types of group columns exist in MSC according to the plane layout of the modules: the double-column, special-shaped tri-column and four posts group column, as shown in Fig. 8. Commonly, there is a gap between the individual columns for the inter-module connection [74]. Meanwhile, the boundary condition of the individual column in the module is different from that of the traditional columns, owing to the various configurations of the inter-module connection. Deng et al. [75], Li et al. [76,77], Chen et al. [78], and Zhang [29] conducted numerical and theoretical studies to determine the effective length of the column in the module, considering the constraints of the floor beam and ceiling beam and the configuration of the connections. However, there is no reported research work on the seismic performance of the group columns in MSC, which requires further research.

4. Recent innovations on the connections

The connections in MSC can be broadly grouped into four types: module-to-module connection, intra-module connection, module-to-foundation connection, and module-to-frame/concrete core connection (if a primary frame or concrete core is adopted to form a hybrid structural system). Fig. 9 identifies and illustrates the classification for the connection system in MSC. It is well known that the mechanical properties of the connections, including the stiffness, strength and ductility are crucial to the overall seismic performance of MSC. Therefore, many investigations and research have been conducted on the connection system of MSC, especially on the module-to-module connection.



(a) Steel brace (Adapted from [46]) *(b) Shape memory alloy brace (Adapted from [48])*

Fig. 6. Braces used in the module.

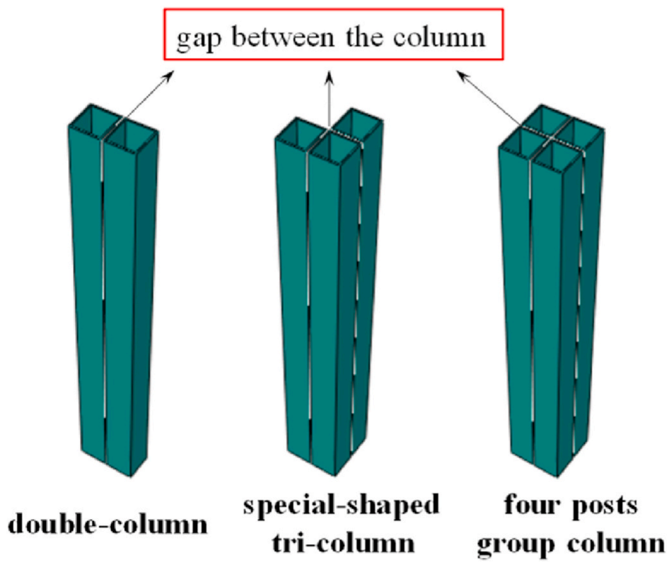


Fig. 8. Group columns in MSC.

4.1. Module-to-module connection

Module-to-module connections connect the individual modules and provide a load path between modules via vertical and horizontal interconnectivity. Thus, they have a profound influence on the overall seismic performance of MSC. As outlined in Table 1, experimental tests have been conducted to examine the seismic performance of currently proposed innovative module-to-module-connections, including the configuration of the connection, failure mode, ultimate inter-story drift ratio (θ_u), ductility coefficient (μ), and connection classification.

Two main loading protocols were considered in the experimental tests on the mechanical properties of the innovative module-to-module connections under axial load and bending: quasi-static monotonic and cyclic. Cyclic loading was undertaken to evaluate the seismic performance of the connection, including the failure mode, strength and stiffness characteristics, deformation capacity, ductility, and energy dissipation capacity. Monotonic loading was additionally conducted to provide a better understanding of the load transferring mechanism of the connection such that the moment-rotation curve could be obtained. Eurocode 3 Part 1–8 [88] has been widely adopted for classifying the innovative connections into rigid, semi-rigid and pinned based on the moment-rotation curve, as shown in Table 1.

It can be concluded from Table 1 that all the connections can satisfy the deformation regulations provided by Code for Seismic Design of Buildings [GB 50011–2010 (2016)] [89], in which the lower limit of the elastic inter-story drift ratio is 0.004 rad and that of the elastic-plastic inter-story drift ratio is 0.02 rad. Furthermore, the required inter-story drift ratio for the intermediate moment frame (IMF) and special moment frame (SMF) are 0.02 rad and 0.04 rad, respectively, as stipulated by Seismic Provisions for Structural Steel Buildings (ANSI/AISC 341–10) [90]. Therefore, the connections listed in Table 1 show potential for IMF systems. However, for SMF system, construction measures are necessary to ensure the deformation capacity and ductility of the module-to-module connection. This may be due to the brittle weld fracture failure mode of the intra-module beam-to-column connection, as shown in Table 1. Although the bolted connection is preferred for the module-to-module connection, the intra-module beam is usually welded to the column directly in the factory, causing weld-intensive of the module-to-module connection. Therefore, special attention should be paid to the quality of the weld connecting the beam and column to limit the risk of weld fracture.

It should be acknowledged that developing the proper module-to-module connection is one of the main challenges hindering the progress of MSC. Apart from the connections listed in Table 1, scholars have proposed other solutions for module-to-module connections. Table 2 presents other possible types of module-to-module connections from the literature, as well as their reported mechanical properties and features. Although the seismic performance of these connections is not available, simplex axial compression, axial tension, bending, and shear behavior have been considered via tests and numerical simulation. It can be concluded from Tables 1 and 2 that bolted connections are preferred over welding for module-to-module connections, owing to the advantages in reduced site work and demountability. In addition, the post-tensioning method has been considered for module-to-module connections except for the traditional welded and bolted connections for steel structures, e.g., *7 in Table 1, and #2, #5 and #6 in Table 2. There is still no reported research work on connections numbered #11~#20 in Table 2. Further research should be conducted to identify the load transferring mechanism and mechanical properties of these connections,

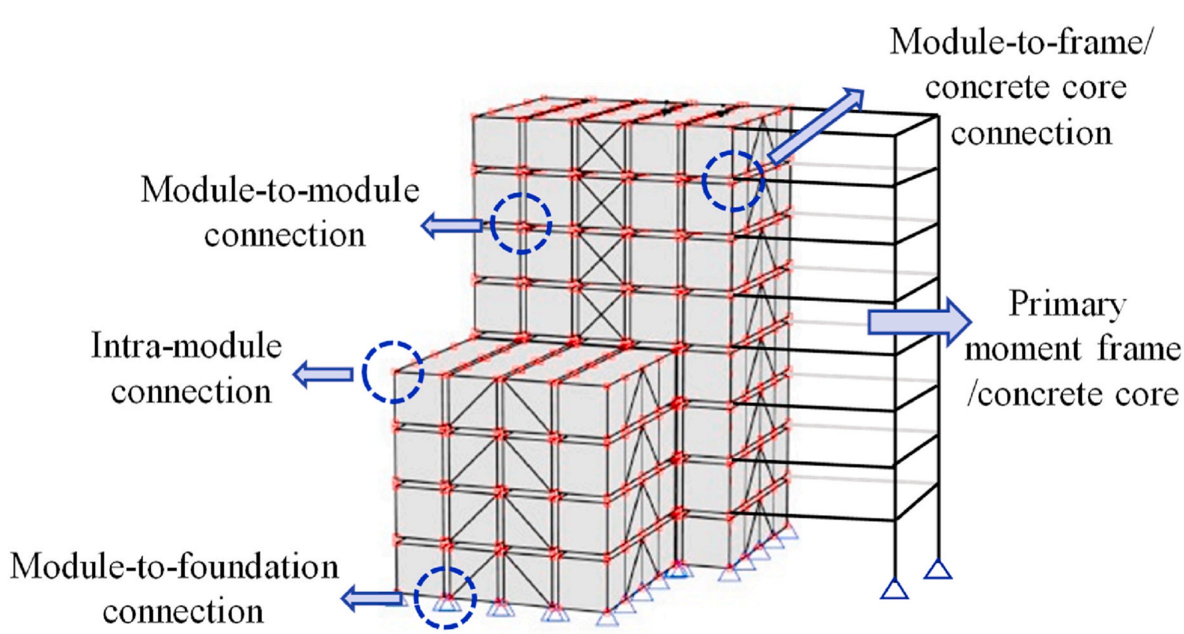
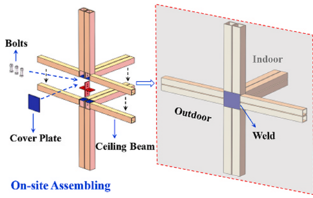
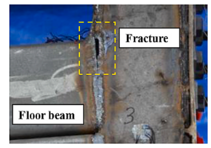
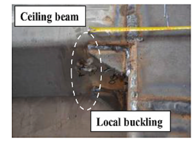
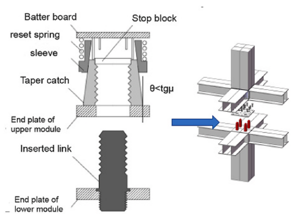
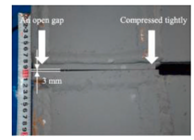
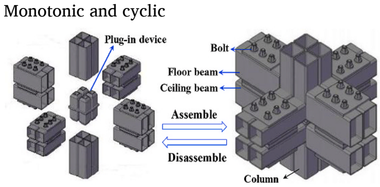
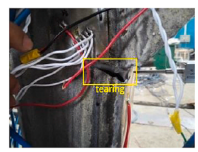
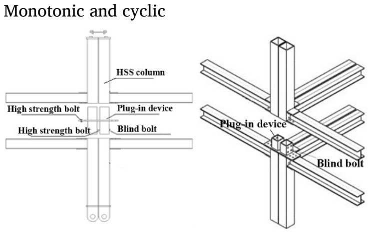
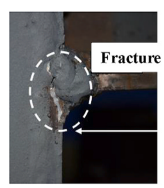
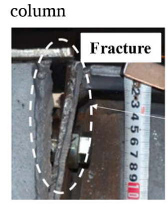
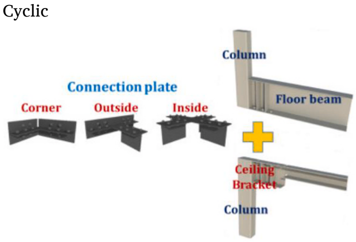
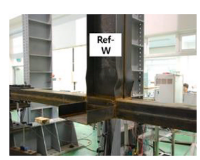
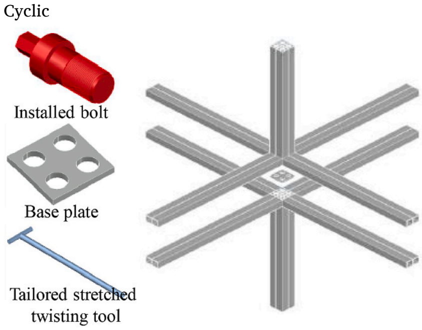
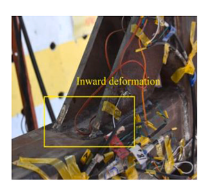
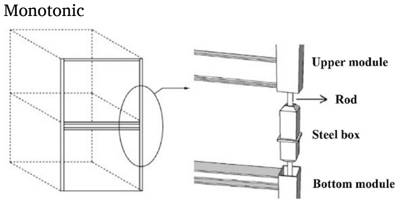
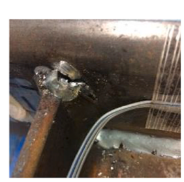
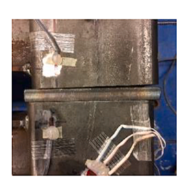


Fig. 9. Connection system in modular steel construction (Adapted from Ref. [30]).

Table 1
Seismic performance of representative module-to-module connections.

Connection type	Illustration and loading protocol	Failure mode		θ_u (rad)	μ	Connection classification
*1 Bolted connection with welded cover plate (Deng et al. [79,80])	 Monotonic and cyclic	 Weld fracture	 Local buckling of the ceiling beam	0.035–0.058	2.64–4.70	Semi-rigid
*2 Plug-in self-lock connection (Dai et al. [81])	 Monotonic and cyclic	 Local buckling of the ceiling beam	 Gap between the columns	0.066–0.136	2.37–5.40	Semi-rigid
*3 Beam-to-beam bolted connection (Chen et al. [21,82])	 Monotonic and cyclic	 Weld fracture	 Local buckling of the column	0.080–0.119	2.09–3.42	–
*4 Blind bolts bolted connection (Li [83])	 Cyclic	 Weld fracture	 Fracture of the column wall	0.020–0.040	1.18–2.00	Semi-rigid
*5 Fully bolted connection by the ceiling bracket (Lee et al. [84,85])	 Cyclic	 Local buckling of the floor beam	 Residual deformation at the floor beam end	0.045–0.07	–	Rigid
*6 Installed bolts bolted connection (Wang et al. [86])	 Monotonic	 Weld fracture	 Local buckling of the floor beam	0.037–0.047	–	Braced frame: rigid Unbraced frame: semi-rigid
*7 Vertical post-tensioned connection (Sanches et al. [87])	 Cyclic	 Weld fracture	 Gap opening	0.030–0.037	–	–

Note: θ_u denotes the ultimate inter-story drift ratio; μ denotes the ductility coefficient, which is defined as the ratio between the ultimate inter-story drift ratio and the yielding inter-story drift ratio; "–" means that it is not mentioned by the authors.

in view of the possibility of these connections for practice.

Conclusively, despite the insistent demand for the thorough understanding of the seismic performance of module-to-module connections, the related research work is limited. The development of module-to-module connections for mid-to-high rise MSC is even more challenging, for the following reasons: (1) easy assembly and lifting: the module-to-module connection should not only accommodate structural demands, but should also satisfy the manufacturing and constructional requirements. (2) deformation capacity and ductility: the intensive welds should be avoided, calling for the innovations on intra-module beam-to-column connections; and (3) tensile and shear capacity: tensile force may occur in the exterior columns at the perimeter of the building under earthquake, and the connection should be capable of transferring the horizonal shear force between the modules. Additionally, current seismic codes are usually adopted for evaluating the seismic performance of existing module-to-module connections. However, it is necessary to establish the theoretical method for evaluating the interstory drift limitation, ductility, and rigid classification of the module-to-module connection for MSC, considering the double-beam and double-column characteristics. This is crucial for providing seismic design criteria for MSC, and is, therefore, worthy of further research.

4.2. Intra-module connection

Intra-module connections are connections within the module that connect the structural form of the module. Traditional welded and bolted connections are widely used for intra-module-connections. Lawson [12] suggested a fin plate for connecting the C section beam and column. This connection is considered as a simple shear connection and has low moment capacity and ductility. The use of such a connection makes the stacked modules prone to progressive collapse. Therefore, the fin plate connection is only suggested for use in low rise (no more than three-story) buildings [12]. Annan et al. [109,110] investigated a directly welded stringer-to-beam connection. They suggested that the floor beam should be designed for hogging moments and axial forces, which is different from traditional steel structures. Xu et al. [111] investigated the bending response of laminated double channel beams connected by bolts in MSC. In addition, Innella et al. [112] investigated the load capacity of the screw connections between the plasterboard panels and cold-formed steel in MSC.

Srisangeerthanan et al. [30] reported that intra-module connections may have less influence on the overall seismic performance of MSC, as that the intra-module connections are completed off-site manufactured in factory conditions. However, it can be concluded from the tests on the module-to-module connection in Table 1 that the intra-module beam--to-column connection have a significant influence on the seismic performance of the module-to-module connections, thereby affecting the overall seismic performance of MSC. Zhang et al. [113,114] studied the seismic performance of the column-to-corner fitting connection in MSC using cyclic tests and finite element analysis, as shown in Fig. 10(a). Nut free bolts were used for connecting the column and corner fitting and the connection exhibited excellent ductility under cyclic load. Luo et al. [115] investigated the monotonic moment-rotation behavior of the intra-module beam-to-column connection with relatively small member size, including the welded connection, end plate connection and end plate stiffener connection, as shown in Fig. 10(b)~Fig. 10(d). It can be concluded that limited research has been conducted on the seismic performance of intra-module connections, and that further work is needed.

4.3. Module-to-foundation connection

The modules should be properly restrained by the foundation to prevent overturning and sliding. Conventional in situ or precast concrete foundations are suitable for MSC. The suggested module-to-foundation connection from Technical specification for modular freight container building (CECS 334–2013) [25] is shown in Fig. 11(a). Anchor bolts are used to connect the precast foundation and connecting corner fitting. In addition, Park et al. [74] proposed and tested an embedded module-to-foundation connection (Fig. 11(b)) that can develop the full column strength under earthquake. The load condition will be more complex for the module-to-foundation connection in mid-to-high rise MSC, as part of the connection will suffer from tensile force under earthquake. Therefore, the design of the module-to-foundation connection will be more complicated and more attention should be paid thereto.

4.4. 4.4 module-to-frame/concrete core connection

In the hybrid structural system, the primary moment frame or concrete core is used to resist lateral forces, such as wind and earthquake. The module-to frame/concrete core connection is crucial for transferring the lateral load from the stacked modules to the frame or concrete core. In practice, traditional embedded steel anchors and welds are typically used for the connection between the module and the frame or concrete core. It is suggested to connect the modules with the frame column using cover plate and high strength bolts in the CECS 334–2013 standard [25], as shown in Fig. 12(a). Choi et al. [116] demonstrated a possible bolted module-to-concrete core connection by embedding stud bolts and gusset plate, as shown in Fig. 12(b). The module could also be welded to the embedded plate in the concrete core directly, based on an angle [99]. However, systematic investigation should be conducted to reveal the load transferring mechanism between the stacked modules and primary frame or concrete core under earthquake and to propose a reasonable simplified analysis model for the connections. Moreover, seismic performance and design considerations should be determined for the module-to-frame/concrete core connection.

5. Global seismic response and design criteria

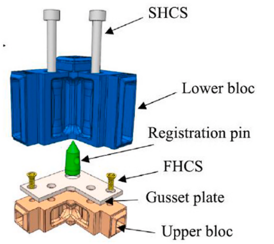
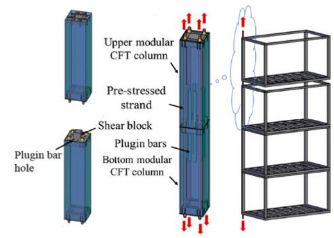
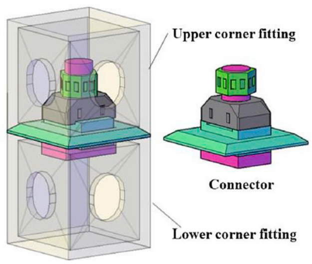
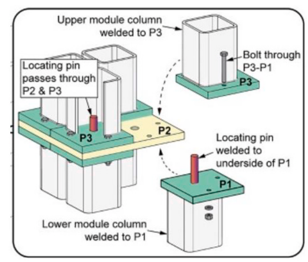
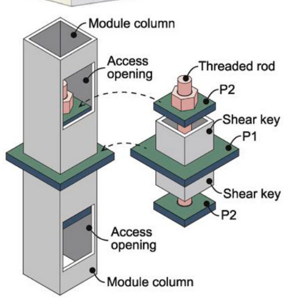
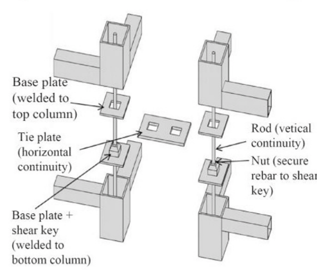
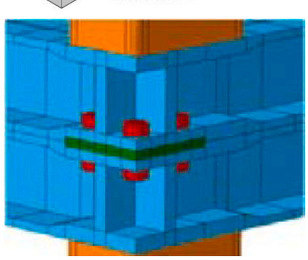
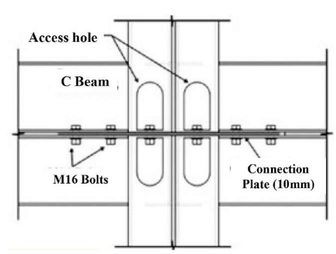
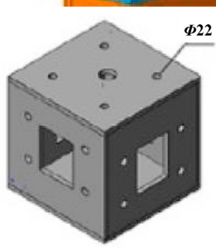
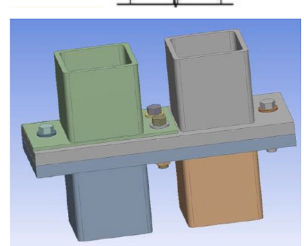
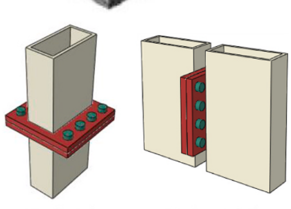
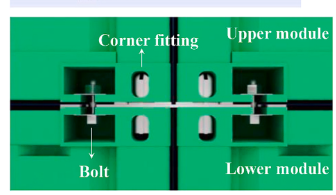
The global seismic response and design criteria of MSC are of great importance for providing a thorough understanding of the seismic performance and practical design guidelines of MSC. With the increasing application of MSC for mid-to-high rise buildings in areas with high seismic hazards, the dynamic response of MSC under earthquake has been investigated by several scholars.

5.1. Seismic response analysis methodology

It is essential to establish a simplified analytical model for MSC to perform the global response analysis, especially for the complicated module-to-module connection. The module-to-module connection was initially assumed to be ideally pinned or rigid in the majority of studies attempting to identify the global response of MSC [29,42,117–119]. However, this assumption of a nominally pinned or rigid connection may not accurately reflect the actual behavior, as the distribution of load throughout the structure largely depends on the connection behavior. Furthermore, the pinned connection might not be conservative enough for the design of the connection, as less force will be transferred to the module-to-module connection [120]. Several studies have been conducted to determine a more reasonable simplified analytical model, i.e., for better presentation of the semi-rigid properties of the module-to-module connection.

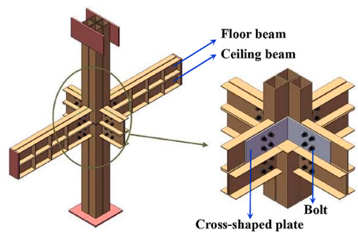
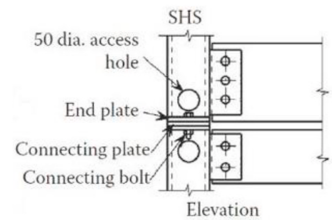
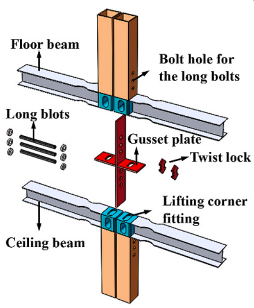
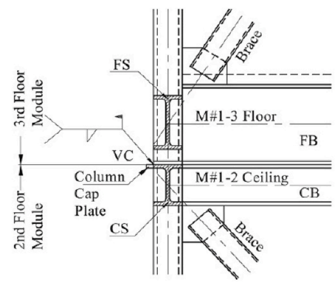
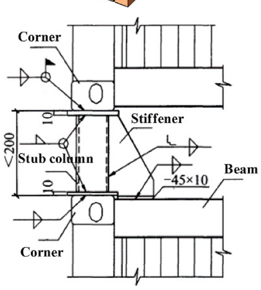
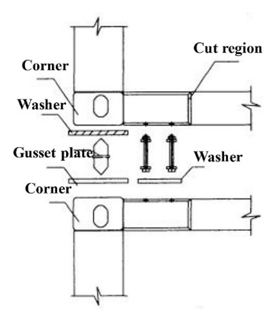
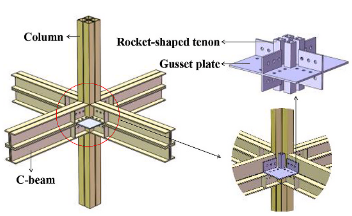
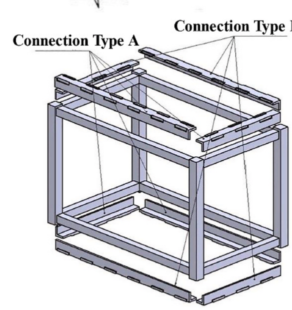
The simplified models available in the literature for the seismic analysis of MSC are listed in Table 3. Gunawardena et al. [104] used spring elements to model the horizontal end plate bolted connection using SAP2000 and RUAUMOKO 3D. The vertical joint was modelled by beam elements considering possible locations for the hinge, whereas the horizontal connection was simulated by a spring whose stiffness was defined as the shear stiffness of the inter-module connection. Similar methods can be found in the modelling of the rotary connection by Chen et al. [95], bolted connection by Styles et al. [105], and rod-base plate

Table 2
Other possible module-to-module connections.

Connection type	Illustration	Reported mechanical property and features	Connection type	Illustration	Reported mechanical property and features
#1 VectorBloc connection (Dhanapal et al. [91, 92])		1. Axial compression, axial tensile and bending behavior were tested 2. Cast steel connectors were adopted	#2 Pretensioned connection (Chen et al. [93] and Yu et al. [94])		1. Moment-transferring performance was tested 2. Concrete-filled tube column was adopted
#3 Rotary connection (Chen et al. [95,96])		1. Bending and shear behavior were tested 2. Excellent installation convenience	#4 Interlocking connection (Lacey et al. [97])		1. Shear force-slip behavior was tested 2. Improved constructability and shear behavior
#5 Post-tensioned connection (Lacey et al. [98])		1. Uniaxial shear force-slip behavior was tested 2. Improved constructability	#6 Rod-base plate connected connection (Liew et al. [22] and Chua et al. [99])		1. Simplified model was proposed 2. Helpful to the alignment of module placement
#7 Up-down connectors connection (Chen et al. [100])		1. Compression and bending behavior were simulated 2. Open steel section beams	#8 Bolted connection (Choi et al. [101,102])		1. Bending behavior was simulated 2. Loss section of the column
#9 Steel bracket connection (Doh et al. [103])		1. Shear behavior was tested 2. Fully bolted connection by the corner casting	#10 End plate bolted connection (Gunawardena et al. [104])		1. Shear behavior was tested 2. Fully bolted connection
#11 Bolted connection (Styles et al. [105])		1. Bending behavior were simulated 2. Fully bolted connection	#12 Corner fitting connection ([106])		1. No reported mechanical property 2. Possible pinned connection
#13 Cross-shaped plate connection		1. No reported mechanical property 2.Incompatiblewith the internal finish	#14 Bolted connection (Lawson [12])		1. No reported mechanical property 2. Loss section of the column

(continued on next page)

Table 2 (*continued*)

Connection type	Illustration	Reported mechanical property and features	Connection type	Illustration	Reported mechanical property and features
(Park et al. [74])					
#15 Liftable connection (Ding et al. [107])		1. No reported mechanical property 2.Fully prefabricated and liftable	#16 Welded connection (Annan et al. [46])		1. No reported mechanical property 2. On-site welding needed
#17 Stub column connection (CECS 334–2013 [25])		1. No reported mechanical property 2. On-site welding needed	#18 Bolted connection (CECS 334–2013 [25])		1. No reported mechanical property 2. Loss section of the beam
#19 Socket-shaped tenon connection (Deng et al. [75])		1. No reported mechanical property 2.Incompatible with the internal finish	#20 Interlocking connection (Sharafi et al. [108])		1. No reported mechanical property 2. Cannot bear vertical tension

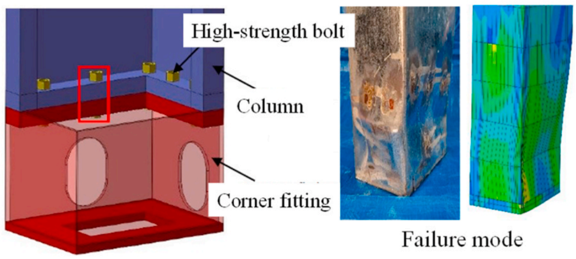
connected connection by Chua et al. [99]. It has been widely accepted that the spring model enables the definition of semi-rigidity and non-linearity of the connection. In this manner, the monotonic force-deformation or moment-rotation behaviors can be incorporated into the simplified global model by defining the stiffness of the spring. Therefore, the spring model has been used for global analysis of MSC under lateral force. However, further verification is required to examine whether the model is accurate in modelling the hysteretic behavior of the connection and to expand the feasibility of the spring-based model for seismic analysis. Annan et al. [46] proposed a simplified analytical model for the welded module-to-module connection and verified it under cyclic loading. The model considered the rigidity of the intra-module beam-to-column welded connection and a pin connection allowing for rotation allowed by the one-side only welding. Similar methods were adopted by Fathieh et al. [122] and Ren et al. [123], by adding an inelastic column segment between the adjacent modules.

Martínez-Martínez and Xu [73] proposed an equivalent shell element model for the steel stud wall to simplify the analysis. In addition, equivalent cross braces were widely employed to simulate the hysteretic behavior of the lateral-force resistant component, e.g., the steel stud wall [68,70,71,121] or corrugated steel plate shear wall [42]. These studies demonstrated the efficiency of finite element analysis in simulating the seismic performance of MSC, despite the complicated configuration.

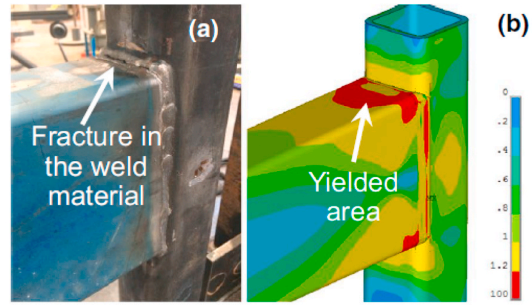
5.2. Seismic response characteristics

5.2.1. Stacked module structure

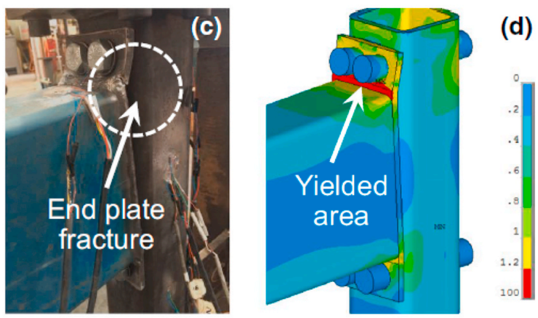
Many numerical studies have been conducted to identify the seismic response of the stacked module structure. The conventional displacement-based design criteria, such as the inter-story drift ratio, and ductility are generally adopted to assess the seismic performance of MSC. Shamim et al. [68] and Leng et al. [72] conducted the time-history seismic analysis of two-story CFS framed building. The sheathed steel stud walls were simplified to equivalent cross braces and the model was verified to be reasonable for further incremental dynamic analysis



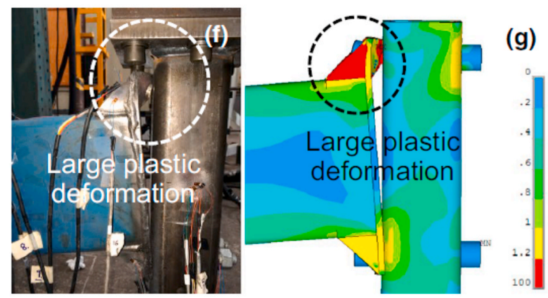
(a) Nut-free bolt bolted column-to-corner fitting connection [113, 114]



(b) Welded beam-to-column connection [115]

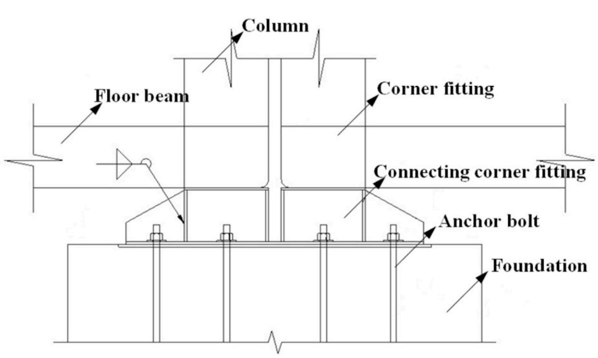


(c) End plate bolted beam-to-column connection [115]

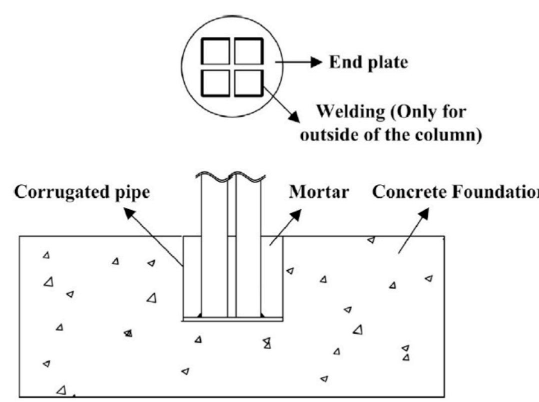


(d) End plate-stiffener beam-to-column connection [115]

Fig. 10. Connections within the module.



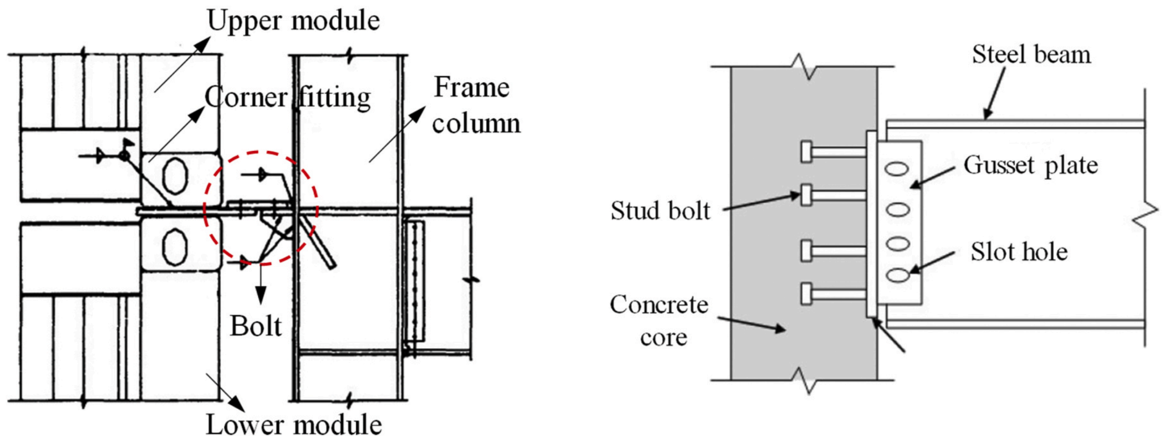
(a) Corner fitting connection (Adapted from [25])



(b) Embedded column connection [74]

Fig. 11. Typical module-to-foundation connection.

(IDA). Leng et al. [124] demonstrated the necessity of modelling the gravity system and architectural sheathing for the CFS framed building by experiment and non-linear IDA. Annan et al. [125] investigated the seismic vulnerability of 2-, 4-, and 6- story MSC via incremental dynamic analysis (IDA), and demonstrated a satisfactory performance of MSC at designed intensity levels. High concentration of inelasticity was found at first level, owing to the limited redistribution of internal forces. Annan et al. [126] demonstrated that the over-strength factor (R_0) and ductility (μ) of MSC decreased with the increase of the height. Fathieh et al. [122] conducted IDA of a 4-story MSC. The diaphragm interactions, relative displacements and rotations between modules, and column discontinuity were considered. It indicated that the high inelasticity concentration at the first story level was caused by the inelastic behavior of braces and limited redistribution of internal forces. It was also observed that the maximum base shear that the structure could resist was higher than that of traditional steel buildings. Srisangeerthanan et al. [127] further investigated the effects of diaphragm discontinuities in MSC by parametric analysis on a 4-story MSC. They found that the stiffness of the diaphragm had a significant influence on the seismic performance of MSC. The MSC with flexible diaphragms was prone to encountering higher mode effects, resulting in a larger inter-story drift ratio. Moreover, the traditional equivalent lateral force procedure provided by current seismic codes was no longer suitable. Shirokov et al. [128] proposed an analytical formula for predicting the first natural vibrations frequency of MSC. In addition, several scholars have investigated the effects of the stiffness of the inter-module connection on the seismic performance of MSC. Nonlinear analyses by Choi et al. [101] indicated that increasing the stiffness of the inter-module connection results in a greater over-strength factor (R_0). It has also been demonstrated that a rigid connection is preferred over a pinned connection for pursing a



(a) Module-to-frame bolted connection (Adapted from [25]) *(b) Module-to-concrete core bolted connection [116]*

Fig. 12. Module-to-frame/concrete core connection.

better seismic performance and reducing the reliance on separate LFRS [29,99,117].

The above-mentioned studies mainly focused on low-rise or multi-story MSC. Several scholars have attempted to further develop high-rise MSC using the stacked module structure and some studies have been conducted. Styles et al. [105] demonstrated that increasing the stiffness of the module-to-module connection is desirable for the seismic performance of MSC in terms of reducing the inter-story drift ratio via the dynamic analysis of an 11-story MSC. Gunawardena et al. [129,130] conducted time history analysis for a 10-story modular construction and found that the column hinge was unavoidable under earthquake, and that the column ductility was important for redistributing the internal force. A concrete infill wall was incorporated in the module, and an effective lateral load resistance of the building can be obtained by strategically placing of the modules. Similarly, Shi et al. [119] recently investigated the seismic performance of a 20-story MSC with various module layouts. The staggered layout program was recommended for addressing the bidirectional inconsistency in stiffness and obtaining reasonable vibration modes.

5.2.2. Module-moment frame hybrid structure

There are fewer studies on the seismic performance of module-moment frame hybrid structure than that on the stacked module structure. Zhang et al. [131] and Chen et al. [132] investigated the seismic performance of 3-story and 4-story module-moment frame hybrid structures, respectively. MIDAS/Gen was employed to establish the numerical model. It was found that the stacked module and moment frame behaved as an overall structure, and that the seismic behavior indexes, including the inter-story drift ratio and stress, satisfied the requirement of the current design code. Ren et al. [123] conducted the isolation design analysis for a 4-story module-moment frame hybrid structure, and demonstrated the base isolation structure had better seismic performance than the inter-story isolation structure. The insufficiency of the research on the seismic performance of module-moment frame hybrid structures may be owing to the limited application of this structural system. Moreover, the primary frame or concrete core is considered to sustain the total lateral force, and the attached modules are considered to only transfer the gravity load. This assumption may be impractical, as the stacked modules can sustain certain lateral force, as discussed in Section 5.2.1. Therefore, further studies should focus on the load transferring and distribution of the module-moment frame hybrid structure.

5.2.3. Module-concrete core hybrid structure

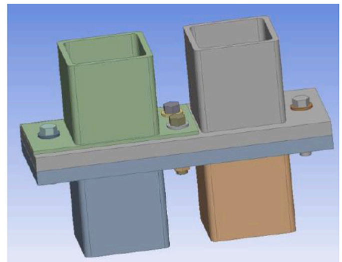
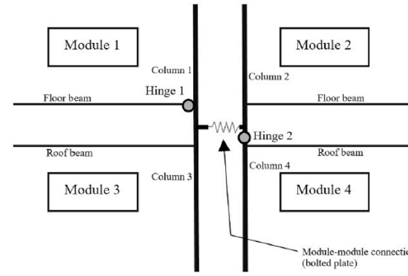
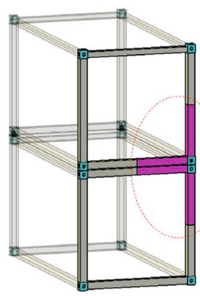
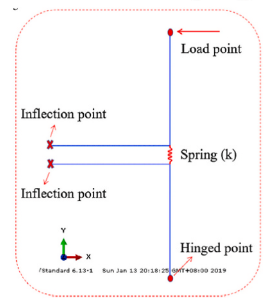
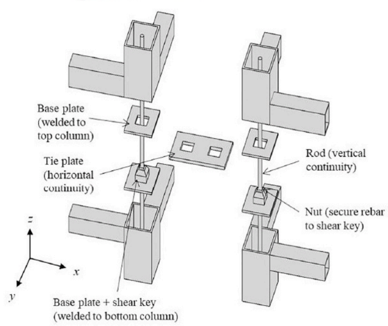
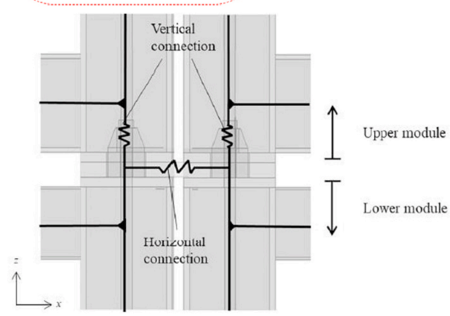
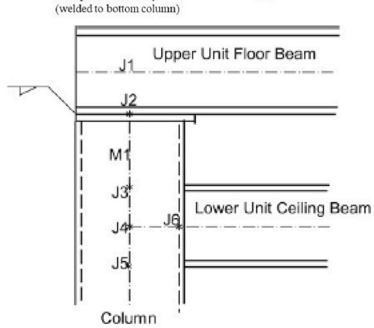
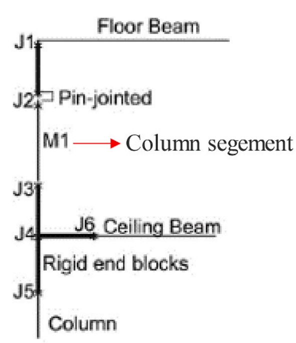
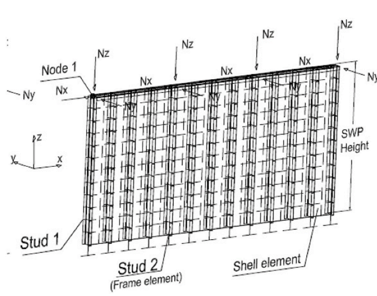
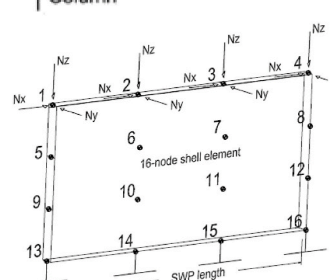
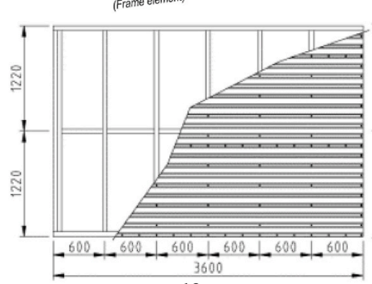
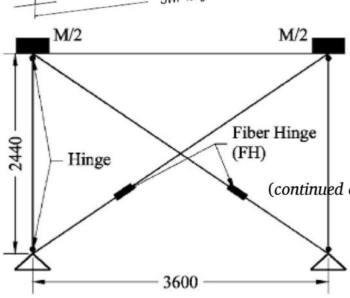
There are also very limited studies on the seismic performance of module-concrete core hybrid structures. Chua et al. [99] numerically investigated the lateral performance of a 40-story module-concrete core hybrid structure and verified that the concrete core efficiently resisted the lateral load. The columns in the modules were subject to compression force, as approximately 95% of the lateral load was resisted by the concrete core. Moreover, the global sway of the module became less sensitive, owing to the stiff core wall that dominated the lateral stiffness of the building. Wang et al. [133] confirmed the seismic performance of a ten-story module-concrete hybrid structure in Zhenjiang, China using numerical analysis. It was reported that the inter-story drift ratio and damage of the concrete core well satisfied the requirement of Code for Seismic Design of Buildings [GB 50011–2010 (2016)] [89]. Owing to the limited research, it is suggested that further work should be conducted on the seismic performance of module-concrete core hybrid structures to reveal the load transferring mechanism and seismic detailing requirements, in view of this hybrid system is being increasingly used for high-rise modular construction.

5.3. Failure mode and robustness

Several scholars have tried to identify the failure mode and robustness of MSC. Zheng et al. [134] investigated the potential failure modes of a post-tensioned modular system under earthquake. Three failure modes were identified: the module structural component failure, local connection failure, and tension link failure. Luo et al. [135] investigated the progress collapse of MSC based on the alternative load path method. Fig. 13 illustrates the failure process of an MSC with pinned module-to-module connection after a corner module removal. To ensure adequate collapse resistance, it was suggested to use inter-module connections with adequate rotational stiffness, and to make the edge modules stronger and stiffer. Similar conclusions were reached from the numerical analysis by Zhao [118].

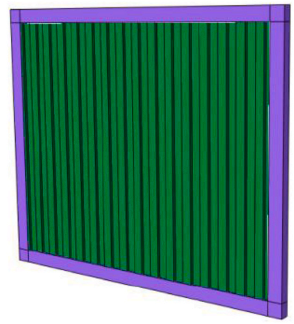
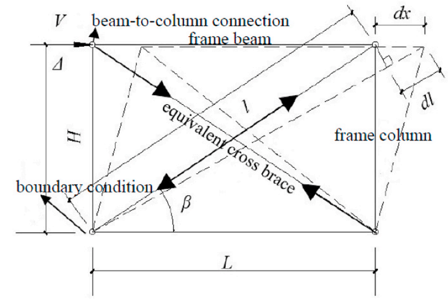
In addition, Alembagheri et al. [136] studied the collapse capacity of modular steel buildings subjected to module loss scenarios. It was shown that modular buildings possess a considerable capacity for collapse, and that the inter-module connections should be designed for capacities more than twice the common static service forces to prevent potential progressive collapse. Lawson et al. [137] analyzed robustness of MSC in situation of the loss of a corner or internal support, and indicated that the torsional stiffness of the module could effectively redistribute loads away from damaged sections. Considering the limited ductility of the connection, further work should be conducted to identify the potential

Table 3
Simplified models for seismic analysis of different forms of modular construction.

Type	Detailed model	Simplified analytical model
End plate bolted connection (Gunawardena et al. [104])		
Rotary connection (Chen et al. [95])		
Rod-base plate connected connection (Chua et al. [99])		
Welded connection (Annan et al. [46])		
Steel stud wall (Martínez-Martínez and Xu [73])		
Steel stud wall (Shamim et al. [68], Fiorino et al. [70], Kechidi et al. [71] and Fulop et al. [121])		

(continued on next page)

Table 3 (*continued*)

Type	Detailed model	Simplified analytical model
Corrugated steel plate shear wall (Wang [42])		

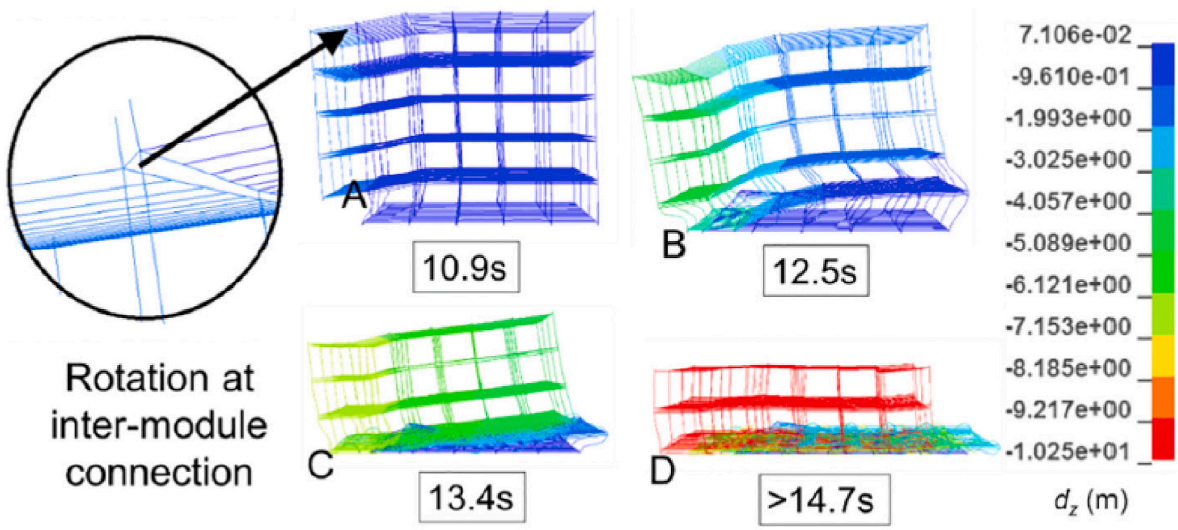


Fig. 13. Typical collapse process of modular steel construction after a corner module removal [135].

failure modes and robustness of mid-to-high rise MSC.

5.4. Critical design criteria

Currently, general design guidance is adopted for the design of MSC. The Handbook for the Design of Modular Structures [138] provides general design and construction considerations for MSC, with an emphasis on Austrian codes and standards. The limit state design approach is adopted for the design criteria, including the stability, strength and reliability. Ductility is the fundamental requirement for seismic design. Consequently, a reduced value of seismic action from a linear analysis is necessary as a measure of the ability to withstand inelastic deformation and other reserved strength. Seismic action derived from an elastic response spectrum analysis is adjusted to account for the non-linear response of the structure. The current adopted seismic design parameters in various design codes are summarized in Table 4. FEMA P695 [144] has been widely adopted to determine the behavior factor of low-rise CFS framed buildings [145,146]. The behavior factor of the CFS shear walls with gypsum board sheathing and CFS strap-braced stud wall are 2.0 and 2.5, as suggested by Shakeel et al. [147] and Fiorino et al. [148], respectively. Further investigation is necessary to determine the behavior factor of different types of mid-to-high rise MSC since current seismic design guidelines are adopted conventionally for the design of MSC.

A series of technical specifications for MSC have been compiled in recent years, based on the increasing application of MSC in China. The current design specifications for MSC in China are listed in Table 5. All specifications contain seismic design criteria, including the building height, story number, and limitations on the inter-story drift ratio, as seismic fortification is mandatory in China. The traditional displacement-based design criteria are adopted to limit the inter-story drift ratio of MSC. However, it has been acknowledged that new design criteria should be proposed, considering the possible rocking and sliding response of the modules [10,22,99,127,149].

It can be concluded from Table 4 that the limitation of the inter-story drift ratio under frequent earthquake is 1/300 for most structural forms of MSC. It is stricter than that for traditional steel structures, where the

Table 4
Summary of the adopted seismic design parameters.

Code	Parameters
North American Standard for Seismic Design of Cold Formed Steel Structural Systems (AISI S400-15) [139]	Ductility related seismic force modification factor (R_d) and the over-strength related seismic force modification factor (R_o)
Eurocode 8: Design of Structures for Earthquake Resistance (EN 1998–1) [140]	Behavior factor (q)
Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7–10) [141]	Response modification coefficient (R)
National Building Code of Canada (NBCC) [142]	Over-strength factor (R_0) and Structural ductility factor (μ)
Australian Standard -Structural Design Actions- Part 4: Earthquake Actions in Australia (AS 1170.4–2007) [143]	Structural ductility factor (μ) and structural performance factor (Sp)

limitation of inter-story drift ratio under frequent earthquake is 1/250, as stipulated by Chinese seismic code GB 50011–2010 (2016) [89]. This consideration is conservative in view of the insufficient understanding of this relatively new structural form, which is worthy of further investigation.

6. Development of seismic isolation system

Recently, it has been recognized that energy dissipative technologies may be useful for MSC. So that, the modules can be economically preserved for reuse even after seismic events, and a damage-controllable system can be established. Such systems are preferred to be incorporated into modules or inter-module connections and should be replaceable. Several attempts have been made to develop a seismic isolation system. Sultana et al. [150] investigated the seismic performance of MSC utilizing superelastic SMA bolts for the bolted inter-module connection. It was reported that the SMA bolts were helpful in optimizing the seismic performance of MSC in terms of reduced inter-story drift, reduced residual inter-story residual drift, and damage as compared to the traditional steel bolted connections. Jing et al. [151,152] proposed a seismic damage-resistant system for a multi-story MSC. An illustration and description of the working mechanism of the passive energy-dissipating slider device are provided in Table 6. Experimental and numerical studies were conducted to determine the seismic performance of this innovative isolation system. It was reported that all the modules could remain stable and were not prone to any collapse while sliding. More than 80% of the input seismic energy was dissipated through the proposed sliding system, indicating a desirable seismic performance.

In addition, Sendanayake et al. [153] proposed two types of seismic mitigation connections for MSC, as shown in Table 5. The numerical simulation results suggested that the proposed connections exhibit excellent seismic performance in terms of moment-carrying capacity, energy dissipation and ductility. In addition, an energy dissipation inter-module connection with a lead rubber bearing (LRB) was proposed by Wu et al. [154], as shown in Table 5. The numerical analysis indicated that the proposed connection has a better energy dissipation capacity than the regular connection and can, therefore, better protect the adjacent components than the regular connection.

7. Conclusions and future development

Modular steel construction (MSC) has great potential in buildings where repetitive units can be manufactured, such as in hospitals, schools, hotels, and dormitories. This innovative construction method may shape the future of the construction industry. However, several challenges regarding the seismic performance of MSC must be addressed, especially with the increasing application of mid-to-high rise MSC. The key areas for further study are identified as follows, based on the critical review in this paper.

(1) Both structural and non-structural components are incorporated in the module to provide a complete building system. Although many studies have been conducted regarding the seismic performance of the lateral force resistant component in the module, only the structural components have been considered. It is recommended to further investigate the seismic performance of the lateral force resistant component containing the attached non-structural finish to reveal the cooperativity between them under earthquake and to develop the corresponding flexible connection technology.

(2) Steel stud walls and group columns are common in MSC and will serve as lateral-force resistant components for the stacked module structure. Extensive investigations have been carried out on the seismic performance of various types of steel stud walls. However, there is limited research on the seismic performance of the group columns, thus, this subject is worthy of further research.

(3) A variety of inter-module connection types have been proposed for practice and some research work has been conducted. Further research is required to better understand the seismic performance of the existing connections. Moreover, further studies are still needed for the development of reliable interlocking inter-module connections and investigation of their seismic performance, as that none of the existing connection can satisfactorily meet all the expected structural demand and constructional considerations. Adding an isolation system into the inter-module connection is a meaningful and appealing concept.

(4) The previous studies mainly focused on the seismic performance of low-rise stacked module structures. Additional efforts should be made to promote the stacked module structure for mid-to-high

Table 5
Summary of the design criteria in the current design specifications.

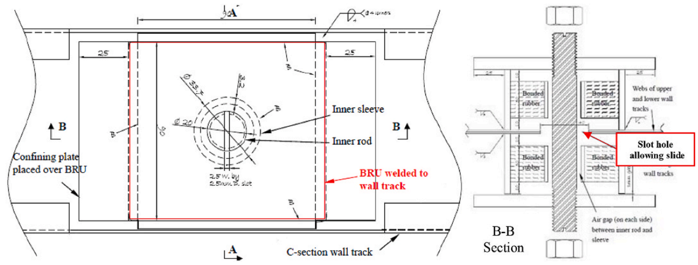
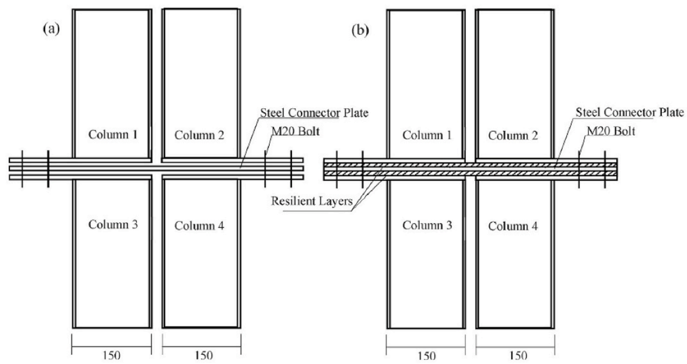
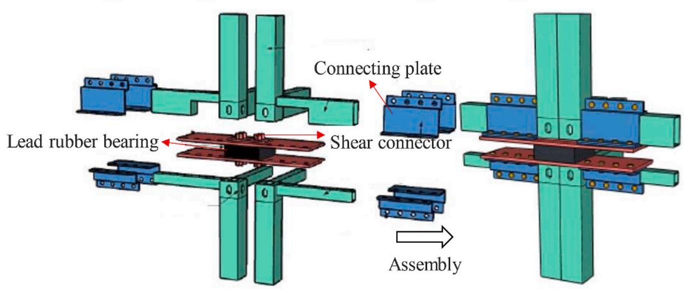
Specification	Structural form	N	H (m)	θ_y (rad)	θ_u (rad)
Technical specification for light steel modular building (JGJ/T466-2019 [24])	Stacked module structure	3	9	1/300	–
	Stacked modules supported by podium structure	4	13	1/300	–
	Recessed modules supported by primary frame structure	8	24	1/300	–
	Module-concrete core hybrid structure				
Technical specification for modular freight container building (CECS 334–2013 [25])	Stacked module structure	3	12	1/300	–
	Stacked modules braced by primary moment frame	6	24	1/300	–
	Stacked modules supported by podium structure				
Technical specification for steel modular buildings (T/CECS 507–2018 [26]) *	Stacked module structure (Unbraced module)	3	9	1/300	1/50
	Stacked module structure (Braced module)	8	24	1/300	1/50
	Module-unbraced moment frame hybrid structure	12	36	1/300	1/50
	Module-braced moment frame hybrid structure	24	72	1/300	1/50
	Module-concrete core hybrid structure	33	100	1/800	1/100

Technical specification for box steel prefabricated prefinished volumetric building (T/CECS 641–2019 [27])

Structural form	H (m) Seismic intensity					θ_y (rad)	θ_u (rad)
	6 (0.05 g)	7 (0.10 g)	7 (0.15 g)	8 (0.20 g)	8 (0.30 g)	1/300	1/50
Stacked module structure	40	35	35	30	30		
Module-unbraced moment frame hybrid structure	60	50	50	40	35		
Module-braced moment frame hybrid structure	100	100	80	60	60		

Note: 1. n denotes the limitation of story number; H denotes the limitation of building height; θ_y denotes the limitation of inter-story drift ratio under frequent earthquake; θ_u denotes the limitation of inter-story drift ratio under rare earthquake.
2. *-The limitation of story number and building height is suitable for the areas with seismic intensity of 7°. For the areas with seismic intensity of 8°, the story number should be decreased by 1 or 2 stories and the building height should be decreased by 3 or 6 m, correspondingly.

Table 6
The current developed seismic isolation system for modular steel construction.

Type	Illustration	Working mechanism
Passive energy-dissipating slider device (Jing et al. [151,152])		A bonded rubber unit (BRU) is welded to the wall track, and the inner rod can slide in the slotted hole.
Seismic mitigation connection (Sendanayake et al. [153])		The additional steel connector plate and resilient layers can deform and provide damping under earthquake.
Energy dissipation connection (Wu et al. [154])		The lead rubber bearing can dissipate energy through shear deformation.

rise applications. In addition, more attention should be paid to the hybrid structure systems, such as the module-moment frame hybrid structure and module-concrete core hybrid structure, which are more suitable for mid-to-high rise MSC. Further systematic research is required to propose a reliable connection between the modules and primary lateral-force resisting system and to reveal the lateral force distribution and transferring mechanism.

(5) Although current studies have revealed the seismic performance of the typical low-rise MSC, there is still a lack of understanding of the failure modes and robustness of MSC under seismic activity, especially for the mid-to-high rise MSC, which are more susceptible to progressive collapse. Further research is necessary to provide a better understanding of the failure mechanism of MSC under seismic effects including redistribution of internal forces and robustness to loss of connectivity.

(6) The traditional equivalent lateral force design method is not applicable for MSC, as each module behaves as a discrete rigid diaphragm for transferring the horizonal load, resulting in a distinguished load transferring mechanism. In addition, the displacement-based seismic design criteria show limitations with regard to MSC, owing to the possibility of overturning and/or slip of the module under earthquake. More reasonable calculation methods and design criteria should be explored in the further.

The application of MSC is active at present, and research into the seismic performance of mid-to-high rise MSC is recommended, to obtain a better understanding of this relatively new construction method. The work reported in this paper is an endeavor toward this improvement.

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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