



A REVIEW ON DIAPHRAGM BEHAVIOUR AND CONNECTIONS FOR MULTI-STORY MODULAR BUILDINGS

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ABSTRACT: *Modular buildings are built using prefabricated units or modules that are transported and assembled on-site. The use of volumetric modules has the potential for achieving complete building systems where on-site work can be reduced to foundation, module assembly and/or the finishing of module-to-module interfaces. However, since the use of volumetric modules for multi-story building construction is relatively new, technical, logistical and regulatory issues have been reported, which constrains its widespread use. Of the limitations identified, the absence of efficient structural systems for lateral load resistance and the lack of high-performance inter-module connectivity are believed to be key enablers for the future development and promotion of such building systems. In this paper, the characteristic requirements for inter-module connections with regard to structural and functional needs are identified and presented. An overview into few key aspects regarding multi-story modular building construction is also discussed.*

KEYWORDS: Prefabrication, Modular Buildings, Module Connections, Diaphragm Behaviour

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1 INTRODUCTION

Modular buildings are constructed using prefabricated building units or modules of various forms including linear (e.g., beams, struts and ties), planar (e.g., trusses, frames, slabs, panels and shells) and volumetric (e.g., large spacious shipping freight container-like units that are load bearing). The use of such linear and/or planar modules for the construction of multi-story buildings (MSB) has long been in practice, where the 30 story T30 hotel building and the 57 story J57 Mini Sky City building in Changsha, China, are modern day examples. Whereas, the use of volumetric modules for MSB construction has been a recent development, where the 44 story La Trobe Tower in Melbourne, Australia, the 32 story 461 Dean Street building in New York, USA and the 28 story Apex House building in London, UK, are few of such examples. Of these building technologies, those that make use of volumetric modules have the potential of being a complete building system (CBS), where the proportion of off-site work is expected to be within 60-70% of the total in terms of value and construction time savings to be within 50-60% [1].

CBSs typically rely on the use of fully finished volumetric modules that are factory manufactured, transported and assembled on-site to form multi-story modular buildings (MSMB). However, due to issues relating to lateral stability and inter-module connectivity, present systems require additional conventionally built support structures, tedious on-site assembly and major post construction finishing. A CBS that addresses the above requires adequately stiffened modules to be strategically placed within the building to form a core and rely on high-performing inter-module connectivity to assure continuous load transfer both vertically and horizontally (see **Figure 1**).

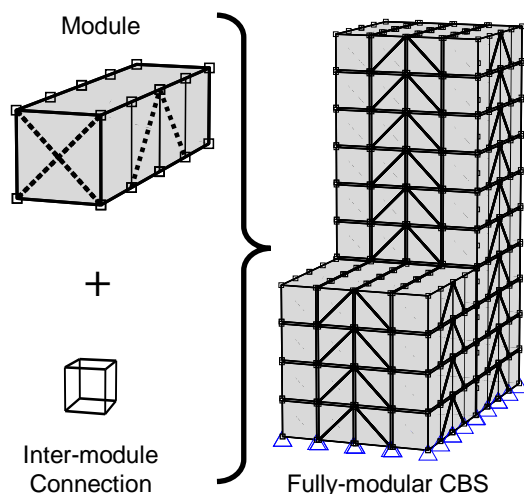


Figure 1: Components of a fully-modular CBS

It is subsequently believed that the inter-module connection system is the key enabler, and an innovative design that satisfies structural and some key functional needs, could further reduce the required on-site work saving on construction time and cost and improve on safety.

Therefore, this paper aims to provide a critical overview on the accumulated research regarding modular building construction that uses volumetric modules and focuses specifically on the technical issues of achieving adequate overall stability and high-performing inter-module connectivity. The outcomes of this paper are expected to assist in the future development and application of such fully-modular systems.

2 MSMB CONSTRUCTION USING VOLUMETRIC MODULES

2.1 ADVANTAGES AND CHALLENGES

The spatial modularisation of a building requires the formation of load bearing volumetric modules that can either be bare structural framing or fully-complete (modules with the structural framing and non-structural components intact, such as finishing, fittings and furnishings). Once dispatched from a manufacturing plant, fully complete modules need only to be assembled on-site to form complete functional buildings; hence, having great potential to be a CBS. The use of such volumetric modules, bare or otherwise, can further improve on the many reported benefits of modular construction, which are (1) reduced construction times, (2) superior overall quality, (3) efficient material and energy consumption, (4) improved occupational health and safety, (5) minimalised environmental disruption and (6) reduced overall construction costs due to mass manufacture [1-9]. However, despite these potential benefits, volumetric module use has not seen the expected widespread adoption for the construction of MSBs. It is speculated that much of this setback could likely be due to the reported technical, logistical and regulatory issues regarding volumetric module use that still plague the construction industry [1, 6, 10-14].

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 that can also handle construction tolerances, (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 parallel than sequential workflow. The regulatory issues encompass the lack of guidelines for design, manufacture, handling, transport and installation of modules including those regarding procurement, conformance, quality assurance, inspections, stakeholder responsibilities and overall project management.

This research project focuses on resolving two specific technical issues as identified, which are the lack of reliable structural systems for efficient lateral load transfer and the lack of high-performance inter-module connections.

2.2 MODULE TYPES, BUILDING FORM AND BASIC CONSIDERATIONS FOR DESIGN

Structural strength, stability and safety of MSMBs are essentially governed by module characteristics and the properties of inter-module connectivity (hereon, a module will refer to a volumetric module). Although a module can be continuously load bearing via its walls or have selective bearing via appropriately spaced columns, the latter provides for better space control and architectural freedom [1] (see **Figure 2**). Modules that are continuously load bearing are typically made of materials such as concrete or timber. Steel modules can also be continuously load bearing via the use of braced stud wall framing systems; however, they are much more versatile and can accommodate different geometric forms including hybrid configurations (steel-concrete, steel-timber, etc.) [1, 6]. Hence, steel module variants are more desirable for use and can easily accommodate a cradle-to-cradle life cycle to achieve highly-sustainable low-carbon low-embodied-energy buildings. 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 or systems that are demountable [4, 5].

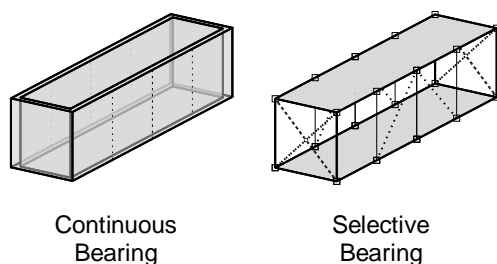


Figure 2: Typical module variants

Module dimensions and mass, on the other hand, are typically governed by transportable size and mass limits. The largest ISO freight container (approx. 2.8 m in height, 2.4 m in width and 13.7 m in length) is indicative of guaranteed transportable size limits, yet, there is preference towards using modules that are 4 m in height and width and 16 m in length. 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. Different states or territories, however, may have permitted different specific allowances [15]. Nevertheless, regardless of size, these modules are to be stacked vertically and scaled horizontally to form MSMBs. Depending on the location of modules within the building, they should have suitable strength and self-stability with sections appropriately sized, intra-module connections designed sufficiently rigid and module floor, ceiling and wall panels or frames adequately stiffened as required. Typically, modules that would form parts of the lateral force resisting system (LFRS) would require stiffened walls, moment resistive frames or braced frames having simple intra-module connectivity. Whereas those that would form other parts of the building, such as to form gravity frames, can be made entirely with simple intra-module connectivity provided that efficient diaphragm action can be guaranteed for stability when under the influence of lateral loads.

Such lateral loads generally relate to both wind as well as regional seismicity, and only a limited few have researched the effects of these on the performance of MSMBs [16-23]. Among these, the works of Annan *et al.* relate to the seismic performance assessment of braced frames in modular steel buildings [24], those of Fathieh *et al.* relate to an overall seismic performance assessment [25] and those of John Jing relate to the development of a seismic damage resistant system [26].

However, with regard to relevant loads and/or load combinations, 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, when afflicted by the loss of a part, the entire module or a group of modules. Other crucial considerations typically include (1) the influence of eccentricities due to manufacturing and construction tolerances which result 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 (consideration of double-skinned systems), (4) achieving adequate fire resistance (incorporation of multiple layers of fire resistant materials and proper containment or other robust technologies) (5) the integration as well as modularised connectivity of services [1] and (6) the design of modules and attached non-structural components for transportation and handling [27].

Nevertheless, upon determining forces and moments through a global analysis, module elements and intra-module connectivity may be designed in accordance with existing codes of practice. In the context of Australasia, load evaluations could be undertaken in accordance with the standard 1170 for permanent, imposed, wind, snow and seismic loads [28-33]; whereas, the design of steel modules and hybrids could be in accordance with 4100 for structural steel [34], 4600 for cold-formed steel [35], 2327 for composite structural systems [36] and parallels drawn from 3711 for shipping freight containers [37-40] along with 3850 for prefabricated concrete elements [41, 42].

3 DIAPHRAGM ACTION IN MSMBs

3.1 GENERAL BEHAVIOUR OF MSMBs

Most MSMB configurations can easily resist gravity loads similar to a tower of shipping freight containers [43]. However, the resistance of lateral loads pose a challenge due to the lack of continuous rigid systems for both efficient load transfer in the horizontal plane and adequate drift resistance in the vertical plane.

A generic MSMB form is considered for demonstration with the peripheral frames assumed to be braced (see **Figure 3**). Through this model, it is evident that spatial modularisation results in vertical (lateral force resisting and gravity frames) and horizontal (diaphragms) structural systems of the building being discretely connected and discontinuous. Overall building behaviour is consequently affected by both module and inter-module connection stiffness. Inadequacies in either one of them could result in excessive relative movement between modules and module deformation. Therefore, any 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.* [44] 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, where different hybrid systems and materials would result in different module stiffness values.

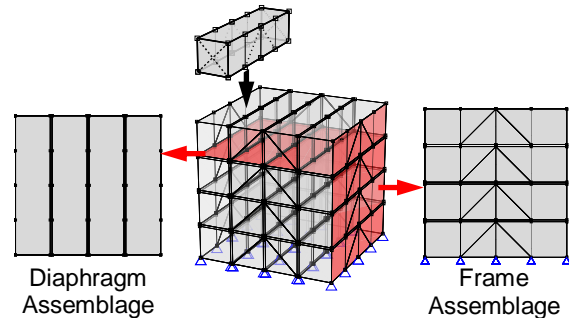


Figure 3: Discontinuities in key structural systems

3.2 BEHAVIOUR OF DIAPHRAGMS

Diaphragms are crucial for the transfer of lateral loads to the LFRS and serve a secondary purpose of being able to tie vertical elements at each story. Conventionally, for buildings with cast in-situ slabs or with concrete filled metal decking, diaphragms are idealised as rigid continuous systems, provided that they have no prescribed irregularities (discontinuities, holes, etc.) and have span-to-depth ratios suitable to the lateral loading cases considered [45, 46]. Such rigid diaphragms tend to distribute lateral loads based on the relative stiffness of the building's LFRS in the absence of torsional effects and gravity frames displace to approximately the same extent of the LFRS due to being held together by the diaphragm [47, 48]. However, not all diaphragms are free from irregularities and fit this rigid idealisation. Classification of diaphragms, as currently prescribed, is more specifically based on the ratio between maximum diaphragm displacement relative to the LFRS and the corresponding average inter-story drift of the LFRS. For an expected rigid diaphragm behaviour, this ratio is to be less than 0.5, for flexible diaphragm behaviour greater than 2.0 and for all values in-between, the diaphragm is considered stiff [32, 33, 45, 49]. Flexible continuous diaphragms, on the other hand, closely resemble the behaviour of simply supported beams, where lateral load distribution is approximated by tributary portions of the diaphragm rather than relative stiffness of the LFRS [47, 48].

This could likely be the case when considering diaphragms of MSMBs due to the consequences of modularisation. These diaphragms are essentially assemblages of discretely connected systems, where behaving rigidly or flexibly as a whole depends substantially on the stiffness of the inter-connectivity, even though the connected units/modules have an influence as well. If these are not carefully considered, the lack of diaphragm

stiffness may result in increased gravity frame drifts inducing second-order effects and potential diaphragm failure, leading to loss of building stability and the likelihood of collapse. Furthermore, when under the action of seismic loads, buildings with flexible diaphragms are likely to encounter higher mode effects, which are essentially the out of phase diaphragm motions from the LFRS. These could result in large unconservative drifts and consequential loss of stability which could lead towards collapse as well [50, 51].

Such effects have been demonstrated in a recent study through nonlinear time history analyses of a MSMB having perimeter LFRS and flexible diaphragms [52]. It was also found in this study that current seismic codes do not provide for the required force nor ductility demand when even a similar MSMB with rigid diaphragms was subjected to strong ground motions scaled to a specific 500 and 2500 year design earthquake. This urges the need to conduct more detailed studies into the seismic behaviour of MSMBs, especially for conditions or regions of moderate to high seismicity. Furthermore, there is a need to look into energy dissipative technologies for MSMBs so that modules can be economically preserved for continued use or reuse after an extreme event. 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, which include strength, stiffness and ductile capacity, have significant influences on the overall strength, stiffness, stability and safety of structures. Additionally, the number of connections affect overall cost and erection time, which includes ~20-40% on material costs and ~60-80% on labour costs for design, fabrication and erection [53]. Forces acting on connections are determined by undertaking a global analysis of the considered structure, where connection stiffness typically governs overall force distribution, and connection ductility could economically provide for additional safety in scenarios of overloading.

Typical framing connections are beam-to-beam, beam-to-column, column-to-column, column-to-foundation and those for bracings. Beam-to-beam connections can be between two mutually perpendicular or parallel beams, where the latter enables composite sections and improves overall capacity as well as deflection control. Similarly, column-to-column connections can be between inline or adjacent columns. Conventionally, such connections made of steel would be held 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 are crucial to achieve any required rigid, semi-rigid or pinned connection behaviour as characterised by the degree of moment resistance they provide. However, due to being less labour intensive to both fabricate and assemble, pinned or simple connections are commonly preferred.

The construction of MSMBs would also require a multitude of such basic connections and they can all be broadly grouped as intra-module, inter-module or foundation. **Figure 4** identifies few such connections within a simple stack of modules. Intra-module connections are those that assist in forming the structural frames of modules; whereas, inter-module connections are those that form the key structural systems of the building by enabling both vertical and horizontal inter-connectivity of modules. Foundation connections, on the other hand, are essentially support connections either on to a strong transfer frame or any conventional foundation.

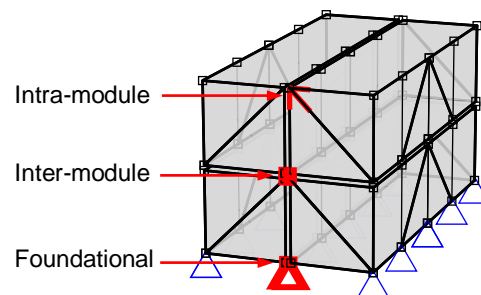


Figure 4: Key structural connection groups in MSMBs

4.2 PERFORMANCE REQUIREMENTS FOR INTER-MODULE CONNECTIONS

In general, it is expected that intra-module connections would provide the required module stiffness and foundation connections would facilitate the efficient transfer of loads effectively to the ground. Simple connections are preferred for intra-module connectivity and any conventional system 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 [54]. Furthermore, intra-module and foundation connections are less likely to influence the outcome of MSMB projects, since intra-module connections would be completed off-site and foundation connections require only a one-off on-site work.

Inter-module connections, on the other hand, are likely to have a profound influence as they affect the assembling of modules. 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 functional needs.

These identified functional needs require inter-module connections to be (1) remotely operable, where they do not require direct external or internal access for assembly thereby improving on safety and avoiding the need for access holes which can lead to undesirable localised effects, (2) simple in functionality, by having an integrated design that is capable of either automatic or semi-automatic function and requires only a few set of tools for operation, (3) scalable, so that modifications can be done easily to accommodate varying load demands and section sizes without the need for rigorous analysis, (4) capable of handling tolerances, so that reasonable amounts of manufacturing and construction tolerances can be accommodated to counter out-of-verticality and out-of-horizontality, (5) easily demountable, so that relocating and/or replacing modules to comply with future demands or if damaged under extreme events is less complicating and (6) capable of mass manufacture, by having simple easily manufacturable components that can be integrated.

5 CONCLUSIONS

MSB construction using volumetric modules has many benefits. However, to further maximise its use, certain limitations have to be addressed. Of these limitations, those that relate to achieving efficient lateral load resistance and robust high-performance tolerance-tolerant inter-module connectivity are believed to be crucial.

Efficient lateral load resistance requires the formation of rigid continuous systems both vertically and horizontally. This greatly depends on the stiffness of modules and inter-module connections. Appropriate analytical and numerical models should be used to approximate actual behaviour so that forces and moments can subsequently be determined for design.

Although any inter-module connectivity can be accordingly designed to meet structural demands, it is believed that only automatic or semi-automatic connections have the potential to address certain functional needs. The addressing of these needs could further reduce construction time, improve on-site safety and reduce overall costs by being mass manufacturable. Such complete building systems that are fully-modular are capable of achieving

construction automation goals and would fall in line with the industry 4.0 initiative.

Furthermore, preserving modules during transport and whilst they are being handled as well as ensuring robustness against disproportionate and/or progressive collapse, are other key technical areas for further study.

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