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Review of performance requirements for inter-module connections in multi-story modular buildings

Sriskanthan Srisangeerthanan, M. Javad Hashemi *, Pathmanathan Rajeev, Emad Gad, Saman Fernando

Department of Civil & Construction Engineering, Swinburne University of Technology, Hawthorn, Melbourne, Victoria, 3122, Australia

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ABSTRACT

Modular buildings are built using factory manufactured building units or modules that are transported and assembled on-site. Among the many different types of building units used, volumetric modules have the greatest potential to achieve complete building systems, where on-site work can be reduced to having only foundation, module assembly and the finishing of module-to-module interfaces. However, despite many reported benefits, the use of volumetric modules have some technical, logistical and regulatory issues that constrain its widespread application. The aims of this paper is to articulate two key technical issues that have been widely reported, namely, the lack of efficient structural systems for lateral load transfer and the lack of high-performance inter-module connectivity. Accordingly, a general overview regarding these two issues is presented that covers the behaviour of diaphragms in multi-story modular buildings and the essential characteristics required for inter-module connections. It is expected that inter-module connectivity should meet structural needs along with satisfying manufacturing and construction requirements. Brief descriptions of existing inter-module connecting systems that are available in both literature and the public domain including a critical review of those connections against the identified performance requirements are also presented. The outcomes of this paper are expected to assist in the future development and application of fully-modular superstructure construction systems for multi-story modular buildings.

1. Introduction

On a historical context, it has been suggested that many factors influenced the development of off-site manufacturing and its relevant systems for construction, where achieving economic, social and environmental sustenance have always been key drivers [1–5]. Automated assembly-line mass-manufacturing technologies have also enabled off-site manufacturing to emerge as a potential solution to address global construction issues which have been widely reported as: (1) increased urbanisation rates, infrastructure demand, energy demand, on-site emissions and environmental disruptions, and (2) constraints on construction productivity, efficiency, quality, on-site safety and access to skilled labour [6–10]. Hence, over the past few decades, much attention has been given towards developing off-site manufactured building construction systems.

Such building construction systems rely on the factory manufacture of transportable building units that are brought to and assembled on-site to form multi-story buildings (MSB). These building units can be of three basic forms, which are: (1) the linear form such as beams, struts and/or ties, (2) the planar form such as trusses, frames, slabs, panels and/or shells, or, the more challenging, (3) volumetric form such as load bearing units that enclose finished or un-finished space and comparable to shipping freight containers. The use of linear and planar units have long been in practice, where the T30 hotel building in Changsha, China (2012) [11–14] and the monumental World Trade Centre Twin Towers that once stood in New York, USA (1973-2001) are few of such examples. The use of volumetric units, on the other hand, is a recent development, where the 44 story La Trobe Tower in Melbourne, Australia (2016), the 32 story 461 Dean Street building in New York, USA (2016) and the 28 story Apex House building in London, UK (2017), are few such examples [15–17]. Of these different forms and their various corresponding construction techniques, those that make use of volumetric building units or modules have the greatest potential for being a complete building system (CBS), where it is expected that 60–70% of the

* Corresponding author.
E-mail address: jhashemi@swin.edu.au (M.J. Hashemi).

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total work in value terms would be completed off-site and project time savings would be within 50–60% of traditional site intensive construction [4]. However, current comparable off-site manufactured modular building construction systems or hybrid-modular building construction systems, though at the forefront of revolutionizing the construction industry, require additional conventionally built support structures, tedious on-site assembly and considerable post construction finishing to meet structural and architectural demands. On the other hand, an ideal CBS or a fully-modular building superstructure construction system, upon factory manufacture and delivery of modules, would only require on-site work that is related to the foundation, module assembly and module-to-module interface finishing with minimum human intervention to form fully complete multi-story modular buildings (MSMB). Such an idealisation not only requires adequately stiffened modules to form a lateral force resisting system (LFRS), but also requires high-performing inter-connectivity to ensure continuous load transfer both horizontally and vertically (see Fig. 1). It is believed that such connections through an innovative design would be the key enabler for satisfying certain structural, constructional and manufacturing requirements to further reduce construction time and subsequently overall costs, and improve on-site safety and overall building performance.

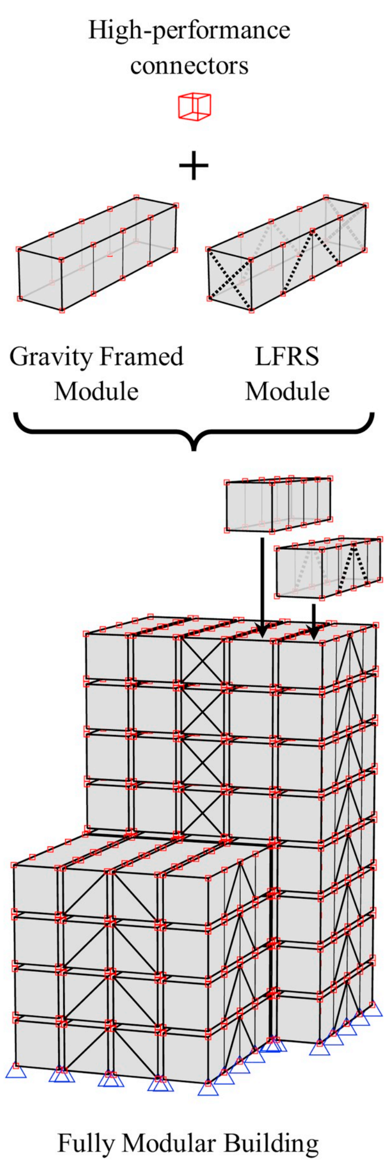


Fig. 1. Essential components of a fully-modular CBS and its apparent versatility.

Furthermore, some studies have also looked into other key aspects that could impact the overall efficiency and feasibility of modular building projects. The outcomes of these studies could greatly assist architects, engineers and project managers in designing and the overall decision-making, where some of the key works are by Tatum et al. [1,18,19], Fisher et al. [20,21], Torre et al. [22], Gibb [2], Lawson et al. [4] and Smith [3]; whereas others broadly cover, (1) the optimum spatial design of MSMBs [23], (2) near-optimum selection for module configuration through evaluating a unified indicator that accounts for on-site connections, mass limits, transportable module size, transportation distances, crane costs and the volume of concrete for foundations [24], (3) achievable trade-offs between module fabrication costs and certain project-related risks by incorporating dimensional and geometric tolerance strategies during structural analysis [25], (4) the logistics of crane selection and optimisation of its on-site location for increased productivity and shorter lifting schedules [26] and (5) the successful implementation of Building Information Modelling (BIM) for the structural design of complicated multi-story modular buildings [27].

Therefore, in light of the above, this paper aims to provide an overview on the accumulated research regarding MSMB construction and focuses specifically on the technical challenges in achieving adequate overall lateral stability and high-performing inter-connectivity between modules. The outcomes of this paper are expected to assist in the future development and application of fully-modularised construction systems for MSMB construction.

2. MSMB construction

2.1. Advantages and challenges

The spatial modularisation of a building requires the formation of load bearing modules, which could either be of bare structural framing, partially complete or fully-complete. Fully-complete modules have both the structural framing and non-structural components intact, such as finishing, fittings and furnishings. Such modules, as mentioned earlier, have the greatest potential to achieve an ideal CBS and once dispatched from a manufacturing plant, upon arrival to a site, they need only to be assembled to form MSMBs. These modules, apart from being useful for remote and robust emergency shelters, can further improve on the reported benefits from existing MSMB construction practices, which are (1) reduced construction time, (2) superior overall quality, (3) efficient material and energy use off- and on-site, (4) improved occupational health and safety, (5) less environmental disruption and (6) reduced overall construction costs through increased utilisation of assembly-line mass-manufacturing [2–4,28–42]. However, despite such potential improvements, fully-complete modules have not seen the expected widespread use for MSMB construction. This setback is widely reported to be due to certain technical, logistical and regulatory issues which still plague the construction industry [3,4,19,22,35–38,43–51].

Of these issues, those that are technical primarily relate to (1) the preservation of modules while being transported or handled, (2) the achievement of simple yet robust high-performing inter-module connectivity, (3) the formation of reliable structural systems, especially for efficient lateral load transfer and (4) the assurance of adequate overall robustness against disproportionate or progressive collapse.

Issues that are logistical commonly relate to (1) the difficulties in transporting and handling modules, (2) the effective use of cranes for on-site erection and (3) the achievement of proper coordination between both manufacturing and on-site activities due to the presence of parallel than sequential workflows.

Regulatory issues are generally (1) the lack of guidelines for design, manufacture, handling, transport and installation of modules as well as those regarding procurement, conformance, quality assurance, inspections, stakeholder responsibilities and overall project management, and (2) the lack of standardised solutions for the industry.

However, despite the need to resolve all challenges, this study is focused on two of the key technical issues identified, which relate to the lack of high-performing inter-module connections and the lack of reliable structural systems for efficient lateral load transfer.

2.2. Module types, building form and basic design considerations

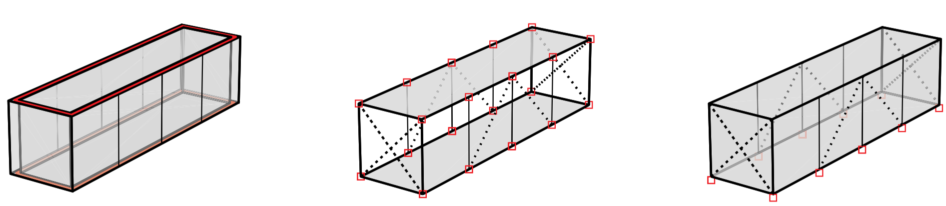
Module characteristics and the properties of inter-module connectivity would essentially govern structural strength, stability and safety of MSMBs, where connections have the most crucial role. Therefore on the basis of structural behaviour, modules can either be made continuously load bearing via their walls or have selective bearing via appropriately-spaced columns or be non-load bearing pods, which require a pre-constructed structural system prior to installation (see Fig. 2). However, space control and architectural freedom could best be achieved through the use of modules with selective bearing [4,29]. Continuously load bearing modules are typically made of concrete or timber. Whereas, steel modules, though can also be made continuously load bearing via the use of braced stud wall framing systems, are much more versatile and can accommodate different geometric forms including hybrid configurations (steel-concrete, steel-timber, etc.) [3,4,36,52–54]. Hence, steel module variants are more desirable and can easily accommodate a cradle-to-cradle life cycle for material use to achieve highly-sustainable low-embodied-energy/-carbon buildings [55,56]. A cradle-to-cradle approach considers a material through the stages of its extraction, refinement and processing to component manufacture, construction and operational use till recycle and/or reuse, where reuse is made possible by considering designs for deconstruction/disassembly [33,57]. Specific studies have shown that building construction using modules, especially those with steel framing, has numerous benefits covering the economic, social and environmental dimensions of sustainability [39,58–60]. Also, though the use of pod-like modules averts the need to tackle the key technical issues of MSMB construction when using load bearing modules [61], it cannot reap the full benefits of an ideal CBS.

On the other hand, mass and dimensions of modules are typically constrained by transportable mass and size limits, including those for on-site handling by cranes. The largest ISO freight container, which is approx. 2.9 m in height, 2.4 m in width and 13.7 m in length [62,63], is indicative of guaranteed transportable size limits globally, yet, there is preference towards using modules that are 4 m in height and width and 16 m in length to achieve large column free spaces (see Fig. 3). As per the National Heavy Vehicle Regulator of Australia, a common semitrailer has a maximum length restriction of 19 m and the 6 axle variant of its kind has a general mass limit of 42.5 tonnes; however, different states or territories in Australia may have permitted different specific allowances [64]. The use of steel and/or steel-hybrid modules (such as steel-concrete or steel-timber) can easily meet transportable and handling mass limits in comparison to modules made principally of concrete, and this advantage is due to steel and timber having comparatively large strength-to-weight ratios than concrete.

However, despite the mass and size control, these modules have to be stacked vertically and scaled horizontally to form MSMBs, and numerous architectural arrangements have been demonstrated [65,66]. Nevertheless, the location of a module within a building would dictate its stability and strength requirements such that local and global performance requirements are fulfilled under service and ultimate conditions. Typically, modules that would form parts of the lateral force resisting system (LFRS) would require sufficiently stiff shear walls, moment resisting frames or braced frames. Whereas those that would form other parts of the building, such as gravity frames, could have module framing made of simple connections provided that efficient diaphragm action is achievable so that stability can be guaranteed when under the action of lateral loads, such as those due to wind and regional seismicity.

On this regard, limited research is available on the performance assessment of MSMBs considering the action of lateral loads [67–78]. Of such works, those of Annan et al. cover the seismic performance assessment of braced frames in modular steel buildings [79–85], Fathieh et al. on an overall seismic performance assessment [86,87] and John Jing on the development of a seismic damage resistant system using a slider device [88]. Other works such as those of Shirokov et al., have attempted to determine the natural vibration frequencies of single story modular buildings assuming rigid inter-connectivity [89]. However, despite such efforts, it is believed that there is much potential for further experimental and numerical study into MSMBs accommodating semi-rigid inter-connectivity and the consideration of module behaviour for more representative outcomes for standardised design methods and practices. Available numerical and experimental research on the application of shipping freight containers for building construction further promotes modular construction and assists in establishing performance characteristics for both modules and inter-module connections as well [90–96].

With regard to applicable loads and/or load combinations for design, it is essential to consider appropriately factored scenarios of (1) permanent and imposed loads for ultimate vertical load effects, (2) lateral loads and permanent loads for ultimate lateral load effects, (3) lateral, permanent and imposed loads for the likelihood of larger compressive forces and (4) accidental loads for the assessment of overall robustness so that disproportionate and/or progressive collapse are avoided when afflicted by the loss of a part/parts of modules, the entire module or a group of modules due to blasts, impacts, fire or other hazards/extreme events. Guidance can therefore be sought from existing codes of practice for determining specific design actions and relevant design combinations for design actions. Examples of codes of practice include ASCE/SEI 7 [97] for America, Eurocode 0 [98], Eurocode 1 [99–103] and Eurocode 8 [104] for regions of Europe and AS1170 [105–110] for Australasia. Moreover, since permanent dead loads are essentially the self-weight of the construction materials used and imposed live loads are based on the intended use of floor space within a building, relevant code conditions pertaining to those loads are applicable to MSMBs. However, with regard to the wind, seismic and accidental loads, care should be exercised when adhering to relevant code conditions that are suggestive of equivalent static approaches since aspects of building geometry, mass, stiffness, strength, damping characteristics and redundancy play crucial roles. Conventional idealisations including relevant prescribed amplification factors may not be applicable for MSMBs, unless they are of a hybrid form as described earlier in section 1, where additional conventional structural systems are relied upon for lateral load resistance and overall robustness.



(a) (b) (c)

Fig. 2. Typical module variants, where (a) continuous bearing (b) selective bearing (c) pod-like.

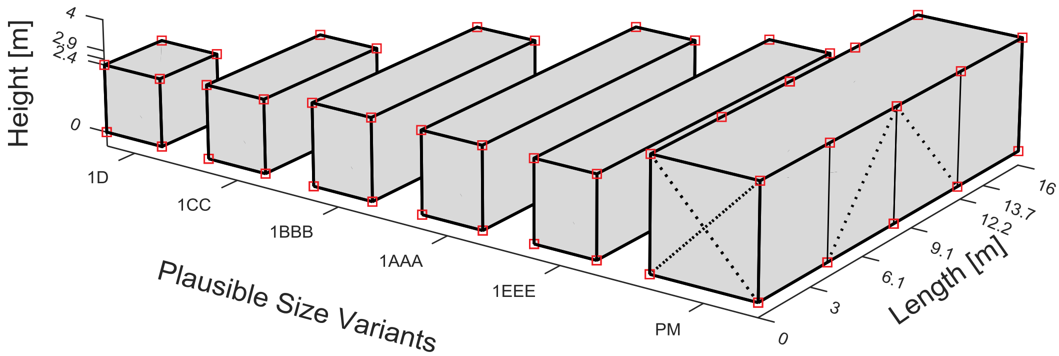


Fig. 3. Possible module size variants, where 1EEE, 1AAA, 1BBB, 1CC and 1D are typical ISO freight container types as per designation [62,63], and PM is the largest preferred module size.

On the other hand, prescribed conditions may likely be used for the initial estimate of design action effects and for the subsequent first-tier design of all structural members prior to adopting more robust analysis methods for refinement where actual behaviour can eventually be captured and the building accordingly designed. Typically, a strength-based design approach, where force demand against force capacity is checked at the component level for all components of a structure, considers linear-elastic analyses to calculate demands under factored loads and is adopted whenever a component or structure is intended to function within the linear-elastic range. This further caters to the use of components that predominantly exhibit brittle behaviour and should therefore always remain elastic. A deformation-based design, where deformation demand against deformation capacity is checked at the component and/or at the structure level, considers nonlinear analyses to establish deformation and strength demands under factored loads and is adopted whenever the structure is allowed to yield to make use of any available ductility to achieve economical solutions to resolve extreme action effects. This is especially the case when considering extreme events such as earthquakes. Performance-based design, on the other hand, seeks to provide reasonable assurance that a structure will satisfy a specific target performance level, such as the fulfilling of the requirements for operational performance, immediate occupancy, life safety or collapse prevention, against a specific hazard level and requires defining and evaluating demand-capacity parameters. On this note, for seismic loads, FEMA 356 proves to be a valuable resource [111].

The design of members in steel modules and hybrids can be undertaken following relevant standards. In the context of Australasia AS4100 [112], AS4600 [113] and AS2327 [114] are used for structural steel, cold-formed steel and composite structural systems, respectively. Parallels can further be drawn from AS3711 [63,115–117] for shipping freight containers along with AS3850 [118,119] for prefabricated concrete elements. ANSI/AISC 360 [120] and Eurocode 3 [121,122] are respectively applicable in America and Europe for steel design, and relevant relatable standards are also applicable therein. However, it should be noted that such standards covering the design of steel structures requires the use of standardised sections assembled through prescribed configurations of standardised bolts and welds.

Other reported design concerns are on (1) the influence of eccentricities due to the presence of manufacturing and construction tolerances, thereby, resulting in the loss of verticality as well as horizontality, (2) the design for attaching non-structural components, such as the building façade and other cladding material, (3) achieving adequate acoustic and thermal performance, in consideration of double-skinned systems, structurally insulated panels, vacuum insulated panels, etc., (4) achieving adequate fire resistance, via the incorporation of multiple layers of fire resistant materials and proper seals, containment or other robust technologies, (5) the integration as well as modularised connectivity of services [4,123,124] and (6) the design of modules including attached non-structural components for transportation and handling [125].

3. Structural performance of MSMBs

3.1. Force-resisting systems in MSMBs

Most MSMB forms can easily resist gravity loads similar to a tower of shipping freight containers. However, the resistance of lateral loads poses a challenge due to the lack of continuous systems for both efficient load transfer in the horizontal plane and adequate drift resistance in the vertical plane. A generic four-by-four bay four-story MSMB form is considered for demonstration, where the peripheral frames are assumed to be braced. Through this model, it is evident that spatial modularisation has resulted in discontinuous vertical and horizontal structural systems, since the modules are connected to each other at discrete locations (see Fig. 4). The vertical structural system comprises of inter-connected gravity and lateral force resisting frames of modules, whereas the horizontal structural system is the diaphragm which is formed by inter-connected floor and ceiling panels of modules. Overall building behaviour is consequently influenced by both module and inter-module connection stiffness and strength, where inadequacies could result in serviceability issues and lack of safety. Therefore, the numerical representation for MSMBs should satisfactorily capture the influence of both individual modules and inter-module connections.

Some analytical and numerical attempts have been presented by Li et al. [126,127] assuming modules to be of rigid frames. However, capturing the semi-rigid behaviour of modules would prove beneficial, especially when considering the need to preserve non-structural components attached to modules and to accommodate variety in module manufacture. Different materials and hybrid systems used for the manufacture of modules could yield different stiffness and strength values and is best if accountable during analyses.

3.2. Behaviour of diaphragms

Diaphragms are crucial for the transfer of lateral loads to the LFRS and serve a secondary purpose of linking all vertical elements at each story. Conventionally, for buildings with cast in-situ slabs or of concrete-filled metal decking, diaphragms can be idealised as rigid continuous systems, provided that they have no prescribed irregularities, such as discontinuities, holes, etc., and satisfy the required span-to-depth ratios for the lateral load being considered [97,128,129]. Such rigid diaphragms, in the absence of torsional effects, tend to distribute lateral loads relative to the stiffness of the LFRS and gravity frames tend to displace approximately to the same extent of the LFRS [130,131]. However, not all diaphragms are free from irregularities and fit such rigid idealisations. The classification of diaphragms, as currently prescribed in codes of practice, is specifically based on the ratio between maximum diaphragm displacement relative to the LFRS and the

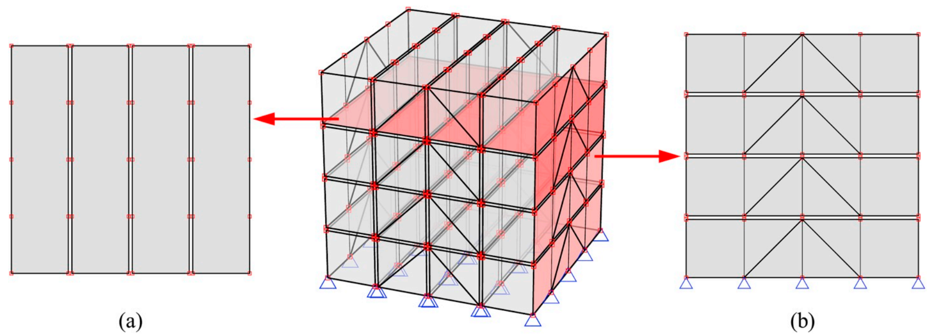


Fig. 4. The demonstrative MSMB model and the apparent discontinuities in key structural systems, where (a) diaphragm assemblage (b) lateral-force-resisting-frame assemblage.

corresponding average inter-story drift of the LFRS. For an expected rigid diaphragm behaviour, this ratio is targeted to be less than 0.5, whereas for flexible diaphragm behaviour it is to be greater than 2.0 and for all values in-between, the diaphragm is considered stiff (see Fig. 5) [97,109–111]. Flexible continuous diaphragms, on the other hand, closely resemble the behaviour of simply supported beams, where lateral load distribution is approximated by load tributaries on the diaphragm rather than relative stiffness of the LFRS [130,131].

It is therefore likely that modularisation of a building could result in the formation of flexible diaphragms. This is essentially due to diaphragms being assemblages of discretely-connected systems, where behaving rigidly or flexibly as a whole is governed substantially by the stiffness of the lateral inter-connectivity between modules, and partly by the in-plane stiffness of the connected module floors and ceilings, which is often neglected via rigid body assumptions. If these factors are not carefully considered, the lack of diaphragm stiffness may result in increased gravity frame drifts inducing aggravated second-order effects and potential diaphragm failure, leading to loss of building stability and the likelihood of collapse.

Furthermore, it has also been reported that when under the action of seismic loads, buildings with flexible diaphragms are likely to encounter higher mode effects. This could result in discrepancies between the diaphragm and LFRS peak displacements. Consequently, this may result in large drifts and loss of stability, which in turn, could trigger partial or total collapse [132,133]. Such effects have been demonstrated in a recent study through nonlinear time history analyses of a MSMB having a perimeter LFRS and diaphragms of varying stiffness [134]. It was also found in this study that current seismic codes do not provide for the required force nor ductility demands for even the MSMB with diaphragms classified at the limit of being rigid, when subjected to strong ground motions scaled to specific 500 and 2500 year design earthquakes. This urges the need to conduct more detailed studies into the seismic behaviour of MSMBs, especially for applicability in regions of high seismicity. However, in that study, for an alternative mode of energy dissipation, two performance-based design options for regions of high seismicity were also explored for the diaphragms of the considered case study MSMB. The two design approaches were based on accommodating (1) inelastic axial and shear behaviour and (2) inelastic axial and elastic shear behaviour for diaphragm connections, to further improve the energy dissipative capabilities of the overall structure on top of that of the incorporated LFRS. The purpose of having considered the latter option was to facilitate the use of steel-framed modules with composite decking made of steel and concrete.

Moreover, conventionally, it is expected that the LFRS of a building will predominantly dissipate seismic energy. Therefore it maybe crucial to ensure that inter-module connections located within the LFRS of fully-modular MSMBs, remain elastic. Nevertheless, a further look into energy dissipative technologies for MSMBs such that modules can be

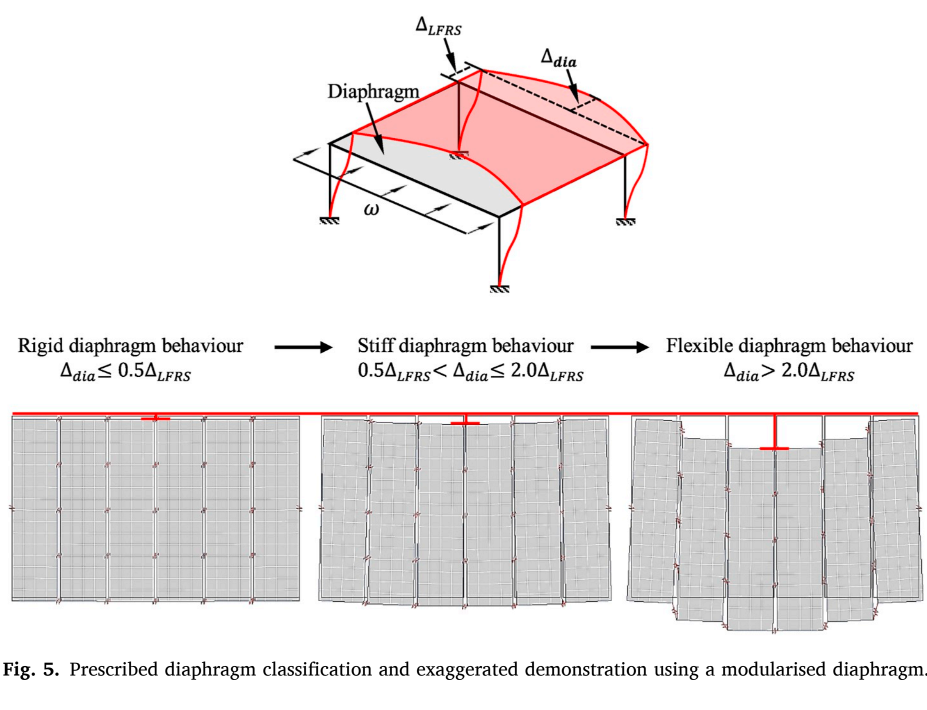


Fig. 5. Prescribed diaphragm classification and exaggerated demonstration using a modularised diaphragm.

economically preserved for continued use or reuse after an extreme event, is also useful. Such systems are preferred to be integrated into modules or inter-module connections and be replaceable.

4. Connections for MSMBs

4.1. General expectations

It is well known that the mechanical properties of connections, such as stiffness, strength and ductility have significant influences on the overall serviceability, strength, safety and stability of structures. Forces acting on connections are determined by undertaking a global analysis, where connection stiffness typically governs overall force distribution and connection ductility can assist in achieving additional safety, economically, in scenarios of overloading. Furthermore, the number of connections are equally important as they would affect the overall cost and erection time. It is generally expected that material cost would be ~20–40% and labour costs for design, fabrication and erection would be ~60–80% of total costs [135]. These overall concerns may also be attributable to the concept of structural resilience, which is defined as consisting of the properties of robustness, redundancy, resourcefulness and rapidity [136], and may therefore relate as the ability of connections to, (1) withstand a given level of stress without loss of function, (2) maintain function in the event of any onset of degradation, (3) be simple such that components and resources are readily available to initiate the process of recovery if a loss of function occurs, and (4) be easily replaceable so that recovery can be expedited and losses mitigated. Hence, apart from having adequate strength, stiffness and ductility, connections are preferred simple for manageable costs and ease in assembly.

In conventional MSBs, common framing connections are likely to be of (1) beam-to-beam, (2) beam-to-column, (3) column-to-column, (4) column-to-footing and (5) those for bracings. Beam-to-beam connections can be between two mutually perpendicular or parallel beams, where the latter can form a composite section improving overall load carrying capacity and reducing deflection. Similarly, column-to-column connections can be between two inline or adjacent columns. Conventionally, these connections, if made of steel, would be put together by either an assembly of bolts, which are inexpensive and simple, or a group of welds, which are expensive, complex and require careful inspections. Furthermore, the arrangement of bolts or welds and other complimentary components are crucial for achieving the required rigid, semi-rigid or pinned behaviour for the connection. However, pinned or simple connections are commonly preferred due to being less labour intensive in both fabrication and assembly. Typically, simple connections make use of bolts and plates, such as cover plates, end plates and fin plates.

The construction of MSMBs would also require a multitude of such basic connections and they can all be broadly grouped into being (1) intra-module, (2) inter-module or (3) foundation. Intra-module connections are those that assist in forming the structural frames of modules; whereas, inter-module connections are those that enable the formation of key structural systems for the whole MSMB via vertical and horizontal inter-connectivity between modules. Inter-module connections can be further sub-divided as (1) 2-column connections or type-a, which are typically between external open (no adjacent modules) corners and longitudinal edges of modules, (2) 4-column connections or type-b, which are typically between external closed corners and internal longitudinal edges of modules and (3) 8-column connections or type-c, which are typically between internal closed corners of modules. Foundation connections, on the other hand, are essentially support connections either on to a strong transfer frame or any conventional foundation [4]. Fig. 6 identifies these connection types within a simple stack of modules.

A distinction also needs to be made with respect to whether an inter-module connection is part of a modularised gravity framing system or a

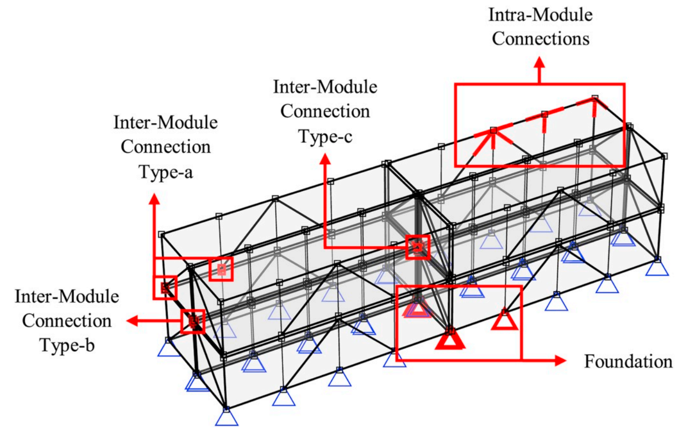


Fig. 6. Key connection groups in a MSMB.

LFRS. Inter-module connections that are part of a modularised gravity framing system transfer vertical loads through one module column to the next and lateral loads are transferred through diaphragm connections to the LFRS. The vertical load transferring mechanism can therefore be decoupled from the lateral load-transferring mechanism for the overall connection. However, inter-module connections that are part of a modularised LFRS, require both vertical and lateral load transfer to be taken up simultaneously and therefore requires coupled load transferring mechanisms. As a result, the development and/or choice of an inter-module connection greatly depends on the needs of the designer as to whether the intended use is for gravity framing alone, where modules will subsequently be connected to conventional LFRSs, or is for both gravity framing and the LFRS. Such would be expected for an ideal CBS or a fully-modular building superstructure construction system for MSMB construction.

4.2. Performance requirements for inter-module connections

In general, it is expected that intra-module connections would account for module integrity and contribute towards achieving the required module stiffness. Whereas, foundation connections would facilitate the transfer of loads to the ground or to transfer frames. Simple connections are preferred for intra-module connectivity and any conventional method is applicable. Foundation connections can also be of any conventional form. An assessment of a particular type of embedded steel column foundation connection for modular buildings has been conducted by Park et al. [137]. Furthermore, intra-module and foundation connections are less likely to influence the overall outcome of MSMB projects, since intra-module connections would be completed off-site under factory conditions and foundation connections are, if properly done, an essential onetime only on-site work.

On the other hand, inter-module connections are likely to have a profound influence as they affect the on-site assembly of modules at each successive story. The nature of these connections can either improve on construction time, safety and cost or be the source of many complications. Therefore, in addition to providing adequate strength, stiffness and ductility to accommodate structural demands, inter-module connections should also satisfy certain manufacturing and constructional/functional needs.

When considering such performance requirements, it has been mentioned by Lytle et al., that the key characteristic features for beam-column connections to achieve automated steel construction are, (1) Self-alignment, (2) Tolerance allowance, (3) Adjustment capable, (4) Adequate stiffness, strength and stability, and (5) Modularity, as in mass producible [138]. Therefore, when focusing on the structural performance requirements for inter-module connections, they should be capable of adequate yet efficient load transfer via a combination of axial and shear resistance in both the plane of the diaphragm and the LFRS, where (1) vertical axial resistance in tension and (2) diaphragm axial as well as shear resistance are essential. Manufacturing performance requirements relate to inter-module connections having (1) less unique components, (2) geometrically simple components, (3) components that can easily be integrated into usable off-the-shelf systems, where simple manufacturing/fabrication techniques can be adopted for rapid cost effective production and (4) components can be attached to modules without much complexity. Constructional/functional performance requirements, on the other hand, expect inter-module connections to be (1) self-aligning or self-locating under gravity by having geometric features that act as guides for positioning modules, (2) remotely operable without needing access through modules nor placing access holes on framing elements which could subsequently lead to undesirable localised effects requiring additional strengthening, (3) simple in functionality by having an integrated design that is capable of automatic or semi-automatic function for quick assembly with less operations, effort, labourers and tools, (4) easily demountable such that relocating and/or replacing modules to comply with future demands or if damaged during assembly or under extreme events is achievable, (5) capable of being integrated within or onto framing elements to minimise the non-usable space between modules, (6) scalable such that modifications can easily be done to accommodate varying load demands and section sizes and (7) capable of handling tolerances or enforcing tolerance control such that reasonable amounts of manufacturing and construction tolerances can be accommodated to address vertical and horizontal alignment issues during module assembly.

4.3. Current systems for inter-module connectivity

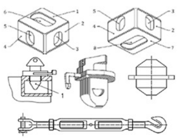
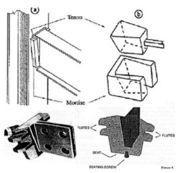
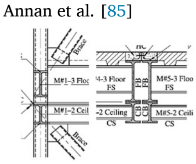
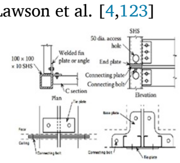
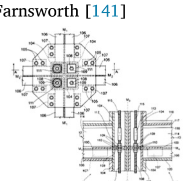
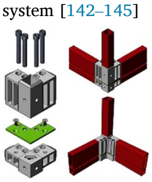
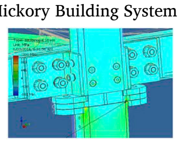
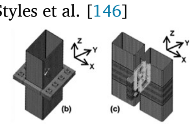
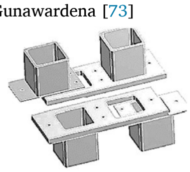
It is believed that automatic or semi-automatic mechanical connections are best suited to address the identified manufacturing and constructional/functional needs for inter-module connectivity. Therefore to assist in the future development of such applicable systems for MSMB construction, an understanding of the capabilities of existing systems is first looked into, and Table 1 presents those that are currently available in both literature and the public domain. Brief descriptions of their apparent and/or reported features are mentioned as well. It is inferable that when considering these systems, the current state-of-the-art for inter-module connectivity has been achieved commonly through the use of bolted or welded assemblies that have several un-integrated components and require laborious on-site work for module assembly. A further assessment on whether these identified systems satisfy the key factors relating to the established structural, manufacturing and constructional needs was conducted as well. The process of evaluation is described below, where a hypothetical type-b inter-module connection, as shown in Fig. 7, is considered as the generic demonstrative example. Furthermore, it is assumed that these connections would be undergoing assembly line mass manufacturing.

Structural needs fulfilment was assessed based on whether a connecting system has the necessary component or components capable of providing (S1) axial tensile resistance in elevation or vertical plane and (S2) diaphragm axial and shear resistance on plan or horizontal plane. When considering the generic connection of Fig. 7, the bolts provide for the required axial tension resistance in the vertical plane and the transfer plate provides for both axial and shear resistance on plan. Therefore both S1 & S2 structural performance criteria are satisfied by the generic connection.

Manufacturing needs fulfilment was assessed based on (M1) the number of unique parts a connection system has that needs to be manufactured individually, (M2) the complexity of each unique component and its manufacturing process complexity which considers the forming of plates, forging of bolts, threaded rods, pins and screws, and the use of other specific methods/processes such as casting and/or the need for machining or drilling, (M3) the complexity and requirement of any post-manufacturing component integration such as the need for welding or fastening the individually manufactured components together than having a simple assembly, (M4) the final number of unique off-the-shelf units after component integration, where a theoretical minimum would be to have both a vertical connector and a horizontal connector, and (M5) the ease in pre-attaching key components onto modules such as through the need for fastening, welding of endplates or angled sections, welding of key connector units, drilling or cutting module elements or requiring length-wise welding, where the weighting factors used were 1.0, 2.0, 2.0, 3.0 and 3.0 respectively. As an example, when considering the generic connection of Fig. 7, it comprises of column end plates, a transfer plate and relevant nuts, bolts and washers, hence requires the forming of the plates, forging of nuts, bolts and washers and the machining of each component as per requirements such as the drilling of holes on plates. The forming of plates and forging of bolts, nuts and washers were assigned a weighting factor of 1.0, whereas casting, simple machining and complex machining were assigned 2.0, 3.0 and 4.0 respectively. Therefore, when considering the demonstrative assembly, it has three unique components and the degree of component/manufacturing complexity equates to five. However, this connection system is independent of the need for any component integration and its initial set of manufactured parts would result in those themselves being sold as off-the-shelf components, where post manufacturing integration was evaluated considering a weighting factor of 1.0 if simple and/or requires only fastening, whereas if requiring welds, a factor of 2.0 was used. Furthermore, this demonstrative assembly, requires end plates to be pre-attached onto the columns of modules through welds, hence the pre-attachment complexity criterion results in a value of two as per the assigned weights.

Constructional/functional needs fulfilment was assessed based on whether (C1) the connection system has self-aligning or self-locating geometric features, (C2) connectivity can be engaged remotely without requiring direct access through modules, (C3) the complexity of engaging the connection system for vertical and lateral inter-module connectivity such that less time and effort is required through the incorporation of a mechanism, simple assembly, fastening of bolts, on-site welding, post tensioning and/or concreting, where the weighting factors considered are respectively 1.0, 1.0, 2.0, 3.0, 4.0 and 5.0, (C4) the number of operations required to engage, for a means of assessment, a type-b inter-module connection (refer to Fig. 5), where the weighting factors used for any vertical or horizontal connector insertion, mechanism operation, fastening, welding, pre/post tensioning, concreting were respectively 1.0, 1.0, 2.0, 3.0, 4.0 and 5.0, (C5) only a few set of tools are required to engage connectivity and can easily be handled, where the weighting factors considered for driving a mechanism, fastening, welding, pre/post tensioning and concreting are respectively, 1.0, 1.0, 2.0, 3.0 and 4.0, (C6) modules can easily be demounted and (C7) the non-usable space between modules can be minimised. For example, the generic connection of Fig. 7 does not have any self-aligning capability and connection engagement requires direct access for fastening bolts, which, in turn, would take much labour, time and effort despite requiring only a few set of tools. For mid-to high-rise construction, this method is likely to be occupationally hazardous as well. Furthermore, the following sequence of work could be expected for securing the connection, where upon having placed two base or bottom level modules side-by-side, the transfer plate would then be positioned prior to the upper level modules being lowered, where the whole assembly will subsequently be secured one module after the other, thereby having the unique operations of horizontal connector insertion and positioning, upper level module lowering and global assembly fastening. Disassembling this connection system is possible, yet would be tedious and difficult. Moreover, the non-usable space between modules would be governed by the specified end distances required for the fastening system. Table 2 further highlights the above evaluation as done for the generic connector and presents its final score for each criterion. The value-column represents a calculated value based on the direct summation of weighted outcomes determined through an understanding of a

Table 1
Comparison of existing inter-module connections.

Connection	Vertical Connectivity	Horizontal Connectivity	Other Remarks
ISO corner casting and securing systems [115,117] 	Vertical connectivity is provided by a variety of mechanical connectors, namely via twist-locks and latch-locks.	Horizontal connectivity is provided in conjunction with stacking cones, tensioning devices and lashing rods, chains or wires secured to strong frames.	All systems act through the corner castings of containers. Manual and semi-automatic variations of the connectors exist. The geometric form and slot type holes enable easy alignment.
ATLSS beam-column connection [139, 140] 	Vertical connectivity is unspecified, nevertheless can be achieved conventionally through either an end plate and bolt assembly or a single connecting bolt or rod.	Horizontal connectivity and possibly tying can only be provided, and it is through a tenon, mortise and seating screw system.	Though it is proposed as a beam-column connection capable of full to partial moment resistance, the concept can be applied to connect the columns of adjacent modules to provide lateral connectivity. The geometric formation of the tenon and mortise can provide gravity assisted aligning of modules.
Annan et al. [85] 	Vertical connectivity is provided through the on-site welding of the column base plate of an upper module to the column cap plate of a lower module.	Horizontal connectivity is provided by field bolting of clip angles which are shop welded to the floor beams of adjacent modules. Cast in place concrete is applied over the connection to seal it.	Robustness or tying maybe provided by the series of bolts clamping the clip angles of adjacent module floor beams.
Lawson et al. [4,123] 	Vertical connectivity is provided via a connecting bolt that clamps the column end plates of modules together.	Horizontal connectivity is provided via a base plate secured between the roof and floor beams of each adjacent module and may interact with the connecting bolts.	Robustness or tying maybe provided via a tie plate connecting each adjacent column. The presence of access holes may require localised strengthening of framing elements.
Farnsworth [141] 	Vertical connectivity is provided by coupled threaded tension rods which are passed through each column. The rods also pass through sleeves which are secured at the location of transfer plates.	Horizontal connectivity is provided via a transfer plate which is secured using bolts through connector/fin plates that are welded onto the roof beams of modules.	Robustness or tying maybe provided by the transfer plate. The transfer plate includes geometric formations that assist in module alignment during assembly.
VectorBloc™ tall modular building system [142–145] 	Vertical connectivity is provided through the securing of corner castings via a bolted assembly.	Horizontal connectivity is provided through transfer plates secured onto the corner castings.	Robustness or tying maybe provided by transfer plates, though other options seem possible where tie plates could be attached onto the castings. Conical guides can be attached onto the casting to assist in module alignment during assembly.
Hickory Building System [15] 	Vertical connectivity is provided through a bolted assembly securing the column end plates of each stacked module.	Horizontal connectivity and tying maybe provided by an additional bolted assembly using transfer or tie plates.	Geometric formations are present to assist in the alignment of modules during assembly and can provide shear resistance as well. Furthermore, since concrete flooring systems are used, it is believed that concrete wet joints or stich joints are relied upon to provide for the required horizontal connectivity to achieve diaphragm continuity.
Styles et al. [146] 	Vertical connectivity is provided through a generic column-column connection using bolts (a simple column end plate connection).	Horizontal connectivity maybe provided between adjacent columns of modules via a bolted assembly using side plates.	Robustness or tying maybe provided by the horizontal bolted assembly.
Gunawardena [73] 	Vertical connectivity is provided by a bolted assembly that secures column end plates of different forms.	Horizontal connectivity is provided through the combined resistance of column end plates.	Robustness or tying maybe provided by this combined set as well.
	Vertical connectivity is provided by clamping the column end plates of each	Horizontal connectivity is provided via a connection transfer plate secured to the	Robustness or tying maybe provided via the transfer plate.

(continued on next page)

Table 1 (*continued*)

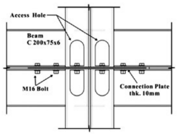
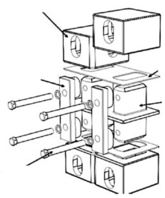
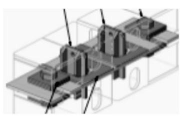
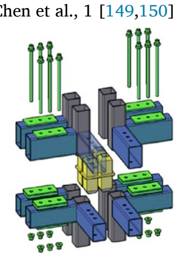
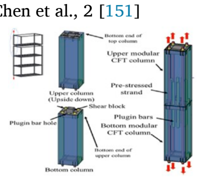
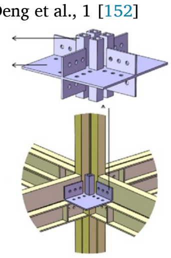
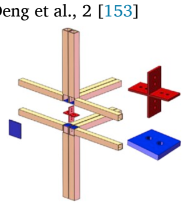
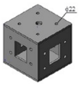
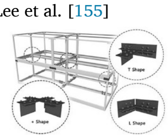
Connection	Vertical Connectivity	Horizontal Connectivity	Other Remarks
Choi et al. [74] 	stacked module together through a bolted assembly.	flanges of both the floor and roof beams of adjacent modules via a bolt assembly.	The presence of access holes may require localised strengthening of framing elements.
Heather et al., 1 [94,147] 	Vertical connectivity is provided by securing standard ISO corner castings through an assembly having a double spigot casting connector (similar to the ISO stacking cone fittings), lock-down plates with spigots and bolts.	Horizontal connectivity is via the transfer plate of the primary double spigot casting connector and additional washer-like or packing plates.	Robustness or tying maybe provided through the transfer plate. The spigots may guide modules during assembly and can provide additional shear resistance.
Heather et al., 2 [94,148] 	Vertical connectivity is provided via connecting bolts.	Horizontal connectivity is via the transfer plate and load transfer will be through interactions between the corner castings, spigot, plate and connecting bolts.	Robustness or tying maybe provided by the transfer plate. A double spigot casting is fit onto modified ISO corner castings and maybe capable of guiding modules during assembly and can function to provide additional shear resistance.
Chen et al., 1 [149,150] 	Vertical connectivity is provided by a bolted assembly that makes use of long stay bolts, cover plates and intermediary plates to secure the floor and roof beams of stacked modules.	Horizontal connectivity is provided through a plug-in device that fits into the hollow column sections, much like the ISO stacking cones used for securing freight containers. The transfer plate of the device may act as the medium through which lateral forces will be transferred. Furthermore, the intermediary plates, if one and spans between adjacent beams, may also provide lateral force transfer.	Robustness maybe provided through the interaction of the plug-in device with the hollow column sections and the device's transfer plate. The plug-in device also serves to provide additional shear resistance. The plug-in device inserted into the hollow column sections can function to align modules during assembly.
Chen et al., 2 [151] 	Vertical connectivity between a stack of modules is provided through pre-stressed strands secured between stiffened sealing plates at the ends of columns.	Horizontal connectivity is unspecified, however it maybe achieved by securing a transfer plate.	Racking resistance for a stack of modules is provided through the use of shear blocks, which can also facilitate the alignment of modules during assembly. The columns of these modules are concrete filled tubes, where the plugin-bars are claimed to assist in preventing the concrete from crushing and to provide additional ductility.
Deng et al., 1 [152] 	Vertical connectivity is provided through an assembly of bolts connecting a singular cruciform assembly of vertical and horizontal gusset plates to the web and flange of both roof and floor beams of stacked modules.	Horizontal connectivity is provided through an assembly of bolts connecting the singular cruciform assembly of vertical and horizontal gusset plates to the web and flange of both roof and floor beams of stacked modules.	Robustness or tying maybe provided by the assembly of web bolts and the horizontal gusset plate and possibly the interaction between the cones and module columns as well. The cones maybe capable of aligning modules during assembly and provide further shear resistance.
Deng et al., 2 [153] 	Vertical connectivity is provided through an arrangement of bolts and a cruciform gusset plate.	Horizontal connectivity is provided via the clamped cruciform gusset plate and a horizontal assembly of bolts.	The welded cover plate may also interact to provide vertical and horizontal resistance, and possibly tying for robustness. The column elements have been cut-out to facilitate access and may result in unwanted localised effects. A plate is proposed to be welded, covering the access hole which maybe beneficial.
Doh et al. [154] 	Vertical connectivity is provided by securing a proposed corner casting through an assembly of bolts.	Horizontal connectivity is provided by securing the proposed corner casting through an assembly of bolts.	Robustness or tying maybe achieved through the proposed assembly of bolts.
Lee et al. [155] 	Vertical connectivity is provided through a bolted assembly and a singular component made of vertical and horizontal plates.	Horizontal connectivity is provided through the bolted assembly and the singular component made of vertical and horizontal plates.	Robustness or tying maybe provided through the bolted assembly. The system connects the web and flanges of both roof and floor beams of adjacent and stacked modules.

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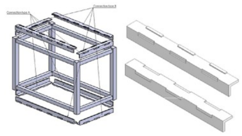
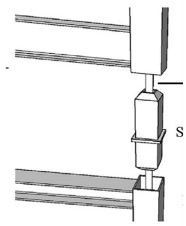
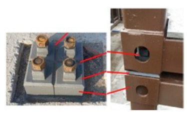
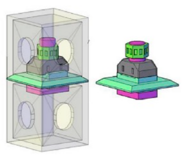
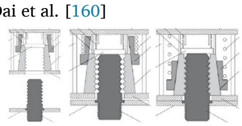
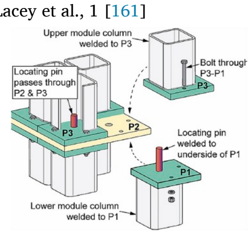
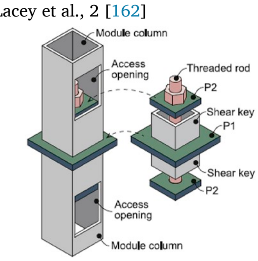
Table 1 (*continued*)

Connection	Vertical Connectivity	Horizontal Connectivity	Other Remarks
Sharafi et al. [156] 	Vertical connectivity is claimed to be provided by a tongue and grove system that is attached to the floor and roof beams of modules.	Horizontal connectivity is claimed to be provided by the tongue and grove system that is attached to the floor and roof beams of modules.	The system may not be capable of resisting vertical tension. Furthermore, tolerance control and module alignment for assembly may prove to be challenging.
Sanches et al. [157] 	Vertical connectivity is provided through the pre tensioning of a threaded rod passed through the columns of modules and is anchored at the ends of a stack of modules.	Horizontal connectivity is via a typical bolted side plate connection between adjacent columns similar to that introduced by Lawson et al. [4].	Robustness or tying maybe achieved through the bolted assembly. A steel box is used for developing shear resistance within a stack and is also used as guides by having conical formations at ends.
Yu et al. [158] 	Vertical connectivity is provided between corner fittings via a single connecting bolt, similar to the concept of the ISO corner casting and connecting systems including that presented by Lawson et al. [4].	Horizontal connectivity is via an intermediate plate that is welded on to the corner fittings.	Robustness or tying maybe provided through this intermediate plate.
Chen et al., 3 [159] 	Vertical connectivity is provided between corner fittings via a connector which comprises of a key like rod, a plate and a nut.	Horizontal connectivity maybe provided by welding the plate elements of adjacent connectors to form a singular transfer plate.	Robustness or tying maybe provided through the overall transfer plate.
Dai et al. [160] 	Vertical connectivity is provided through a connector box housing a threaded latching mechanism which engages a threaded stud attached to another connector box upon being triggered by the stud.	Horizontal connectivity maybe provided through a transfer plate held in position by the stud.	Robustness or tying maybe provided by the transfer plate.
Lacey et al., 1 [161] 	Vertical connectivity is provided through a bolted assembly connecting the end plates of columns together, much like the generic connector considered for demonstration (Fig. 7)	Horizontal connectivity is provided through a transfer plate held in position by the through bolts used for establishing vertical connectivity and the locating pins used for easing on-site assembly.	Robustness or tying maybe provided by the transfer plate.
Lacey et al., 2 [162] 	Vertical connectivity is provided through the pre-tensioning of a threaded rod passed through the columns of modules and a plug-in shear key, and are anchored within the zone of inter-connectivity through the aid of access holes.	Horizontal connectivity maybe provided through the central transfer plate forming the plug-in shear key much like the ISO stacking cone fittings.	Robustness or tying maybe provided by the interaction of the plug-in shear key with the columns and possibly by the transfer plate as well. The shear keys further provide additional lateral load resistance. It may however be a challenge to insert the threaded rod through the access holes if not sufficiently large, which may subsequently have detrimental localised effects. Additional strengthening may therefore be required.

connector's given description in addressing a performance criterion. The mean-column represents the mean value obtained from all the value-columns of all the surveyed connectors for each respective criterion and the column for the standard deviation is similarly obtained from those respective distributions. The standardised-value-column represents the standard or normalised value assigned to each connector based on the ratio between the deviation of a value from mean and the standard deviation for each respective criterion. The range between the maximum and minimum of the standardised values obtained from all of the surveyed connectors was divided into five segments for each criterion and each segment was assigned a value falling within a range from zero to unity, where unity was considered the most favourable and zero the least. These scores were subsequently categorised for simplified interpretations on whether a connector would satisfy, partially satisfy or not satisfy the demands of each criterion.

Likewise, the outcomes of this assessment for each connection system has been qualitatively presented in Table 3. Although these systems have some unique merits and can be made to fulfil any structural demand, most require further modifications to satisfy the identified manufacturing and constructional/functional needs. Hence, it is evidential that there is a need for innovations in inter-module connectivity.

5. Conclusions

Off-site manufacturing of modules and their use for multi-story building construction, has many potential benefits. However, certain limitations hinder the widespread use of such techniques and its potential to achieve the concept of an ideal complete building system, where on-site work would essentially comprise of foundation, module assembly and module-to-module interface finishing. Among these reported limitations, those that relate to achieving efficient lateral load resistance and robust high-performance inter-module connectivity are believed to be crucial. Therefore, this overview was confined towards exploring those two limitations, where specific focus was given unto identifying available technologies for inter-module connections and evaluating them against proposed performance criteria.

Efficient lateral load resistance requires the formation of rigid continuous structural systems both vertically and horizontally within multi-story modular buildings. Achieving such systems greatly depend on the stiffness of modules and that of inter-module connections. Appropriate analytical and numerical models should be used to capture the influence of both modules as well as connections to approximate actual behaviour so that forces and moments can be determined with reasonable accuracy for economical and safe designs. Care should be exercised when considering rigid diaphragm assumptions, where if inter-module connections are not capable of providing the required stiffness, out-of-phase diaphragm motions and subsequent gravity frame drifts could be aggravated and may lead to the potential collapse of multi-story modular buildings.

Although any inter-module connectivity can be designed accordingly to meet structural demands, it is believed that only automatic or semi-automatic connections have the potential to address certain identified constructional/functional needs. The addressing of these needs and having mass manufacturable components that can be easily integrated and attached to modules, could further reduce construction time, improve on-site safety and reduce overall costs. Complete building systems capable of such improvements are essentially fully-modular building superstructure construction systems which have been tailored for multi-story modular building construction, and have the greatest potential to achieve automation in construction. However, the current state-of-the-art for inter-module connectivity, on average, achieves only a partial satisfaction in fulfilling, at a whole, the identified structural, constructional and manufacturing performance requirements. Therefore, innovations are required with regard to inter-module connectivity and structural framing solutions that can enable large column free spaces could further strengthen the acceptance and use of modular building solutions.

Nevertheless, it should be noted that though the identification of performance requirements were based on past research and the understanding of current needs, the assessment of existing inter-module connections against those identified requirements was a subjective process based on the authors' interpretation of how an existing system would satisfy a particular need. Furthermore, the selected weighting factors may not entirely be representative of the true scope and scale of each identified sub-category pertaining to each performance criterion, and many more sub-categories may be included for a more robust and comprehensive assessment for presenting an index for a connection's overall suitability. Moreover, it should be noted that the connections identified are those that were accessible in literature and the public domain, and it should therefore be acknowledged that proprietary systems may exist and may meet the identified requirements.

Moreover, despite this overview being focused on highlighting the issues of lateral stability and inter-module connectivity, the following are other key areas for potential study.

- Inter-module connections that can handle appreciable levels of construction tolerances without the need for on-site module adjustments, would prove to be a crucial development.
- Robustness against disproportionate and/or progressive collapse due accidental loads, requires further study, where either the inter-module connections should meet the required demand or additional structural systems require to be integrated. Such is critical for mid-to high-rise modular buildings.
- Exploring structural framing strategies to achieve composite beam actions or those capable of forming equivalent grillage systems, could potentially address the need for large column free spans.
- Developing optimised module forms that can circumvent transport and crane-handling restrictions which could potentially solve logistics related issues.
- Vibrations and other action effects induced during the transport of modules could have potentially damaging effects on both intra-module connections and attached non-structural components. Design spectrums to account for such effects or countermeasures to alleviate any such vibrations, impacts or relevant action effects are crucial for ensuring that a module is delivered free of defects or of those irreparable. There is therefore potential to consider chassis design for transport vehicles or the design of temporary support systems.
- Modules of steel, steel-timber (cross laminated timber), steel-concrete (geopolymer or autoclaved aerated concrete) or other hybrid forms with satisfactory acoustic and thermal performance could potentially achieve the greatest savings on embodied energy/carbon and energy efficiency. There is therefore potential to study the behaviour of module variants and their acoustic and thermal performance.

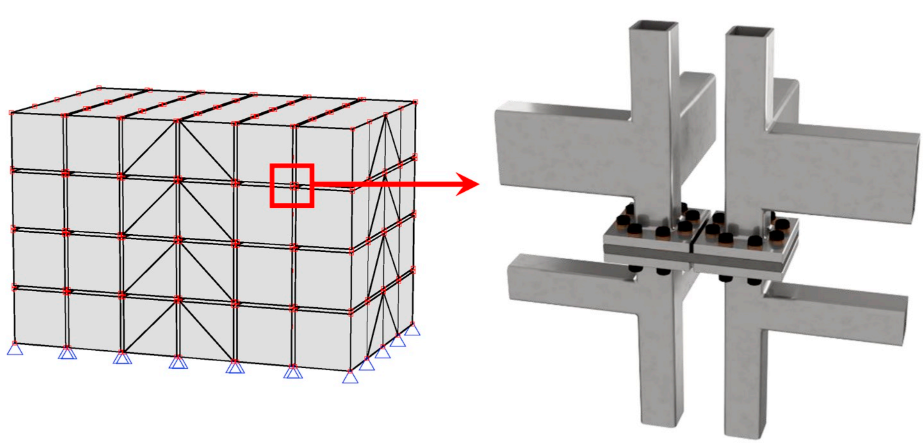


Fig. 7. A generic connection assumed for demonstrative purposes.

Table 2
A sample calculation as done for the Generic Connector (Fig. 7).

	Description	Weighting Method	Value	Mean	Standard Deviation	Standardised value	Final Score	Colour Code
S1	Vertical tension is resistible by the assembly of bolts.	0 = Satisfies 1 = Doesn't satisfy	0	0.04	0.19	-0.20	1.0	■
S2	Diaphragm axial and shear is resistible by the transfer plate.	0 = Satisfies 1 = Doesn't satisfy	0	0.00	0.00	0.00	1.0	■
M1	The assembly requires, • Column end plates • Transfer plates • Fastener components.	Number of unique components = 3	3	5.33	2.39	-0.97	1.0	■
M2	The following manufacturing processes are required, • Forming of plates • Drilling of holes on plates • Forging of fastener components.	1 = Forming plates 1 = Forging of fastener components 2 = Casting of components 3 = Machining - simple (e.g. drilling) 4 = Machining - complex (e.g. milling)	5	6.19	1.42	-0.84	1.0	■
M3	The assembly does not require integration of components.	0 = Doesn't require integration 1 = Simple fixing or fastening 2 = Welding	0	0.89	0.92	-0.97	1.0	■
M4	The number of off-the-shelf components are similar to M1.	Number of off-the-shelf components = 3	3	3.93	1.33	-0.70	1.0	■
M5	The end plates require to be welded onto the columns of modules.	1 = Requires fastening 2 = Requires welding at column locations 3 = Requires module length-wise welding 3 = Requires module modifications	2	3.15	1.33	-0.86	1.0	■
C1	The assembly doesn't have any features for self-alignment or guidance.	0 = Satisfies 1 = Doesn't satisfy	1	0.41	0.49	1.20	0.0	□
C2	The assembly requires direct access to engage connectivity.	0 = Satisfies 1 = Doesn't satisfy	1	0.85	0.36	0.42	0.0	□
C3	The assembly requires fastening of column end plates together, where a transfer plate is also required to be positioned in between.	Assigned weight for complexity of inter-connectivity 1 = Mechanism or Insertions 2 = Fastening 3 = Welding 4 = Post tensioning 5 = Concreting	3	4.70	2.64	-0.64	1.0	■
C4	The operations required to establish a type b inter-module connection after having placed two foundational modules are, • Placement of transfer plate • Lowering the first, first-level module • Fastening of lowered module • Lowering the second first-level module • Fastening of lowered module.	Assigned intensity weights for operations 1 = Lowering modules 1 = Vertical or lateral connector insertion 1 = Connector mechanism operation 2 = Vertical or lateral connectivity fastening 3 = Vertical or lateral connectivity welding 4 = Vertical or lateral connectivity post-tensioning 5 = Vertical or lateral connectivity concreting	7	9.85	3.94	-0.72	1.0	■
C5	Since being a bolted assembly, tools and equipment for fastening are only required to establish interconnectivity.	Weights assigned for tools and equipment complexity, 1 = Mechanism operation or fastening 2 = Welding 3 = Post-tensioning 4 = Concreting	1	2.30	1.94	-0.67	1.0	■
C6	The assembly is demountable and the modules can be reused having minimum to no incurred damage, however it would be work intensive.	Assigned weights for the complexity of demounting, 0 = Easily demountable 1 = Demountable, but strenuous 2 = Not demountable	1	1.11	0.57	-0.19	0.4	■
C7	The considered arrangement requires spacing between module columns.	0 = Satisfies 1 = Doesn't satisfy	1	0.19	0.39	2.08	0.0	□

Table 3
Comparison of existing inter-module connections against key performance requirements.

Connections	Structural (S) Requirements		Manufacturing (M) Requirements					Construction (C) Requirements						
	S1	S2	M1	M2	M3	M4	M5	C1	C2	C3	C4	C5	C6	C7
ISO [115, 117]	■	■	▣	■	▣	■	■	■	□	■	■	■	■	■
ATLSS [139, 140]	■	■	■	▣	■	▣	□	■	□	■	▣	■	▣	□
Annan [85]	■	■	■	■	■	■	□	□	□	□	□	□	□	■
Lawson *et al.* [4, 123]	■	■	■	■	■	■	□	□	□	■	■	■	▣	■
Farnsworth [141]	■	■	▣	▣	■	▣	□	■	■	▣	□	▣	▣	■
VectorBloc™ [142-144]	■	■	▣	▣	■	▣	■	■	□	■	■	■	▣	■
Hickory [15]	■	■	▣	▣	■	□	□	■	□	□	▣	▣	□	■
Styles *et al.* [146]	■	■	■	■	■	■	■	□	□	■	▣	■	▣	□
Gunawardena [73]	■	■	■	■	■	■	■	□	□	■	■	■	▣	□
Choi *et al.* [74]	■	■	■	■	■	■	□	□	□	■	■	■	▣	■
Heather *et al.*, 1 [147]	■	■	▣	▣	□	▣	■	■	□	■	■	■	▣	■
Heather *et al.*, 2 [148]	■	■	▣	▣	□	▣	■	■	□	■	■	■	▣	■
Chen *et al.,* 1 [149, 150]	■	■	■	▣	□	■	□	■	□	■	■	■	▣	■
Chen *et al.,* 2 [151]	■	■	▣	■	□	□	■	□	□	□	□	□	□	■
Deng *et al.*, 1 [152]	■	■	■	▣	□	■	▣	■	□	■	▣	■	▣	■
Deng *et al.,* 2 [153]	■	■	▣	■	□	▣	□	□	□	▣	▣	■	□	■
Doh *et al.* [154]	■	■	■	■	■	■	■	□	□	■	▣	■	▣	■
Lee *et al.* [155]	■	■	■	■	□	■	▣	□	□	■	▣	■	▣	■
Sharafi *et al.* [156]	□	■	■	■	■	■	▣	□	■	■	■	■	■	■
Sanches *et al.* [157]	■	■	▣	▣	□	▣	□	■	□	▣	□	▣	▣	■
Yu *et al.* [158]	■	■	■	▣	■	■	■	■	□	▣	■	■	□	■
Chen *et al.*, 3 [159]	■	■	■	▣	▣	■	■	■	□	▣	▣	▣	▣	■
Dai *et al.* [160]	■	■	□	□	▣	■	□	■	■	■	■	■	□	■
Lacey *et al.*, 1 [161]	■	■	■	■	□	■	■	■	□	■	■	■	▣	□
Lacey *et al.*, 2 [162]	■	■	■	■	□	■	■	■	□	▣	□	▣	▣	■
Generic (**Fig. 7**)	■	■	■	■	■	■	■	□	□	■	■	■	▣	□

□	Requires modifications (0 ≤ weighted score (WS) < 0.34)
▣	Can partially meet requirements (0.34 ≤ WS < 0.67)
■	Can meet requirements (0.67 ≤ WS ≤ 1)
S1	Capable of withstanding vertical plane tension
S2	Capable of horizontal plane or diaphragm axial and shear resistance
M1	Number of unique parts in a connecting system to achieve vertical and horizontal connectivity
M2	Complexity of parts and the manufacturing process complexity as per assinged modifiers
M3	Complexity and requirement of post-manufacturing integration of parts as per assigned modifiers
M4	The final number of unique off-the-shelf parts after integration
M5	Ease in pre-attaching the connecting system to modules, as per assigned modifiers
C1	Incorporates self-aligning or self-guiding features
C2	Capable of achieving inter-module connectivity remotely without requiring direct access
C3	Complexity of engaging inter-module connectivity as per assigned modifiers
C4	The number of operations to engage a type-b inter-module connectivity as per assigned modifiers
C5	The number of tools required to engage connectivty as per assigned modifiers
C6	Capable of being easily demounted
C7	Capable of minimising non-usable space between modules

Research into addressing logistical and regulatory issues are still largely active, however an industry-wide standardisation is yet to be achieved. A standardised fully-modular superstructure construction system for multi-story modular buildings would revolutionise the construction industry.

Declaration of competing interest

No conflict of interests known to the authors.

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References

[1] C.B. Tatum, J.A. Vanegas, J.M. Williams, Constructionability Improvement Using Prefabrication, Preassembly, and Modularization, The Construction Industry Institute, Austin, Texas, 1987.
[2] A.G.F. Gibb, Part One CONTEXT, in Off-Site Fabrication: Prefabrication, Pre-assembly and Modularization, Whittles Publishing, 1999, pp. 1–31.
[3] R.E. Smith, Prefab Architecture, in A Guide to Modular Design and Construction, John Wiley & Sons, Inc., 2010, pp. 3–366.
[4] M. Lawson, R. Ogden, C. Goodier, Design in Modular Construction, CRC Press, 2014, pp. 1–253.
[5] D. O'Neill, S. Organ, A literature review of the evolution of British prefabricated low-rise housing, Struct. Surv. 34 (2) (2016) 191–214.
[6] IPCC, in: O. [Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, J.C. Minx (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate

Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014, p. 1454.
[7] D. Ürge-Vorsatz, et al., Heating and cooling energy trends and drivers in buildings, Renew. Sustain. Energy Rev. 41 (2015) 85–98.
[8] Global Construction Perspectives (GCP), Oxford Economics, in: Mike Betts, et al. (Eds.), Global Construction 2030: A Global Forecast for the Construction Industry to 2030, 2015.
[9] United Nations (UN), Urbanization and Development: Emerging Futures, in World Cities Report 2016, 2016.
[10] T. Townsend, International Construction Market Survey 2017, 2017.
[11] X. Liu, et al., Design and model test of a modularized prefabricated steel frame structure with inclined braces, Adv. Mater. Sci. Eng. 2015 (2015) 1–12.
[12] X. Liu, et al., Design and compilation of specifications for a modular-prefabricated high-rise steel frame structure with diagonal braces. Part I: integral structural design, Struct. Des. Tall Special Build. 27 (2) (2018) e1415.
[13] X. Liu, et al., Design and specification compilation of a modular-prefabricated high-rise steel frame structure with diagonal braces part II: elastic-plastic time-history analysis and joint design, Struct. Des. Tall Special Build. 27 (2) (2018) e1414.
[14] X.C. Liu, et al., Bending-shear performance of column-to-column bolted-flange connections in prefabricated multi-high-rise steel structures, J. Constr. Steel Res. 145 (2018) 28–48.
[15] S. Kumar, Hickory Building System (HBS) innovation and successful application in a 44 storey building in Melbourne, in: Australian Structural Engineering Conference, 2016 (Australia).
[16] R. Krulak, Modular high-rise: the next chapter, CTBUH J. (II) (2017) 4.
[17] The Chartered Institute of Building (CIOB), Up, up and away: on site at Europe's tallest modular tower in Wembly, which will take just a year to complete, in: Construction Manager, Atom Publishing, London, 2017, p. 60.
[18] C.B. Tatum, Improving constructibility during conceptual Planning, J. Constr. Eng. Manag. 113 (2) (1987) 191–207.
[19] C.B. Tatum, Management challenges of integrating Construction Methods and Design Approaches, J. Manag. Eng. 5 (2) (1989) 139–154.
[20] D.J. Fisher, M. Skibniewski, Computerized Decision Support for Modularization of Industrial Construction, Construction Industry Institute, Austin, Texas, 1992.
[21] M.B. Murtaza, D.J. Fisher, M.J. Skibniewski, Knowledge-based approach to modular construction decision support, J. Constr. Eng. Manag. 119 (1) (1993) 115–130.
[22] M.L.D.L. Torre, et al., Review and Analysis of Modular Construction Practices, in ATLSS Reports, Lehigh University, 1994, pp. 1–109 (1-1 to B-6).
[23] P. Sharafi, et al., Automated spatial design of multi-story modular buildings using a unified matrix method, Autom. ConStruct. 82 (2017) 31–42.
[24] T. Salama, et al., Near optimum selection of module configuration for efficient modular construction, Autom. ConStruct. 83 (2017) 316–329.
[25] Y. Shahtaheri, et al., Managing risk in modular construction using dimensional and geometric tolerance strategies, Autom. ConStruct. 83 (2017) 303–315.
[26] J. Olearczyk, M. Al-Hussein, A. Bouferguène, Evolution of the crane selection and on-site utilization process for modular construction multilifts, Autom. ConStruct. 43 (2014) 59–72.
[27] I.J. Ramaji, An integrated building information modeling (BIM) framework for multi-story modular buildings, in: Department of Architectural Engineering, Pennsylvania State University, 2016, p. 612.
[28] D.E. Charrett, P.H. Incoll, N. Kozlovsky, Modular buildings for Antarctica, in: First National Structural Engineering Conference, 1987, p. 6. Melbourne, Australia.
[29] R.M. Lawson, et al., Modular construction using light steel framing: an architect's guide, in: The Steel Construction Institute (SCI): Ascot, Berkshire, United Kingdom (UK), SCI Publication P272, 1999, p. 105.
[30] A.L. Rogan, R.M. Lawson, N. Bates-Brkljac, Value and Benefits Assessment of Modular Construction, in Modular Matters, The Steel Construction Institute, London, 2000, pp. 1–19.
[31] L. Jaillon, C.S. Poon, The evolution of prefabricated residential building systems in Hong Kong: a review of the public and the private sector, Autom. ConStruct. 18 (3) (2009) 239–248.
[32] L. Jaillon, C.S. Poon, Y.H. Chiang, Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong, Waste Manag. 29 (1) (2009) 309–320.
[33] L.C. Jaillon, The Evolution of the Use of Prefabrication Techniques in hong kong Construction Industry, in Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong, 2009, p. 337.
[34] McGraw-Hill Construction, Prefabrication and Modularization: Increasing Productivity in the Construction Industry, 2011, p. 56.
[35] R.M. Lawson, R.G. Ogden, R. Bergin, Application of modular construction in high-rise buildings, J. Archit. Eng. 18 (2) (2012) 148–154.
[36] Shonn Mills, Dave Grove, Matthew Egan, Breaking the pre-fabricated ceiling: challenging the limits for modular high-rise, in: CTBUH Conference, 2015 (New York).
[37] R.E. Smith, Permanent modular construction, in: Off-Stie Studies, Modular Building Institute (MBI), National Institute of Building Sciences (NIBS) and Integrated Technology in Architecture Center (ITAC) at University of Utah, 2015, p. 95.
[38] Sustainable Built Environment National Research Centre (SBEnrc) and Cooperative Research Centre for Low Carbon Living (CRC-LCL), Investigating the Mainstreaming of Building Manufacture in Australia, Curtin University, Perth, Griffith University, Brisbane Australia, 2015, p. 18.
[39] Steel construction institute (SCI), *Report on sustainability Benefits of modular construction*, in: R.M. Lawson (Ed.), MODCONS European Funded Research Project: Development of Modular Construction Systems for High-Rise Residential Buildings, 2015, p. 153. United Kingdom (UK).
[40] F. Boafo, J.H. Kim, J.T. Kim, Performance of modular prefabricated architecture: case study-based review and future pathways, Sustainability 8 (6) (2016) 558.
[41] O. Lambina, Modular Emergency Housing, in Departmen, in: t of Steel Structures and Structural Mechanics, Politehnica University Timisoara, 2016, p. 79.
[42] The Building and Construction Authority (BCA), *Design For Manufacturing and Assembly (DfMA): Prefabricated Prefinished Volumetric Construction*, Ministry of National Development, Singapore, 2018.
[43] J.P. Cartz, M. Crosby, Modular Construction: building high-rise modular homes, Struct. Eng. 85 (1) (2007) 1–2.
[44] P.M. Lawson, et al., Robustness of light steel frames and modular construction, Proc. Inst. Civ. Eng. Struct. Build. 161 (1) (2008) 3–16.
[45] A.C. Jellen, A.M. Memari, *The State-Of-The-Art Application of Modular Construction to Multi-Story Residential Buildings* in *1st Residential Building Design & Construction Conference*, Sands Casino Resort, Bethlehem, PA, USA, 2013.
[46] Issa J. Ramaji, A.M. Memari, Identification of Structural Issues in Design and Construction of Multi-Story Modular Buildings, in *1st Residential Building Design & Construction Conference*, Sands Casino Resort, Bethlehem, PA, USA, 2013, p. 10.
[47] S. Azhar, M.Y. Lukkad, I. Ahmad, An investigation of critical factors and constraints for selecting modular construction over conventional stick-built technique, Int. J. Constr. Educ. Res. 9 (3) (2013) 203–225.
[48] L. Pham, et al., Performance framework for modular construction, in: Mechanics of Structures and Materials XXIV : Advancements and Challenges : Proceedings of the 24th Australian Conference on the Mechanics of Structures and Materials (ACMSM24), CRC Press, Perth, Western Australia, Australia, 2016.
[49] J.-S. Lee, Y.-S. Kim, Analysis of cost-increasing risk factors in modular construction in Korea using FMEA, KSCE J. Civ. Eng. 21 (6) (2016) 1999–2010.
[50] J.O. Choi, X.B. Chen, T.W. Kim, Opportunities and challenges of modular methods in dense urban environment, Int. J. Constr. Eng. Manag. (2017) 1–13.
[51] A.W. Lacey, et al., Structural response of modular buildings – an overview, J. Build. Eng. 16 (2018) 45–56.
[52] R.M. Lawson, R.G. Ogden, 'Hybrid' light steel panel and modular systems, Thin-Walled Struct. 46 (7–9) (2008) 720–730.
[53] C. Loss, M. Piazza, R. Zandonini, Connections for steel–timber hybrid prefabricated buildings. Part II: innovative modular structures, Constr. Build. Mater. 122 (2016) 796–808.
[54] A. Hassanieh, H.R. Valipour, M.A. Bradford, Composite connections between CLT slab and steel beam: experiments and empirical models, J. Constr. Steel Res. 138 (2017) 823–836.
[55] British Constructional Steelwork Association (BCSA), TATA Steel, The Whole Story, in New Steel Construction, 2011.
[56] B.A. Burgan, M.R. Sansom, Sustainable steel construction, J. Constr. Steel Res. 62 (11) (2006) 1178–1183.
[57] P. Crowther, Designing for disassembly to extend service life and increase sustainability, in: 8th International Conference on Durability of Building Materials and Components, 1999 (Vancouver, Canada).
[58] L. Aye, et al., Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules, Energy Build. 47 (2012) 159–168.
[59] J. Quale, et al., Construction matters: comparing environmental impacts of building modular and conventional homes in the United States, J. Ind. Ecol. 16 (2) (2012) 243–253.
[60] M. Kamali, K. Hewage, Life cycle performance of modular buildings: a critical review, Renew. Sustain. Energy Rev. 62 (2016) 1171–1183.
[61] H.K. Park, J.-H. Ock, Unit modular in-fill construction method for high-rise buildings, KSCE J. Civ. Eng. 20 (4) (2015) 1201–1210.
[62] ISO, ISO 668, Series 1 Freight Containers - Classification, Dimensions and Ratings, The International Organization for Standardization, Switzerland, 2013, p. 23.
[63] Standards Australia, AS 3711, 1: Freight Containers: Part 1: Classification, Dimensions and Ratings, SAI Global Limited, 2015, p. 33 (ISO 668:2013, MOD).
[64] National Heavy Vehicle Regulator (NHVR), *National Heavy Vehicle Mass and Dimension Limits*, 2016 (Australia).
[65] M.T. Gorgolewski, P.J. Grubb, R.M. Lawson, Modular Construction Using Light Steel Framing: Design of Residential Buildings, in SCI Publication P302., Steel Construction Institute (SCI): Ascot, Berkshire, United Kingdom (UK), 2001, p. 112.
[66] Steel construction institute (SCI), *Report on modular System for European residential market*, in: R.M. Lawson (Ed.), MODCONS European Funded Research Project: Development of Modular Construction Systems for High-Rise Residential Buildings, 2013, p. 160. United Kingdom (UK).
[67] H.E. Keshtkar, *Optimum Design of Earthquake Resistant Modular Structures* in *Department of Civil Engineering*, The Universeity of Michigan, 1991, p. 99.
[68] M. Sadeghinia, An Analytical Investigation into Shear Wall and Slab Interconnections between Reinforced Concrete Modules for High-Rise Buildings Utilising Modular Construction under Extreme Seismic and Wind Loading, in Department of Civil Engineering, Florida International University, 2005, p. 271.
[69] S.-G. Hong, et al., Behavior of framed modular building system with double skin steel panels, J. Constr. Steel Res. 67 (6) (2011) 936–946.
[70] T. Gunawardena, et al., Structural performance under lateral loads of innovative prefabricated modular structures, in: Bijan Samali, Mario M. Attard, C. Song (Eds.), 22nd Australasian Conference on the Mechanics of Structures and Materials (ACMSM22), CRC Press, Sydney, Australia, 2012.
[71] Steel construction institute (SCI), *Report on structural guidance*, in: R.M. Lawson (Ed.), MODCONS European Funded Research Project: Development of Modular

Construction Systems for High-Rise Residential Buildings, 2015, p. 58. United Kingdom (UK).

[72] T. Gunawardena, et al., Innovative flexible structural system using prefabricated modules, J. Archit. Eng. 22 (4) (2016), 05016003.

[73] T. Gunawardena, Behaviour of Prefabricated Modular Buildings Subjected to Lateral Loads, in Department of Infrastructure Engineering, The University of Melbourne, 2016, p. 247.

[74] K.-S. Choi, H.-C. Lee, H.-J. Kim, Influence of analytical models on the seismic response of modular structures, J. Korea Inst. Struct. Mainten. Insp. 20 (2) (2016) 74–85.

[75] Y. Ding, et al., Cyclic tests on corrugated steel plate shear walls with openings in modularized-constructions, J. Constr. Steel Res. 138 (2017) 675–691.

[76] P. Sultana, M.A. Youssef, Seismic performance of modular steel-braced frames utilizing superelastic shape memory alloy bolts in the vertical module connections, J. Earthq. Eng. (2018) 1–25.

[77] A.W. Lacey, et al., Numerical study of the structural response to wind loading: modular building case study, in: 13th International Conference on Steel, Space and Composite Structures, 2018 (Perth, Western Australia, Australia).

[78] A.W. Lacey, et al., Structural response of modular building subjected to earthquake loading, in: 13th International Conference on Steel, Space and Composite Structures, 2018 (Perth, Western Australia, Australia).

[79] C.D. Annan, M.A. Youssef, M.H. El Naggar, Analytical investigation of semi-rigid floor beams connection in modular steel structures, in: 33rd Annual General Conference of the Canadian Society for Civil Engineering, 2005 (Toronto, Ontario, Canada).

[80] C.D. Annan, M.A. Youssef, M.H. El Naggar, Effect of directly welded stringer-to-beam connections on the analysis and design of modular steel building floors, Adv. Struct. Eng. 12 (3) (2008) 373–383.

[81] C.D. Annan, M.A. Youssef, M.H. El Naggar, Seismic overstrength in braced frames of modular steel buildings, J. Earthq. Eng. 13 (1) (2008) 1–21.

[82] C.D. Annan, M.A. Youssef, M.H. El Naggar, Effect of directly welded stringer-to-beam connections on the analysis and design of modular steel building floors, Adv. Struct. Eng. 12 (3) (2009) 373–383.

[83] C.D. Annan, M.A. Youssef, M.H. El Naggar, Experimental evaluation of the seismic performance of modular steel-braced frames, Eng. Struct. 31 (7) (2009) 1435–1446.

[84] C.D. Annan, M.A. Youssef, M.H. El Naggar, Seismic vulnerability assessment of modular steel buildings, J. Earthq. Eng. 13 (8) (2009) 1065–1088.

[85] C.D. Annan, Applicability of Traditional Design Procedures to Modular Steel Buildings, in Civil and Environmental Engineering, University of Western Ontario, London, Ontario, Canada, 2009, p. 255.

[86] A. Fathieh, Nonlinear Dynamic Analysis of Modular Steel Buildings in Two and Three Dimensions, in Department of Civil Engineering, University of Toronto, 2013, p. 225.

[87] A. Fathieh, O. Mercan, Seismic evaluation of modular steel buildings, Eng. Struct. 122 (2016) 83–92.

[88] J. Jing, Seismic Damage-Resistant System for Modular Steel Structures, in Department of Civil Engineering, The University of Auckland, Auckland, New Zealand, 2016, p. 396.

[89] V.S. Shirokov, I.S. Kholopov, A.V. Solovejv, Determination of the frequency of natural vibrations of a modular building, Procedia Eng. 153 (2016) 655–661.

[90] K. Giriunas, H. Sezen, R.B. Dupaix, Evaluation, modeling, and analysis of shipping container building structures, Eng. Struct. 43 (2012) 48–57.

[91] X. Zha, Y. Zuo, Theoretical and experimental studies on in-plane stiffness of integrated container structure, Adv. Mech. Eng. 8 (3) (2016), 168781401663752.

[92] X. Zha, Y. Zuo, Finite element study of container structure under normal and high temperature, Math. Probl. Eng. 2016 (2016) 1–15.

[93] Y. Zuo, X. Zha, FEM and experimental study on mechanical property of container building with holes, Int. J. Steel Struct. 17 (1) (2017) 175–194.

[94] A. Robinson, ISBU Modular Construction and Building Design Prototypes, in Department of Civil & Building Engineering, Loughborough University, Loughborough, 2017, p. 239.

[95] Y. Zuo, X. Zha, FEM and experimental study on mechanical property of integrated container building, Int. J. Steel Struct. 18 (2) (2018) 699–718.

[96] The German Insurance Association (GDV), The Container Handbook, 2018 [cited 2018 5th July]; Available from, http://www.containerhandbuch.de/chb_e/stra/index.html.

[97] American Society of Civil Engineers and Structural Engineering Institute, ASCE/SEI 7-10: Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers, 2010, pp. 49–85.

[98] European Committee for Standardisation, EN 1990 (2002): Eurocode - Basis of Structural Design, 2002.

[99] European Committee for Standardisation, EN 1991-1-1 (2002): Eurocode 1: Actions on Structures - Part 1-1: General Actions - Densities, Self-Weight, Imposed Loads for Buildings, 2002.

[100] European Committee for Standardisation, EN 1991-1-2 (2002): Eurocode 1: Actions on Structures - Part 1-2: General Actions - Actions on Structures Exposed to Fire, 2002.

[101] European Committee for Standardisation, EN 1991-1-3 (2003): Eurocode 1: Actions on Structures - Part 1-3: General Actions - Snow Loads, 2003.

[102] European Committee for Standardisation, EN 1991-1-4 (2005): Eurocode 1: Actions on Structures - Part 1-4: General Actions - Wind Actions, 2005.

[103] European Committee for Standardisation, EN 1991-1-7 (2006): Eurocode 1: Actions on Structures - Part 1-7: General Actions - Accidental Actions, 2006.

[104] European Committee for Standardisation, EN 1998-1 (2004): Eurocode 8: Design of Structures for Earthquake Resistance - Part 1: General Rules, Seismic Actions and Rules for Buildings, 2004.

[105] Standards Australia and Standards New Zealand, AS/NZS 1170.0: Structural Design Actions: Part 0: General Principles, SAI Global Limited and Standards New Zealand, 2002, p. 41.

[106] Standards Australia and Standards New Zealand, AS/NZS 1170.1: Structural Design Actions: Part 1: Permanent, Imposed and Other Actions, SAI Global Limited and Standards New Zealand, 2002, p. 33.

[107] Standards Australia and Standards New Zealand, AS/NZS 1170.2: Structural Design Actions: Part 2: Wind Actions, SAI Global Limited and Standards New Zealand, 2011, p. 101.

[108] Standards Australia and Standards New Zealand, AS/NZS 1170.3: Structural Design Actions: Part 3: Snow and Ice Actions, SAI Global Limited and Standards New Zealand, 2003, p. 41.

[109] Standards Australia, AS 1170.4: Structural Design Actions: Part 4: Earthquake Actions in Australia, SAI Global Limited, 2007, pp. 36–42.

[110] Standards New Zealand, NZS 1170.5: Structural design Actions: Part 5: Earthquake actions – New Zealand, Standards New Zealand, 2004, pp. 5–74.

[111] American Society of Civil Engineers and Federal Emergency Management Agency, Prestandard and Commentary for the Seismic Rehabilitation of Buildings, in *FEMA 356*, Federal Emergency Management Agency (FEMA), Washington, D.C, 2000, p. 99 (3-5).

[112] Standards Australia, AS 4100: *Steel Structures*, SAI Global Limited, 1998.

[113] Standards Australia and Standards New Zealand, AS/NZS 4600: Cold-Formed Steel Structures, SAI Global Limited and Standards New Zealand, 2005, p. 153.

[114] Standards Australia and Standards New Zealand, Composite Structures: Composite Steel-Concrete Construction in Buildings, SAI Global Limited and Standards New Zealand, 2017, p. 273.

[115] Standards Australia, AS 3711.3: Freight Containers: Part 3: Corner Fittings, SAI Global Limited, 2015, p. 45 (ISO 1161: 1984, MOD).

[116] Standards Australia, AS 3711.4: Freight Containers: Part 4: General Purpose Containers, SAI Global Limited, 2015, p. 45 (ISO 1496-1: 2013, MOD).

[117] Standards Australia, AS 3711.10: F*rieght Containers: Part 10: Handling and Securing*, SAI Global Limited, 2000, p. 85.

[118] Standards Australia, AS 3850.1*: Prefabricated Concrete Elements: Part 1: General Requirements*, SAI Global Limited, 2015, p. 77.

[119] Standards Australia, AS 3850.*2: Prefabricated Concrete Elements: Part 2: Building Construction*, SAI Global Limited, 2015, p. 69.

[120] American National Standards Institute and American Institute of Steel Construction, ANSI/AISC 360-16: Specification for Structural Steel Buildings, American Institute of Steel Construction, 2016, p. 676.

[121] European Committee for Standardisation, EN 1993-1-1 (2005): Eurocode 3: Design of Steel Structures - Part 1-1, General Rules and Rules for Buildings, 2005.

[122] European Committee for Standardisation, EN 1993-1-8 (2005): Eurocode 3: Design of Steel Structures - Part 1-8: Design of Joints, 2005.

[123] R.M. Lawson, J. Richards, Modular design for high-rise buildings, Proc. Inst. Civ. Eng. Struct. Build. 163 (3) (2010) 151–164.

[124] Steel Construction Institute (SCI), Definition of requirements for acoustic design of a modular building, in: R.M. Lawson (Ed.), MODCONS European Funded Research Project: Development of Modular Construction Systems for High-Rise Residential Buildings, 2013, p. 12. United Kingdom (UK).

[125] S. Godbole, et al., Dynamic loading on a prefabricated modular unit of a building during road transportation, J. Build. Eng. 18 (2018) 260–269.

[126] G.-Q. Li, et al., Effective length factor of columns in non-sway modular steel buildings, Adv. Steel Const. 13 (4) (2017) 412–426.

[127] G.-Q. Li, K. Cao, Y. Lu, Column effective lengths in sway-permitted modular steel-frame buildings, in: Proceedings of the Institution of Civil Engineers - Structures and Buildings, 2018, pp. 1–12.

[128] R. Sabelli, T.A. Sabol, W.S. Easterling, Seismic Design of Composite Steel Deck and Concrete-filled Diaphragms, A Guide for Practicing Engineers, National Institute of Standards and Technology, Gaithersburg MD, 2011. GCR 11-917-10, NEHRP Seismic Design Technical Brief No. 5.

[129] Applied Technology Council, et al., Seismic Design of Cast-In-Place Concrete Diaphragms, Chords, and Collectors, A Guide for Practicing Engineers, second ed., National Institute of Standards and Technology, Gaithersburg MD, 2016. GCR 16-917-42, NEHRP Seismic Design Technical Brief No. 3.

[130] F. Naeim, The Seismic Design Handbook, Springer, US, 2001. XIV, 830.

[131] B.S. Taranath, Tall Building Design: Steel, Concrete, and Composite Systems, CRC Press, Boca Raton, 2016, p. 872.

[132] R.B. Fleischman, K.T. Farrow, Dynamic behavior of perimeter lateral-system structures with flexible diaphragms, Earthq. Eng. Struct. Dyn. 30 (2001) 745–763.

[133] H.J. Lee, M.A. Aschheim, D. Kuchma, Interstory drift estimates for low-rise flexible diaphragm structures, Eng. Struct. 29 (7) (2007) 1375–1397.

[134] S. Srisangeerthanan, et al., Numerical study on the effects of diaphragm stiffness and strength on the seismic response of multi-story modular buildings, Eng. Struct. 163 (2018) 25–37.

[135] Steel Construction Institute (SCI), in: B. Davison, G.W. Owens (Eds.), Steel Designers' Manual, seventh ed., John Wiley & Sons, Ltd, 2012, 1369.

[136] M. Bruneau, A. Reinhorn, Exploring the concept of seismic resilience for acute care facilities, Earthq. Spectra 23 (1) (2007) 41–62.

[137] K.-S. Park, et al., Embedded steel column-to-foundation connection for a modular structural system, Eng. Struct. 110 (2016) 244–257.

[138] A.M. Lytle, et al., Report of the NIST Workshop on Automated Steel Construction, National Institute of Standards and Technology (NIST), Gaithersburg, MD, 2002.

[139] B.V. Viscomi, W.D. Michalerya, L.-W. Lu, Automated construction in the ATLSS integrated building systems, in: 10th International Symposium on Automation and Robotics in Construction (ISARC), 1993, p. 8. Houston, Texas, USA.
[140] B.V. Viscomi, W.D. Michalerya, L.W. Lu, Automated construction in the ATLSS integrated building systems, Autom. ConStruct. 3 (1994) 35–43.
[141] D. Farnsworth, Modular Building Unit Connection System, FC+Skanska Modular, LLC, US, 2014.
[142] Vector Praxis *VectorBloc - Precision HSS Connection System for Modular Buildings*, vol. 36, 2015.
[143] Vector Praxis *VectorBloc/Atlas Tube/Connexio - Test Stack Project*, vol. 42, 2015.
[144] Vector Praxis Vector Block: ScalaCble Precision Modular Construction System, vol. 108, 2016.
[145] J. Dhanapal, et al., Structural performance of state-of-the-art VectorBloc modular connector under axial loads, Eng. Struct. 183 (2019) 496–509.
[146] A.J. Styles, et al., Effects of joint rotational stiffness on structural responses of multi-story modular buildings, in: The International Conference on Smart Infrastructure and Construction (ICSIC), ICE, 2016.
[147] D. Heather, et al., Building Modules, Verbus Limited, United States, 2007.
[148] D. Heather, Building Including a Connector System for Building Modules and Method of Constructing a Building, Verbus International Limited, Great Britain, 2008.
[149] Z. Chen, J. Liu, Y. Yu, Experimental study on interior connections in modular steel buildings, Eng. Struct. 147 (2017) 625–638.
[150] Z. Chen, et al., Experimental study of an innovative modular steel building connection, J. Constr. Steel Res. 139 (2017) 69–82.
[151] Z. Chen, et al., Research on pretensioned modular frame test and simulations, Eng. Struct. 151 (2017) 774–787.
[152] E.-F. Deng, et al., Analytical and numerical studies on steel columns with novel connections in modular construction, Int. J. Steel Struct. 17 (4) (2017) 1613–1626.
[153] E.-F. Deng, et al., Monotonic and cyclic response of bolted connections with welded cover plate for modular steel construction, Eng. Struct. 167 (2018) 407–419.
[154] J. Hwan Doh, et al., Steel bracket connection on modular buildings, J. Steel Struct. Const. 02 (02) (2017).
[155] S. Lee, et al., Verification of the seismic performance of a rigidly connected modular system depending on the shape and size of the ceiling bracket, Materials 10 (3) (2017).
[156] P. Sharafi, et al., Interlocking system for enhancing the integrity of multi-storey modular buildings, Autom. ConStruct. 85 (2018) 263–272.
[157] R. Sanches, O. Mercan, B. Roberts, Experimental investigations of vertical post-tensioned connection for modular steel structures, Eng. Struct. 175 (2018) 776–789.
[158] Y. Yu, Z. Chen, Rigidity of corrugated plate sidewalls and its effect on the modular structural design, Eng. Struct. 175 (2018) 191–200.
[159] Z. Chen, et al., Rotational stiffness of inter-module connection in mid-rise modular steel buildings, Eng. Struct. 196 (2019) 109273.
[160] X.-M. Dai, et al., Experimental study on seismic behavior of a novel plug-in self-lock joint for modular steel construction, Eng. Struct. 181 (2019) 143–164.
[161] A.W. Lacey, et al., New interlocking inter-module connection for modular steel buildings: experimental and numerical studies, Eng. Struct. 198 (2019) 109465.
[162] A.W. Lacey, et al., Shear behaviour of post-tensioned inter-module connection for modular steel buildings, J. Constr. Steel Res. 162 (2019) 105707.