LOW CARBON LIVING CRC

RP1031

Development and optimisation of low-carbon, affordable, medium-rise modular structural system using innovative connections

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Title	Development and optimisation of low-carbon, affordable, medium-rise modular structural system using innovative connections
ISBN	
Date	
Keywords	Prefabrication, Modular Buildings, Inter-Module Connections
Publisher	CRC for Low Carbon Living
Preferred citation	

SWINBURNE UNIVERSITY OF TECHNOLOGY

Australian Government
Department of Industry, Innovation and Science

Business Cooperative Research Centres Programme

Acknowledgements

This research is funded by the CRC for Low Carbon Living Ltd supported by the Cooperative Research Centres program, an Australian Government initiative.

The authors also acknowledge the generous support extended by project partners AECOM, Bluescope, Multiplex, Hassell and the Victorian Building Authority (VBA).

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The author(s) confirm(s) that this document has been reviewed and approved by the project's steering committee and by its program leader.

Contents

List of Tables

List of Figures

Acronyms

CBS	Complete Building System
FEA	Finite Element Analysis
LFR	Lateral Force Resisting
LFRS	Lateral Force Resisting System
LVDT	Linear Variable Differential Transducer
MSB	Multi-Story Building
MSMB	Multi-Story Modular Building
OSM	Off-Site Manufacturing
UTM	Uniaxial Testing Machine

Executive Summary

Due to the increasing rates of urbanisation and the ever growing urban population, it is inferable that the demand on multi-story construction industry will continue to increase. In Australia, having an urban population of approximately 21 million, equivalent to 90% of the total population, the construction industry is a key driver and contributes to approximately 7.8% of the country's GDP in value added terms, where issues regarding quality control, reduced workplace productivity, onsite safety, skilled labour shortages, rising costs and environmental impacts are of great concern.

Aligned with Industry 4.0, the new era for automation in construction promotes on shifting from traditional on-site construction and design for prefabrication and modularization. This may provide the best set of tailored solutions to address the above-mentioned issues in a time and cost efficient manner. Particularly, modular construction would deliver significant reductions in embodied energy as well as operational energy through optimal use of materials, labour and technology.

Although the use of prefabricated volumetric components such as fully-completed modules have been successfully introduced to low-rise construction, its application beyond low-rise forms is still a challenge and yet to achieve a fully-modular status. The identified limitations in utilising modules for such cases are the lack of high-performance connections that provide efficient horizontal and vertical load transfer and lack of guidelines addressing overall design, handling of modules and erection of modular buildings. Further, very few research works have looked into the extreme load performance of modular buildings and have satisfactorily captured the behaviour and influence of individual modules and their connections on overall system-level building response.

This study aims to address this urgent need by conducting a comprehensive study on performance requirement of modular buildings under service/extreme loads and accordingly develop an innovative structural connections for modular connection. This report presents the outcomes of this study, which was done through a multi-institutional collaborative research project between Swinburne University of Technology, Melbourne University and the industry partners AECOM, Bluescope, Multiplex, Hassell and the Victorian Building Authority (VBA).

In this report, a systematic study 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.

An entirely new concepts for inter-module connectivity is then proposed. A preliminary assessment on overall functionality and structural conformance via simplified kinematic and finite element models is performed. Model development and kinematic checks are done using the software AutoDesk Inventor, whereas preliminary finite element analyses are undertaken using the software ANSYS.

Upon having verified the functionality of the prototype connector and its expected structural behaviour, it is then opted for experimental verification and proof of concept validation. Therefore, a series of static load tests are planned for determining the factor of safety in design and to evaluate the actual load bearing capacities and deformability when under service and ultimate loads. The loading represents the forces generated in the connector when it serves as part of horizontal and vertical load resisting systems within a modular building. Finally, the study is extended to investigate the dynamic loads experienced by modular units during transportation.

The outcomes of this comprehensive study are expected to provide quantum improvements on the current modular construction industry through fast on-site assembly, in-life adaptation to service/extreme loads, post-life disassembly, and affordability. This will assist in the future development and application of fully-modular superstructure construction systems for multi-story modular buildings.

General Introduction

In a global context, there are many issues faced by the construction industry and these have been extensively reported in literature [1-5]. Typically these issues relate to, (1) the access of skilled labour, (2) work safety, (3) construction productivity, (4) construction efficiency, (5) construction quality, (6) project duration, (7) project cost, (8) construction related environmental impacts, (9) weather effects on construction, (10) on-site emissions, (11) building operational efficiency and (12) building end-of-life use or re-use. These issues are still being addressed today, despite the introduction of prefabrication technology many decades ago.

Prefabrication or off-site manufacturing, relies on the factory manufacture of building units [6, 7]. These units can be of the typical linear (e.g., beams, struts and ties), planar (e.g., trusses, frames, slabs, panels and shells) or of the more challenging volumetric form (e.g., load bearing units that enclose finished or un-finished space and are analogous to shipping freight containers). The use of linear and planar units have long been in practice and it consequentially follows that they would still require considerable on-site work with respect to the assembly of units into structural forms, constructing additional structural systems for lateral load resistance and spatial finishing. However, it was not until a few decades ago, that the potential benefits of using volumetric building units was realised and sporadic developments for its application soon begun in regions of Europe, USA and Japan.

A volumetric building unit can be defined as an off-site manufactured structural framing unit that encloses fully-, partially- or un-finished space. These units are more favourably referred to as modules and the construction of buildings using such units is known as modular building construction (hereon any reference to module or modular construction is based exclusively on the use of volumetric building units). The numerous benefits of modular building construction have since then been widely documented. However, due to a few challenges faced in design, construction, logistics and regulation, fully-modular superstructure construction was mostly deemed suitable for low-rise building construction (a superstructure typically refers to the entire region of a building that is above ground- or foundation-level). This restriction was eventually overcome through hybrid construction techniques involving both modular and conventional methods, and mid- to high-rise buildings were soon realised and successfully built. 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 of such exemplary buildings [8-10]. The use of such hybrid modular and conventional technologies are currently at the forefront of revolutionising multi-story building (MSB) construction, and henceforth, it can be inferred that a fully-modular mid- to high-rise building superstructure construction system which is independent of any conventional methods could potentially be the most beneficial among all.

Therefore, with the aim of contributing towards the realisation of a fully-modular mid- to high-rise building superstructure construction system, this project was focused on addressing two key technical limitations which encompass overall structural performance and general building assembly, for which conventional methods have since been relied upon for resolving. It was evidentially found that the key limiting factor was widely reported to be the lack of a standardised scalable high-performance inter-module connector that can cater to any required structural performance level and can simplify on-site module assembly.

On the aspect of one-site module assembly, upon factory manufacture and delivery of modules, they need only to be assembled on to foundations or strong frames and on to themselves, and have module-to-module interfaces finished as required. This considerably reduces on-site work and potentially on-site work related emissions in comparison to buildings built via conventional or hybrid methods. Moreover, the added enhanced quality pertaining to the insulation of a finished space contained within a module further improves the operational efficiency of a fully-modular building with respect to its operational energy demand, and could potentially reduce operational emissions as well. It further follows that the crucial enabler of such an ideal construction, would be the inter-module connection, where it would have to be not only safe to engage, but also reliable and simple in functionality.

On the aspect of structural performance, any assembled multi-story modular building (MSMB) would have vertical and horizontal structural systems that are discretely connected due to modularisation, and the overall structure may well be lacking in the required overall stiffness and strength than what typically would be expected. The overcoming of such lapses in stiffness and strength is typically achieved by integrating additional load transferring systems through conventional means which entails site-intensive work. Therefore, to overcome the need for rectification via conventional means, the performance of a MSMB requires to be carefully studied, where it can be said that the overall building performance would exclusively be governed by the characteristics of modules and inter-module connections. Requirements for strength and stiffness are collectively met by both modules and connections, and they should both be capable of providing basic life-safety when under the action of extreme events such as earthquakes, cyclones or other potential hazards. However, arguably, inter-module connections may prevail as the most critical component, since a widespread practice exists where modules are assumed or made appreciably rigid.

Therefore, working towards addressing these identified key limitations, this report proposes and presents a high-performance inter-module connector. The Identified essential performance requirements and the overall structural response studies including prototyping and testing of the proposed connector are key highlights of this report.

Key literary findings

MSMB Construction

Advantages and Challenges

Modular construction, as mentioned, relies on fully fabricated fully finished volumetric units, made under factory conditions, which are then transported to a site to be assembled into complete structures or buildings enabling stackable and scalable open spaces. Key *benefits* of modular construction are as identified below.

- Due to OSM, superior quality can be achieved due to implementation of better quality control methods [8, 11, 12] achieving a greater degree of reliability, where also highly efficient thermal and acoustic insulation is achievable as well as enhanced fire safety due to the likely double-skin nature effectively isolating modules.
- Modular construction methods can significantly reduce construction time (30~50% than traditional methods [12], adoption of prefabrication can reduce construction time by 20% [11], Hickory building systems reduced construction time by 50% [13]).
- Advanced manufacturing technologies as those adopted by the automotive industry can lead to energy efficient production as well as efficient use of materials which results to waste reduction, where the factory environment enables efficient recyclability and reduced on-site waste, where also the need for skilled workmanship is reduced (the Hickory building system produces 90% less waste than conventional systems [13]).
- Due to controlled working conditions and implementation of high quality control methods, improved occupational health and safety can easily be expected both off-site and on-site (on-site safety greatly improved with reports of upto 80% reduction with respect to reported accidents [14]).
- Disruption to the surrounding environment is significantly reduced including the reduction of pollution and is less impacted by weather or climatic changes.
- Mass producing modular units of similar form can bring about an Economy of scale (repetitive manufacture) which can result to reduced construction costs (up to 10% [15]) and increased profitability to the industry, where also benefits such as reduced interest charges due to early "start-up" are realised [14].
- Deems to be highly suited where site constraints may exist for deliveries regarding traditional methods and thus improves site productivity significantly (can overcome many on-site constraints in construction [16] and could improve productivity up to 50% [15]).
- Can easily be made to accommodate any alterations or extensions especially concerning with stacking and future demand variations (renovations can be done easily and is highly adaptable for future needs retaining asset value when modules are reused).

The following can be considered as *technical limitations* associated with modular construction.

- Lack of on-site self-aligning high performance connections for limited access assembly.
- Maximum module size is limited by transport limitations of size and mass, where also the lack of robust structural systems to connect modules to provide for large column free spaces limits architectural versatility.
- Module construction should allow for effects due to transportation (the requirement of transport vibration spectrum), handling and installation considering vibration, shock and impact loads at such stages (where walls should have adequate in-plane strength to act as bracing and also sufficient lateral strength to resist accidental damage)
- Inability to provide robust lateral load resistance against increased wind and earthquake loads without using concrete/steel structural cores for medium to high-rise modular buildings, hence unable to achieve a fully modular construction [for modular residential buildings upto 25 storys requires a structural core and for such tall modular buildings the clustering of modules around a core or alternatively be connected to braced corridors which in turn are connected to such structural cores could be adopted for stability [14]].
- The need to consider manufacturing tolerances (dimensional variations) and on-site erection tolerances (vertical and horizontal tolerances) in the design of modules accounting for their overall influence on the building as well as the inability of modules to withstand large stack pressures due to limitations of the material or framing element geometry.
- Difficulty in customisation of interior architecture and skins due to limited non-versatile shapes resulting from the lack of large open spaces due to small module sizes.
- Limited utilisation of hybrids of new and existing materials which offer optimum structural and environmental benefits due to incompatibility with connectivity to module framing as well as for effectively accounting for lateral load transfer.
- Limited integration between structural and non-structural components.
- Requires high capital costs to setup manufacturing facilities and the fixed cost of such manufacturing facilities could be as high as 20% of the total building cost, where also a significant

portion of work (as high as ~55%) even for highly modular projects takes place at sites leading to costs as much as 30% of that of the whole building [14].

- When considering high-rise modular buildings, the authors Cartz and Crosby [17], list the following as key structural challenges faced for the construction of the modular building, Paragon, in London
    - Overall stability had to be provided by conventional concrete shear cores and steel columns
    - Designing to prevent disproportionate collapse
    - Differential movement between the structural core and modules required to be handled by connections and additional horizontal bracings
- The following are relevant challenges facing the modular construction industry as extracted from the works of Jellen and Memari [18],
    - Modular construction projects have physical constraints such as the acceptability of using the dimensionally constrained 3d modules, accessibility for crane systems and module delivery, successful transportation of modules and the availability of a modular facility within reasonable distances.
    - Need for standardisation across the industry for cost-effective design and standard dimensions
- A few key technical limitations as identified by Torre et al [19] are as indicated below.
    - Need for additional material due to the structural requirements of modules and the need for additional bracing for overall structural strength, stability and stiffness as well as stability against transportation loads, thus resulting to an increase in costs.
    - The requirement of redesigned connections having increased capacities.
    - The need for additional construction effort in areas such as planning & scheduling, design & engineering, procurement, fabrication, inspection, transportation, handling and erection.
    - The need for additional coordination of activities due to the increase of interdependent construction activities, especially when modules are fabricated and assembled at various locations and since work takes place in parallel than in series (the authors highlight the works of.
    - Increased cost due to additional man hours required for design and engineering of a modular construction project, procurement (20%), fabrication (17%) and transportation (13%, 1-2% of module value due to requiring specialised methods and insurance). Also, the first modular construction project could be 50-60% more than a conventional design if done well.
    - Increased Risk due to utilizing non-qualified engineering & construction firms, encountering module loss & module transport damage, having improper project management, encountering problems with fabrication shops, encountering engineering & procurement problems and by an "all eggs in one basket" approach.
    - Reduced adaptability to design changes due to many interdependent design features and construction activities.
- A few key hidden costs and other disadvantages relating to prefabrication technology as extracted from the works of Smith [20, 21] are as follows,
    - Overhead due to full-time employment of staff and facilities costs
    - Savings made on time and labour may not be felt by the client as offsite fabricators would charge more than general contractors to a make a profit as well as cover overhead costs
    - Transportation per unit volume is much higher for prefabrication than compared to tightly packed onsite-erected materials and products
    - Skilled staff for erecting buildings using prefabricated components is required especially when considering the operation of cranes for module installations
    - Design fees can be excessive due to greater requirement of coordination between design, fabrication and construction teams due investment of time.
    - Structural bulkiness hence reduction in clear floor heights
    - Transportation restrictions limit module and panel size
    - Design spans and configurations are somewhat restricted
    - Flexibility and changeability of structure through future renovations becomes more difficult

However, despite the above technical limitations associated with modular building construction, Torre, Sause [19] suggest the following key *recommendations* for the further advancement of modular construction.

- The development of new modules, constructed facilities and suitable construction equipment.
- Prefabricating extensive 3-dimensional modules for building frame systems rather than 1-dimensional (beams, columns, braces, etc.) or 2-dimensional components.
- Increase the use of onsite self-aligning connections.
- Reduce the number of onsite connections.
- Being able to create innovative modular building frame designs within the limitations of available transportation methods.
- Increasing modularisation by integrating service systems (electrical, mechanical, plumbing, insulation, etc.) and building frame systems at fabrication stage.
- Developing new building frame systems specifically for exploiting onsite preassembly methods.
- Increasing the standardisation of required structures and creating more complete standardised modules

Therefore, despite the need to resolve all challenges, this research project is focused on two of the key technical issues identified, which pertain to the lack of high-performance inter-module connections and the lack of reliable structural systems for efficient lateral load transfer.

Module Types and Restrictions

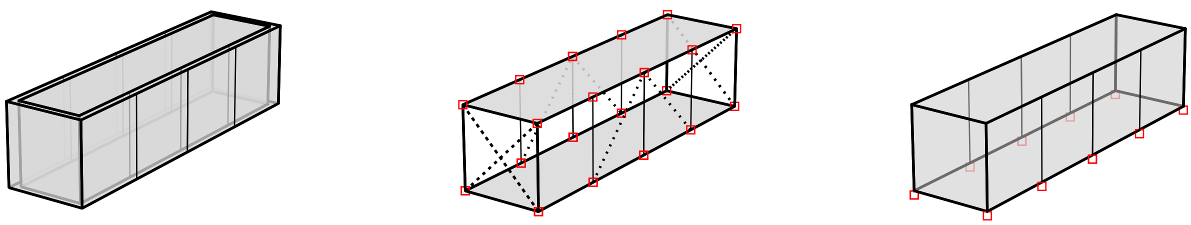
When considering the structural behaviour of modules, they can either be made continuously load bearing via its walls or have selective bearing via appropriately spaced columns or be non-load bearing pods which require pre-constructed structural systems prior to installation (see **Fig. 1**). However, space control and architectural freedom is best achieved through the use of modules with selective bearing [12, 22].

Continuously load bearing modules are typically made of concrete or timber. Modules of precast concrete are often used for high-security applications, as they are extremely resistant to damage and normally contain reinforced concrete walls and slabs which would form the roof of one module and the floor for the other above. Modules of timber framing had seen its use in temporary and relocatable shelters and single- or two-story residential buildings. Modules of steel framing can be deemed to be the most versatile and can be made continuously load bearing via the use of braced stud wall framing systems or be of selective bearing, and can also accommodate different geometric forms including hybrid configurations (steel-concrete, steel-timber, etc.) [12, 20, 23-26]. Hence, steel module variants are likely to be more desirable and can easily achieve a cradle-to-cradle life cycle to achieve highly-sustainable low-carbon low-embodied-energy buildings [27, 28]. Furthermore, specific studies have shown that modular construction, especially of steel framing, has numerous benefits covering the social, economic and environmental dimensions of sustainability [29-32]. Moreover, the use of pod-like modules, of any material form, though averts the need to tackle the key technical issues of MSMB construction using load bearing modules [33], it cannot reap the full benefits of the targeted fully-modular building superstructure construction system which is independent of any conventional methods.

On the other hand, module dimensions and mass are typically governed by transportable size and mass limits. The largest ISO freight container (approx. 2.9 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 much larger. Furthermore, 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 specific restrictions may apply for the various different states [34]. Moreover, it is crucial to consider the restrictions imposed by cranes due to limitations on lifting capacities, hence on-site locations of cranes requires careful strategic planning. Therefore, in-light of these restrictions, steel and steel hybrid (such as steel-concrete or steel-timber) modules are most suited to meet transportable mass limits in comparison to modules made only of concrete due to steel and steel hybrids having comparatively large strength-to-weight ratios. Furthermore, the structural framing of steel or steel hybrid modules are easily optimisable to achieve desired complementary stiffness-to-weight ratios as well.

Building Forms and Basic Design Considerations

To form MSBs, continuously or selectively load bearing modules and/or combinations of both would have to be stacked vertically and scaled horizontally, and numerous architectural forms are possible and have been



(a) (b) (c)

Figure 1: Typical module variants, where (a) continuous bearing (b) selective bearing (c) pod-like.

demonstrated in literature [35, 36]. However, the location of a module within an assembly would eventually dictate the required strength and self-stability of that module, where subsequently its sections would have to be appropriately sized, framing connections made sufficiently rigid or simple and floor, ceiling and wall panels or frames be sufficiently stiffened.

Typically, modules that would form parts of the lateral force resisting system (LFRS) would require stiffened walls, moment resistive frames or braced frames with appropriate connection stiffness. Whereas those that would form other parts of the building, such as to form gravity frames, can be made with simple module framing connections provided that efficient diaphragm action is achievable to guarantee stability when under the action of lateral loads which generally relate to wind and regional seismicity.

Furthermore, only a limited few have researched the effects of lateral loads on the performance of MSMBs [37-46] and among these, the works of Annan *et al.* cover the seismic performance assessment of braced frames in modular steel buildings [47-53], those of Fathieh *et al.* relate to an overall seismic performance assessment [54, 55] and those of John Jing relate to the development of a seismic damage resistant system using a slider device [56]. Other examples involve Shirokov *et al*. who have attempted to determine the natural vibration frequencies of modular buildings, where a single story building having rigid inter-connectivity was considered for the study [57]. However, it is believed that there is potential to extend this work to include MSMBs, where semi-rigid interconnectivity and module behaviour are incorporated for more representative outcomes. Moreover, research work into the analysis, design and application of shipping freight containers for building construction are equally valuable and would prove to be vastly helpful in establishing performance characteristics for modules and inter-module connections [58-64].

When considering the design of modular buildings, the relevant loading and load combinations may be taken from Australian standards such as AS/NZS 1170.1 for permanent, imposed and other actions, AS/NZS 1170.2 for wind actions, AS/NZS 1170.3 for snow and ice actions and AS 1170.4 for earthquake actions in Australia [65-70]. Furthermore, it is essential to consider appropriately factored scenarios of,

- Permanent and imposed loads for critical vertical load effects
- Lateral loads and permanent loads for critical lateral load, load reversal and uplift effects
- Lateral, permanent and imposed loads for potentially more critical vertical load effects than when only permanent and imposed loads.
- Extreme or Accidental loads such as those imposed by cyclones, earthquakes and other potential hazards, which include also the assessment of overall robustness against disproportionate or progressive collapse, where the effects of the loss of a part, the entire module or a group of modules are considered.

Lawson et al have highlighted the issues of robustness and have demonstrated the use of finite element methods to evaluate the robustness of MSMBs [12, 71].

Therefore, upon determining the design actions through structural analyses (which maybe linear-elastic, non-linear or based on target performance levels), module elements and module framing connections may be designed in accordance with existing codes of practice exercising great care in evaluating conformance. The design of steel elements of modules (corner posts, edge beams, joists, ceiling panels and floor panels) and intra-module connections (panels to corner posts, panels to joists, joists to edge beams and edge beams to corner posts) may be undertaken using AS/NZS 4100 [72] for steel structures and AS/NZS 4600 [73] for cold-formed steel structures as well as other relevant standards mentioned therein. Furthermore, the following are considered as key factors to be taken into account in the design of high-rise modular buildings as extracted from the works of Lawson and Richards [74],

- Influence of eccentricities/construction tolerances (taking into account maximum permitted tolerances for manufacturing and construction out of verticality and horizontality, where inter-module connections capable of accommodating such are preferred).
- Application of design standards for steel buildings to modular technology using notional horizontal forces (the notional horizontal force is suggested to be taken as 1% of the factored vertical load acting on each module and is further suggested to be use in combination with wind forces).
- Second-order effects resulting from sway-stability of group of modules, especially for the design of corner columns
- Mechanism of force transfer of horizontal loads to the stabilising system (where horizontal forces maybe transferred via tension and compression in the ties between modules by utilising diaphragm action of the base and ceiling of modules).

Other reported design concerns are on, [12, 74-76],

- The attaching of non-structural components, such as the building façade and other cladding material.
- The achievement of adequate acoustic and thermal performance, in consideration of double-skinned systems, structurally insulated panels, vacuum insulated panels, etc.
- The achievement of adequate fire resistance, via the incorporation of multiple layers of fire resistant materials and proper seals, containment or other robust technologies.
- The integration as well as modularised connectivity of services.
- The design of modules, including attached non-structural components, for transportation and handling

It should be noted that parallels can further be drawn from AS3711 [77-80] for shipping freight containers along with AS3850 [81, 82] for prefabricated concrete elements. Similarly, standards of other countries are respectively applicable therein, and the overall performance of a MSMB should be comparably the same or better than that of its similar conventional building form.

Achieving Efficient MSMB Construction

Some studies have looked into key aspects that could impact the overall efficiency and feasibility of modular building projects. The outcomes of these studies can greatly assist architects, engineers and project managers to make design as well as managerial decisions. Some of the key works are by Tatum *et al* [6, 83, 84], Fisher *et al* [85, 86], Torre *et al* [19], Gibb [7], Lawson *et al* [12] and Smith [20]. Others cover, (1) the optimum spatial design of MSMBs [87], (2) near optimum selection for module configuration by evaluating a unified indicator that accounts for on-site connections, transportable module size and mass limits, transportation distances, crane costs and foundation concrete volumes [88], (3) achievable trade-offs between module fabrication costs and certain project related risks by incorporating dimensional and geometric tolerance strategies during structural analysis [89], (4) the logistics of crane selection and optimisation of its on-site location for increased productivity as well as shorter lifting schedules [90] and (5) the successful implementation of BIM for the structural design of complicated MSMBs [91].

Structural Behaviour of MSMBs

Force Resistance 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 rigid 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 the vertical (lateral force resisting and gravity frames) and horizontal (diaphragms) structural systems of the building to be discretely connected and essentially discontinuous (see **Fig. 2**). Overall building behaviour is consequently affected by both module and inter-module connection stiffness, where inadequacies in either one could result in excessive module deformation and large relative movement between modules. 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.* [92] 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 would yield different stiffness values and is best if accounted for.

Behaviour of Diaphragms

Diaphragms are crucial for the transfer of lateral loads to the LFRS and serve also a secondary purpose of being able to tie 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 (discontinuities, holes, etc.) and satisfy the required span-to-depth ratios for the lateral load being considered [93-95]. 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 [96, 97]. 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 corresponding average inter-story drift of the LFRS (see **Fig. 3**). For an expected rigid diaphragm behaviour, this ratio is expected to be less than 0.5, whereas for flexible diaphragm behaviour greater than 2.0 and for all values in-between, the diaphragm is considered stiff [69, 70, 93, 98]. Flexible continuous diaphragms, on the other hand, closely

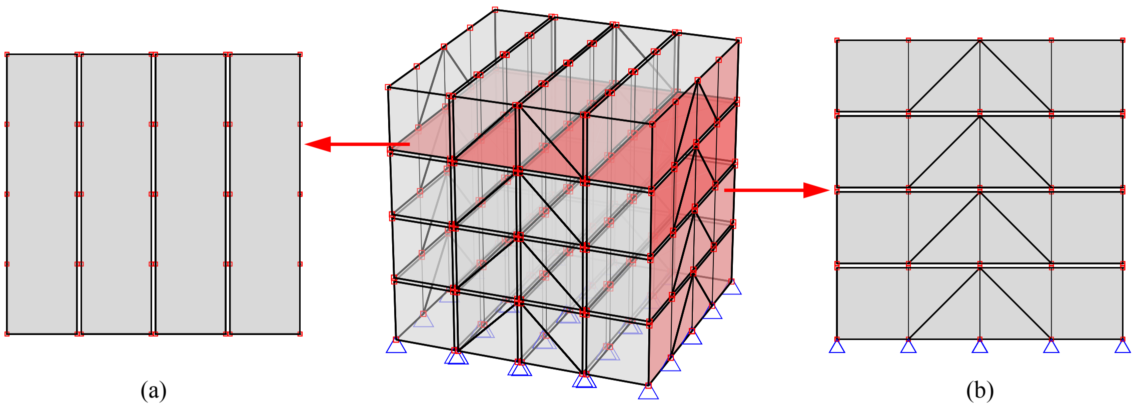
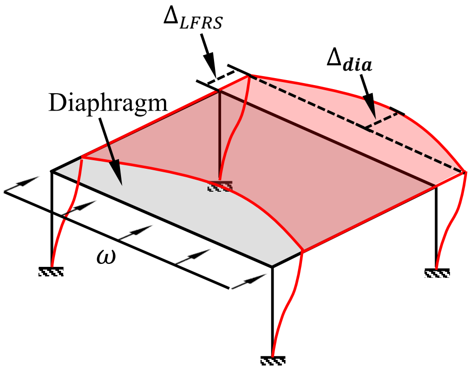


Figure 2: Demonstrative model depicting (a) the diaphragm assemblage (b) lateral-force-resisting-frame assemblage.



$\Delta_{dia} \leq 0.5\Delta_{LFRS}$ ⟶ Rigid diaphragm
$0.5\Delta_{LFRS} < \Delta_{dia} \leq 2.0\Delta_{LFRS}$ ⟶ Stiff diaphragm
$\Delta_{dia} > 2.0\Delta_{LFRS}$ ⟶ Flexible diaphragm

Figure 3: Prescribed conditions for diaphragm classification.

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 [96, 97].

Therefore, it is likely that modularisation of a building could result in the prevalence/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 inter-connectivity, and partly by the stiffness of the connected module floors and ceilings which impart an influence as well (this influence is often neglected via rigid body assumptions). If these 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, which are essentially the out of phase diaphragm motions from the LFRS. These could result in large drifts and consequential loss of stability which could lead towards collapse [99, 100]. 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 [101]. It was also found in this study that current seismic codes do not provide for the required force nor ductility demand for even the MSMB variant with diaphragms of rigid behaviour which was subjected to strong ground motions scaled to specific 500 and 2500 year design earthquakes (design basis earthquake and maximum considered earthquake, respectively). This urges the need to conduct more detailed studies into the seismic behaviour of MSMBs, especially for regions with moderate to high seismicity.

Connections in MSMBs

General Features

For a general steel structure or building, it is well known that the mechanical properties of connections have significant influences on the overall strength, stiffness and stability, where the number of connections influence the overall cost as well as erection time [20-40% on material costs & 60-80% labour costs (from design to erection)]. General steel connections are made of steel elements that are either bolted together (in-expensive and simple) or welded together (more expensive, complex and requires careful inspection), where it is expected that connections would have comparable properties to that of the steel used in terms of strength, stiffness and ductile capacity. For adequacy in strength, forces on connections requires to be determined through a global analysis of the structure, where connection stiffness governs force distribution and ductility provides for safety in scenarios of connection overloading.

If the use of bolts are progressed further, depending on elemental orientation (direct elemental connectivity or through web cleats, flange cleats, end plates, flange plates, T-sections, etc.) and the nature of loading, bolts will either be subjected to axial forces [tension (pull-out) or compression], transverse shear forces (via bearing on connected plates) or combined axial and shear forces (for moment resistance). In general practice for static loading, it is recommended that non-preloaded bolts be used (bearing type connections) due to the additional procedures required for preloaded bolts (slip resistant connections) which add to costs, however for dynamic loading the contrary is recommended. Furthermore, weak zones within the connection which can cause local yielding or local buckling may decisively govern the overall load resistance of the connection. Linear-elastic analysis is generally used for connection design, however non-linear analysis maybe undertaken in consideration of load-deformation characteristics of all components of the connection.

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. Moreover, 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.

In multi-story modular buildings, connections can be classified into three different groups based on the purpose of their use. Connections that enable the fabrication of modules are termed as "intra-module connections". Connections that enable the assembly of modules are termed "inter-module connections" and can further be sub-divided as 2-column connections or type-A (typically between external open corners and longitudinal edges of modules), 4-column connections or type-B (typically between external closed corners and internal longitudinal edges of modules) and 8-column connections or type-C (typically between internal closed corners of modules). Connections that enable the transfer of forces to foundations or strong frames are termed, "foundation connections". **Fig. 4** identifies the various connection types observable within a simple stack of modules.

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. The structural properties of inter-module connections will affect the overall response of MSMBs as they play a key role in forming essential vertical and horizontal structural systems for load resistance, where if within gravity frames, the connections can have decoupled vertical and lateral load transfer mechanisms whereas when forming the LFRS, they require coupled vertical and lateral load resistance. 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.

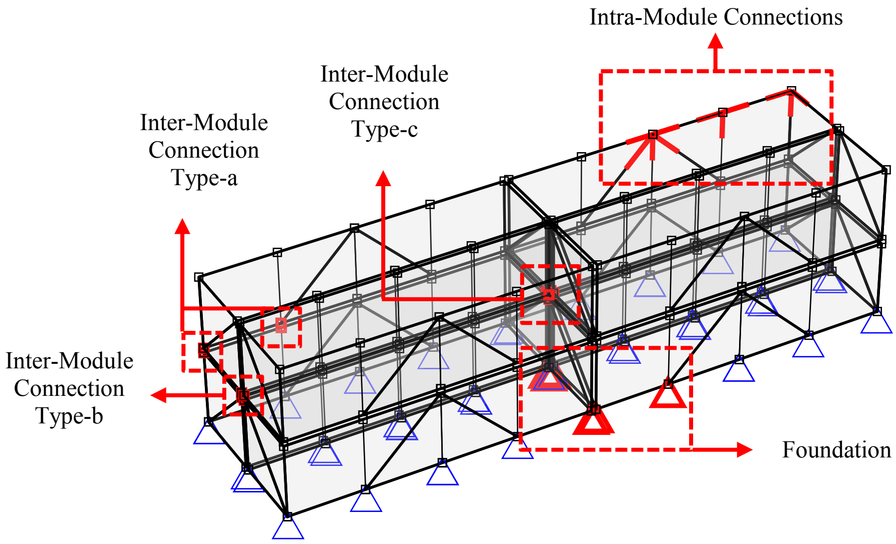


Figure 4: Key connection groups.

Performance Requirements

In general, it is expected that intra-module connections would account for module integrity and contribute towards achieving the required module strength and stiffness. Whereas, foundation connections would facilitate the efficient transfer of loads effectively to the ground or to transfer frames. Simple connections are preferred for intra-module connectivity and any conventional method is applicable. If modules are to form gravity frames, intra-modular connections can be simple shear connections, whereas if modules are to form lateral force resisting frames, then either moment resistive or shear with connections for bracings are required. 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.* [102]. 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 a one-time only on-site work which focuses on securing the first layer of modules to receive all subsequent layers.

On the other hand, inter-module connections are likely to have a profound influence as they affect the on-site

The structural requirements for inter-module connections would entail their capability to provide force and moment resistance as well as adequate stiffness along and about the three key principle directions, where (1) vertical axial resistance in tension and (2) diaphragm axial as well as shear resistance are crucial.

Manufacturing requirements relate to inter-module connections having (1) less unique components, (2) geometrically simple components and (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.

Constructional/functional 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 to position modules, (2) remotely operable, where they do not require access through modules nor require access holes to be provided on framing elements which can lead to undesirable localised effects and the need for additional strengthening, (3) simple in functionality, by having an integrated design that is capable of either automatic or semi-automatic function via mechanisms and enabling quicker assembly with less operations, effort, labourers and tools, (4) easily demountable, so that relocating and/or replacing modules to comply with future demands or if damaged during assembly or under extreme events, (5) capable of being integrated within or onto framing elements to minimise the non-usable space between modules, (6) scalable, so that modifications can easily be done to accommodate varying load demands and section sizes and (7) capable of handling tolerances or enforcing tolerance control, so that reasonable amounts of manufacturing and construction tolerances can be accommodated to address out of verticality and horizontality during module assembly.

Inter-module connection systems

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 for the future development of such systems applicable to MSMB construction, **Table 1** presents those that are currently available or relatable and briefly describes some of their apparent and/or reported features. It is inferable from these systems that the current state-of-the-art for inter-module connectivity is commonly achieved through the use of bolted or welded assemblies that have several un-integrated components and require comparatively labourious on-site work for module assembly. Although these systems can be made to fulfil structural demands, most may fail at satisfying the manufacturing and constructional/functional requirements.

Summary

It is evident through the surveyed body of literature that MSMB construction not only has many advantages but also some challenges. These challenges can broadly be grouped as being technical, logistical or regulation related. Though each group has a set of issues that are vital and requires resolving, this project focuses on those that are technical in nature.

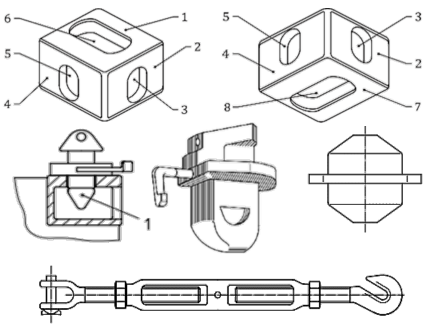
Among the many identified technical issues, the incapability to form reliable structural systems without additional conventionally built support structures, especially for lateral load transfer, is a critical concern. The formation of MSMBs using gravity and LFRS modules would result in structural systems that are discretely connected, therefore lacking in rigidity. Under the action of lateral loads, apart from having to account for module deformation, there would be relative movement between modules as well. If adequate module and inter-module connection stiffness and strength could be provided, desired performance levels for MSMBs may be achieved. Therefore the structural performance of MSMBs needs to be investigated and the output would be the required levels of stiffness and strength for both modules and inter-module connections.

Another key limitation pertains to the lack of simple high-performance inter-module connections. It is well known that the level of connection complexity and number will affect cost (material and labour) and erection time. Therefore, there is a need to develop and use connections that are simple in both design and functionality. A typical MSMB, has three identifiable varieties for inter-module connections, where a type-a connection would only require to establish vertical connectivity, whereas type-b and type-c would require to establish both vertical and horizontal connectivity. Structural performance requirements for these connections comprise of the need to have adequate stiffness and strength in tension, compression and shear for efficient diaphragm action and drift resistance. Furthermore, simple, quick, safe and cost effective connectivity requires certain manufacturing and functional/constructional needs to be fulfilled. If inter-module connections were to have several unintegrated components, as in generic bolted or welded assemblies, much labour and time would be required to engage connectivity. Such generic connections would also require direct access through modules and, in some cases, access holes to be provided on framing elements, where additional cost for localised strengthening would be incurred. Furthermore, avoiding complex configurations and having less unique components (preferably two or three) or designing for the integration of components, could achieve quick and easy manufacture via cheaper manufacturing techniques. Making use of mechanisms and being capable of remote operation could yield a quick and safe assembly process as well. Gravity assisted locking using the weight of modules could prove ideal, however innovations are required for un-locking capabilities. Moreover, the ease in demounting enables rapid relocation of modules to avoid impending hazards and easy replacement if damaged. Nevertheless, the survey on existing systems has revealed the current state-of-start and will help identify fundamental aspects that can be combined and/or improved upon to develop an inter-module connection that is easily manufactured and satisfies structural and functional/constructional needs. Therefore, innovations in inter-module connectivity are required and the output would be high-performance inter-module connection concepts.

It is important to verify any claimed functional superiority and test to understand the actual behaviour of any proposed inter-module connection concept. Material and geometric inconsistencies, unknown component interactions and environmental conditions can all have an effect and can never comprehensively be accounted for at the developmental stage. Connection stiffness, strength, ductile capacity and failure modes in tension, compression and shear are vital to understand mechanical behaviour. Furthermore, a calibrated finite element model can reveal the state of stress at inaccessible regions and can be used to perform a parametric study for design optimisation such that connection weight is minimised while staying within allowable stresses and displacements. Therefore, prototyping and testing is crucial and the outcomes would be the actual mechanical properties of the connection and a calibrated finite element model that could assist in developing guidelines for connection use such that both module section compatibility and demand are satisfied.

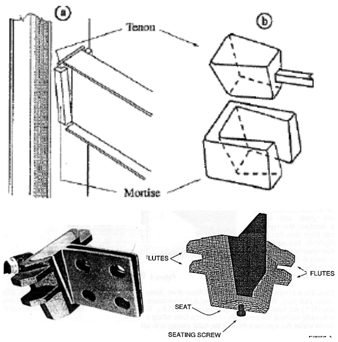
Table 1: Existing systems for inter-module connectivity.

<table>
<tr><th>Connection</th><th>Description</th></tr>
<tr><td>ISO corner casting and securing systems [78, 80]


</td><td>Vertical connectivity is provided by a variety of mechanical connectors, namely via twist-locks and latch-locks. Manual and semi-automatic variations of these connectors exist. The geometric form and slot type holes enable easy alignment.

Horizontal connectivity is provided in conjunction with stacking cones, tensioning devices and lashing rods, chains or wires secured to strong frames.

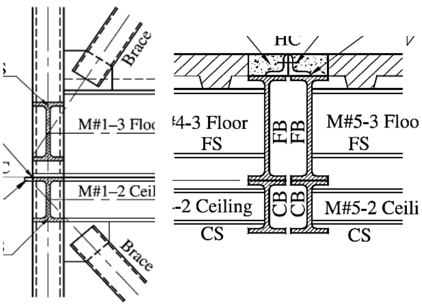
All systems act through the corner castings of containers.</td></tr>
<tr><td>ATLSS beam-column connection [103, 104]



</td><td>Horizontal connectivity and possibly tying can only be provided, and it is through a tenon, mortise and seating screw system. The geometric formation of the tenon and mortise can provide gravity assisted aligning of modules.

Though it is used as a beam-column connection capable of full to partial moment resistance, the concept can be applied to connect the columns of adjacent modules thereby ensuring lateral connectivity.

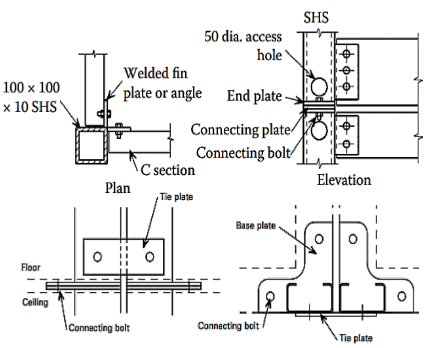
Vertical connectivity, however, requires conventional means through either an end plate and bolt assembly or a connecting bolt or rod.</td></tr>
<tr><td>Annan [52]



</td><td>Vertical connectivity is provided 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 floor beams of adjacent modules. Cast in place concrete is applied over the connection sealing it.

Robustness or tying maybe provided by the series of bolts clamping the clip angles of adjacent module floor beams.</td></tr>
<tr><td>Lawson et al. [12, 74]

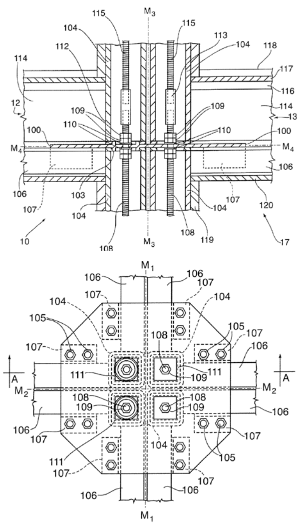


</td><td>Vertical connectivity is provided via a connecting bolt that clamps the column end plates of each stacked module together. The presence of access holes may require localised strengthening of framing elements.

Horizontal connectivity is provided via a base plate secured to the edge 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.</td></tr>
</table>

Farnsworth [105]

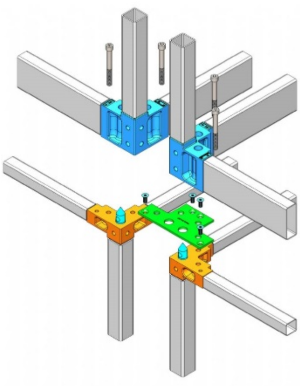


Vertical connectivity is provided by threaded tension rods which are passed through within the columns of each module. The rods also pass through sleeves which are secured at the location of transfer plates and are also coupled to each other for continuity.

Horizontal connectivity is provided via a transfer plate which is secured through welded connector/fin plates onto the edge beams of adjacent modules. The transfer plate includes geometric formations that assist in module alignment during assembly.

Robustness or tying maybe provided by the transfer plate.

VectorBloc™ tall modular building system [106-109]

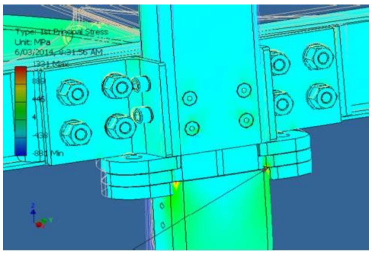


Vertical connectivity is provided through the securing of corner castings via a bolted assembly. Conical guides can be attached onto the casting to assist in module alignment during assembly.

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.

Hickory Building System [8]

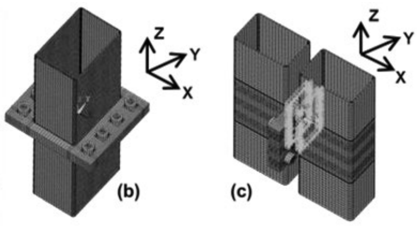


Vertical connectivity is provided through a bolted assembly securing the column end plates of each stacked module. Geometric formations are present to assist in the alignment of modules during assembly.

Horizontal connectivity and tying maybe provided by an additional bolted assembly using transfer or tie plates.

However, 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.

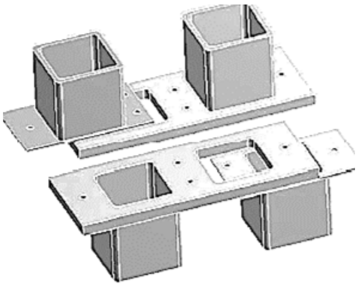
Styles *et al*. [110]



Vertical connectivity is provided through a generic column-column connection using bolts (a simple column end plate connection).

Horizontal connectivity and tying are provided between adjacent columns of modules via a bolted assembly using side plates.

Gunawardena [42]

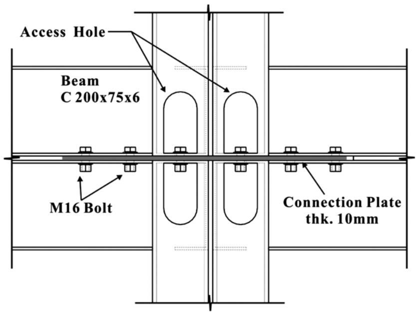


Vertical connectivity is provided by a bolted assembly that secures column end plates of different sizes.

Horizontal connectivity is provided by the combined set of column end plates that are secured to each other.

Robustness or tying maybe provided by this combined set of end plates as well.

Choi *et al*. [111]

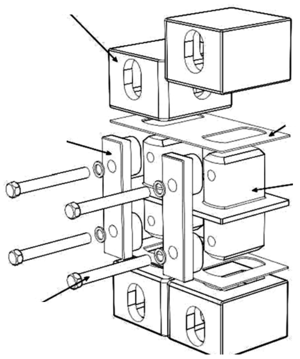


Vertical connectivity is provided by clamping the column end plates of each stacked module together through bolts. The presence of access holes may require localised strengthening of framing elements.

Horizontal connectivity is provided via a connection transfer plate secured to the flanges of both the floor and roof beams of adjacent modules via bolts.

Robustness or tying maybe provided via the transfer plate.

Robinson [62] (a proposed concept)

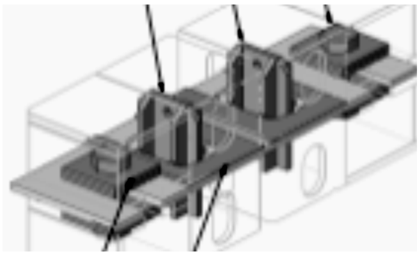


Vertical connectivity is provided by securing standard ISO corner castings through an assembly having a double spigot casting connector (similar to the ISO stacking cone fittings), lock-down plates with spigots and bolts. The spigots may guide modules during assembly.

Horizontal connectivity is via the transfer plate of the primary double spigot casting connector.

Robustness or tying maybe provided through the transfer plate.

Buro Happold (Robinson [62])

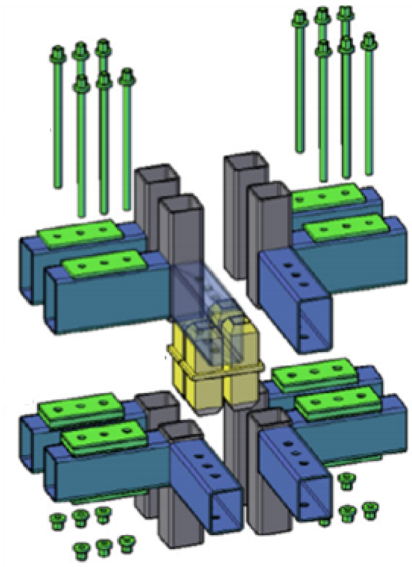


Vertical connectivity is provided via bolts. A double spigot casting is fit onto modified ISO corner castings and maybe capable of guiding modules during assembly.

Horizontal connectivity is via the transfer plate and load transfer will be through the plate via interactions with the spigot as well as bolts.

Robustness or tying maybe provided by the transfer plate.

Chen et al bolted assembly [112, 113]

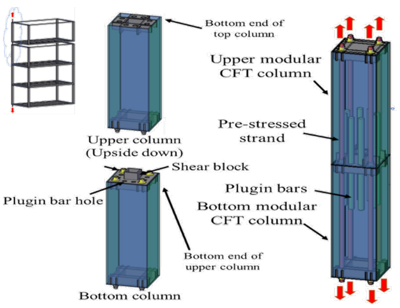


Vertical connectivity is provided by a bolted assembly that secures the floor beam of a module to the roof beam of the one below. The assembly makes use of long stay bolts, cover plates and intermediary plates. The plug-in device inserted into the hollow column sections can function to align modules during assembly. The holes drilled onto the framing elements may result in unwanted localised effects.

Horizontal connectivity is provided through the 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.

Robustness maybe provided through the interaction of the plug-in device with the hollow column sections and the device's transfer plate.

Chen et al, pre-stressed assembly [114]

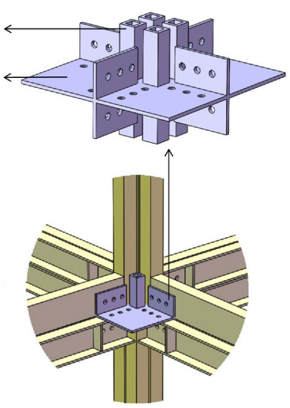


Vertical connectivity and racking resistance for a stack of modules can only be provided, and it is through the securing of pre-stressed strands between stiffened sealing plates at the ends of columns along with the use of plugin-bars and shear blocks. The shear blocks facilitate the alignment of modules 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.

Horizontal connectivity between modules requires to be provided and the securing of a transfer plate maybe a suitable option.

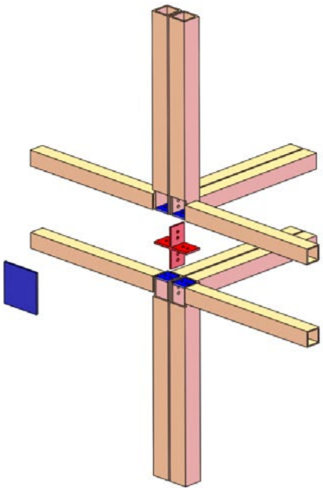
Deng et al [115]



Vertical and horizontal 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 adjacent modules. The cones maybe capable of aligning modules during assembly. The holes drilled onto the framing elements may result in unwanted localised effects and may require stiffening.

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.

Deng et al, welded cover plate [116]

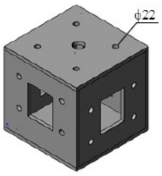


Vertical connectivity is provided through an arrangement of bolts and a cruciform gusset plate. The column elements have been cut-out to facilitate access and may result in unwanted localised effects. A plate is proposed to be welded, covering the access cut-outs and sealing the connection. Achieving this detail for an internal connection maybe tedious or unlikely.

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.

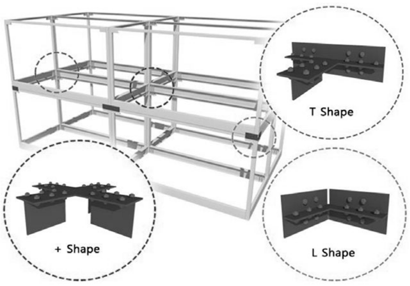
Doh et al [117]



Vertical and horizontal connectivity is provided by securing a proposed corner casting through an assembly of bolts.

Robustness or tying maybe achieved through the proposed assembly of bolts.

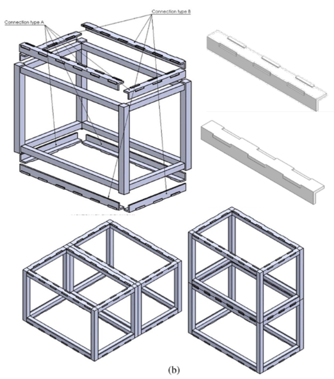
Lee et al [118]



Vertical and horizontal connectivity as well as robustness or tying is provided through a bolted assembly and a singular component made of vertical and horizontal plates.

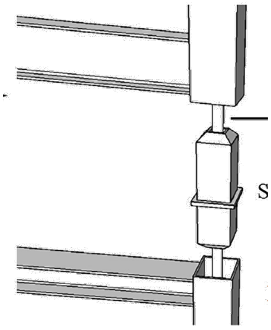
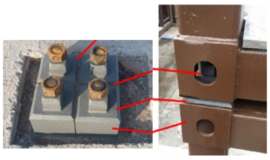
The system connects the web and flanges of both roof and floor beams of adjacent modules.

Sharafi et al [119]



Vertical and horizontal connectivity is claimed to be provided by a tongue and grove system that is attached to the floor and roof beams of modules.

However it seems that the system may not be capable of resisting vertical tension, which is crucial for providing overall moment resistance.

Sanches *et al.* [120] 	Vertical connectivity is provided through the post 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 proposed to be via a typical bolted side plate connection between adjacent columns. 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. The steel box may interact to provide additional resistance as well.
Yu *et al.* [121] 	Vertical connectivity is provided between corner fittings via a single connecting bolt, similar to the concept of the ISO corner casting and connecting systems. Horizontal connectivity is via an intermediate plate that is welded on to the corner fittings. Robustness or tying maybe provided through this intermediate plate

Behaviour of Key Structural Systems

Introduction

This section describes the work undertaken to study the behaviour of vertical and horizontal structural systems in MSMBs. Current hybrid modular construction practices, rely on conventionally built vertical structural systems made either of concrete and/or steel to form shear walls, moment resistive frames and/or braced frames. For such a scenario, off-site manufactured modules are typically gravity framed modules. Gravity framed modules lack the ability to resist lateral forces, and hence require to be connected to a LFRS, which is the conventionally built shear wall, moment resisting frames or braced frames. The structural system that restricts the lateral movement of gravity frames to that relative to the LFRS at every floor level, is the diaphragm. The design of diaphragms for MSMBs, is not as straightforward as that of conventional diaphragms. Conventional diaphragms would typically be idealised as in-plane rigid continuous bodies, however care is exercised to identify any prescribed irregularities which may result in the loss of in-plane rigidity [93, 94, 96, 122]. Whereas, diaphragms of MSMBs are inherently more flexible as they are formed by the discrete inter-connectivity of modules, and the overall behaviour would be governed by the stiffness of the diaphragm connections and the modules themselves. In current modular construction practices, the lack of diaphragm stiffness is overcome by having concrete floors and concrete wet or stitch joints to achieve continuity and satisfactory in-plane rigidity. This results to increased on-site work and imposes restrictions on the level of pre-on-site-delivery-finish achievable for modules. Therefore it is identified that the stiffness of diaphragms in modular buildings is a crucial concern for both hybrid modular construction technologies and the proposed fully-modular building superstructure construction systems. Diaphragm failure due to lack of stiffness and strength would result in a catastrophic building failure due to the loss of stability among gravity frames.

Methodology

The first step was to identify the structural performance factors that affect diaphragm stiffness. These were considered to be diaphragm connection axial and shear stiffness (referred to as diaphragm connection stiffness) and modular floor and/or ceiling cassette shear and flexural stiffness (referred to as module horizontal-plane stiffness).

The second step was to establish a method to determine the service stiffness of diaphragms in MSMBs relating all key governing parameters. This was approached analytically and numerically.

The third step was to study the influence of different diaphragm service stiffness values on the overall behaviour of MSMBs. A case study MSMB was considered and having classified its diaphragms as being either entirely rigid, stiff or flexible, its performance was assessed against lateral loads, especially earthquake loads.

The forth step was to evaluate design strategies for diaphragms in MSMBs. Extreme cases of loading were considered to asses overall performance and quantify the required levels of force and ductility amplification for diaphragm connections.

The software OpenSees [123] was used to develop numerical models and conduct the necessary analyses in conjunction with MatLab. Case study building designs were undertaken using ETABs.

Case Study MSMB and Numerical Models

General Description

The case study MSMB was assumed to be a four-by-four-bay four-story modular building built using 16 modules of $16\ m$ length, $4\ m$ width and $4\ m$ height, where each module was assumed to be connected to each other at five discrete locations which were along the length of each module. The inter-module horizontal spacing was kept at $0.1\ m$ and the inter-module vertical spacing was neglected assuming that module floor and ceiling cassettes would rest one on top of the other and that the combined floor and ceiling cassette would function in unison to respond to external loads. Furthermore, the modules were assumed to be made of steel and the LFRS made of braced frames along the perimeter of the building. The case study building is shown in **Fig. 5**. A 2D numerical model of a diaphragm and a simplified 3D numerical model, both of the case study building were generated to establish a method to determine diaphragm service stiffness and to explore the influence of diaphragm stiffness on the building's seismic response, respectively.

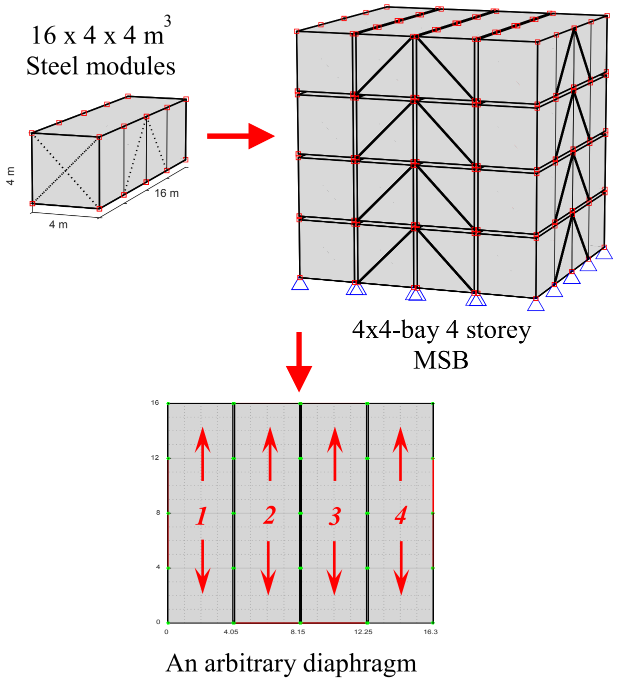


Figure 5: Considered case study building.

2D Numerical Model of Diaphragm

The 2D numerical model was developed considering a single row of modules and the inter-connections between those modules, where the modules were reduced to their combined floor and ceiling units. To accommodate the in-plane stiffness contribution from diaphragm connections, two-node link elements were used. The axial and shear stiffness of the two-node link element were considered representative of the diaphragm connection axial (k_A) and shear (k_V) stiffness and were assigned linear-elastic force-deformation behaviour. To accommodate the in-plane stiffness contribution from modules, zero-length rotational springs were used. The rotational spring stiffness (k_R) was considered representative of the combined module floor and ceiling unit's shear stiffness and were assigned linear-elastic moment-rotation behaviour. Furthermore, for the purpose of this demonstration, diaphragm connection axial and shear stiffness values were assumed to be the same for simplicity. The developed numerical model is shown in **Fig. 6**, where the individual effects of each key component on the overall diaphragm deformation, Δ_{dia}, when under the action of a uniformly distributed diaphragm load (ω) is also shown, where Δ_f and Δ_s are respectively the axial and shear deformation of diaphragm connections, and Δ_m is the in-plane shear deformation of modules.

3D Numerical Model of the Case Study Building

The 3D numerical model was developed in consideration of reducing computational demand for conducting nonlinear time history analyses. Key simplifications were, (1) the exclusion of gravity frames in the model, (2) the combining of floor and ceiling units of adjacent modules into one representative floor unit that was rigid in itself with respect to its horizontal in-plane stiffness and (3) the LFRS was reduced to a member providing vertical connectivity and a representative vertical in-plane shear resistance. These assumptions were reasonable since the study was focused on the diaphragms and their influence on overall response.

Similar to the diaphragm representation in the 2D numerical model, diaphragm connections were represented by two-node link elements. The simplified LFRS members were represented by two-node link elements as well. Additionally, mass nodes were assigned at the centre of each combined floor unit and the peripheral nodes of each unit were rigidly restrained to their respective mass nodes. This enables each floor unit to behave rigid independently. The mass nodes were assigned a combined floor and ceiling mass of 15 tonnes except at the roof level, where they were assigned 7.5 tonnes. The LFRS shear stiffness was determined by matching the fundamental period of the simplified structure to that of the actual case study building, and was assigned an elastic-perfectly plastic force-deformation behaviour. The corresponding yield strength and yield deformation were all based on the outcomes of a seismic design using the New Zealand seismic design code [70], where the selection of New Zealand was due to the country being located in a region of high seismicity and enables studying the response of MSMBs under low-to-moderate and high-seismic forces.

The developed 3D numerical model of the building is shown in **Fig. 7**.

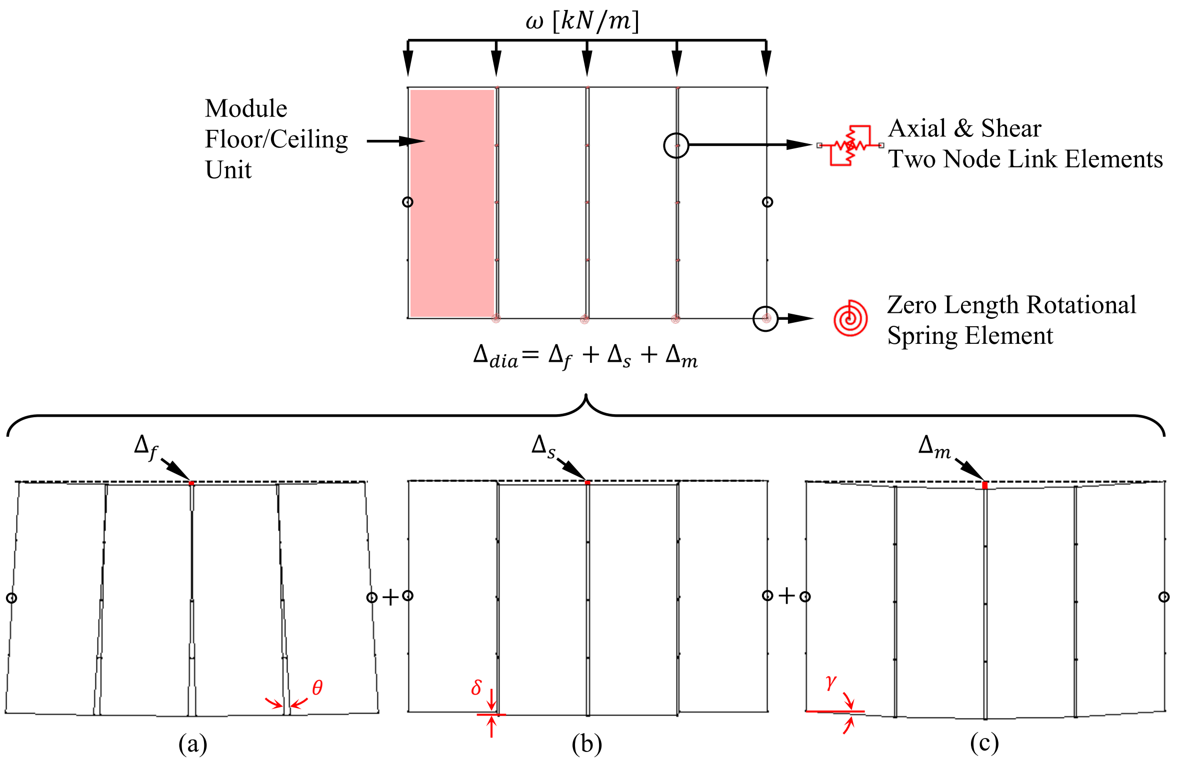
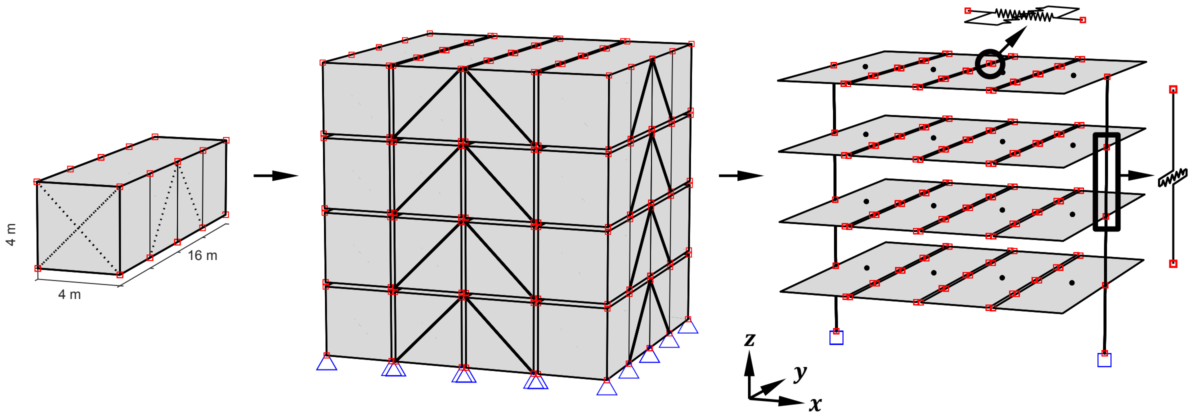


Figure 6: The developed numerical model of the arbitrary diaphragm with its components of deformation when the governing stiffness is (a) connection axial (b) connection shear (c) module shear.



(a) (b)

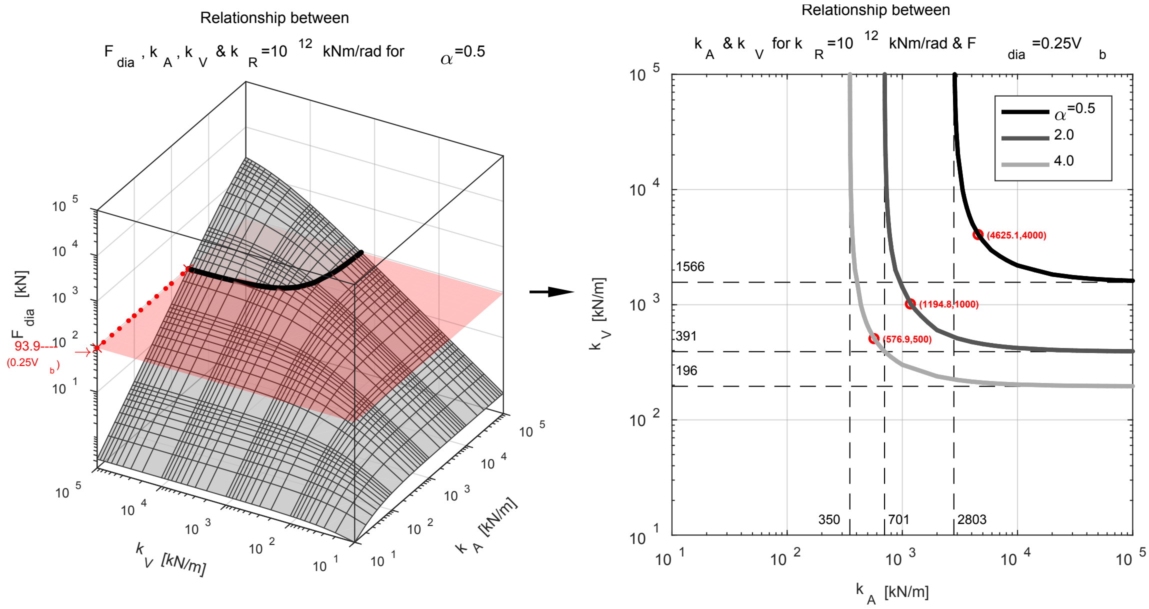
Figure 7: 3D numerical model of the case study building for diaphragm influence studies.

Outcomes

Establishing Diaphragm Service Stiffness

Using the 2D numerical model of the diaphragm from the case study MSMB, the process of establishing diaphragm service stiffness is briefly explained as follows. For various combinations of axial (k_A), shear (k_V) and rotational spring (k_R) stiffness values, the diaphragm was pushed till a target displacement was reached and the corresponding force read. The target displacement was based on the prescribed conditions shown in **Fig. 3** for achieving a specific diaphragm behaviour of being either rigid, stiff or flexible.

For each prescribed limiting case, the outcomes were a series of surface plots relating diaphragm connection and module stiffness to the total diaphragm design force determined from the applied uniformly distributed lateral load ($F_{dia} = \omega l_d$; $\omega =$ magnitude of uniformly distributed load and $l_d =$ total length of diaphragm span). This is demonstrated for the arbitrary case where the expected behaviour was to be rigid as shown in **Fig. 8(a)**. It is derived from these surface plots that for a particular horizontal in-plane module stiffness and a particular diaphragm design force, a range of corresponding diaphragm connection stiffness values would prove viable to satisfy the prescribed limiting case for the targeted diaphragm behaviour. This is demonstrated in **Fig. 8(b)** when considering a rigid limiting behaviour for the overall diaphragm ($\alpha = 0.5$), a representative module horizontal in-plane stiffness of $k_R = 10^{12}\,kN.m/rad$ and a diaphragm design force of $F_{dia} = 93.9\,kN$. The range of corresponding diaphragm connection stiffness values for the limiting cases where the overall diaphragm would be stiff ($\alpha = 2.0$) and flexible ($\alpha = 4.0$) are also shown in the



(a) (b)

Figure 8: (a) Surface plot for the case $\alpha = 0.5$ and $k_R = 10^{12}\,kNm/rad$ (b) the limiting range of connection stiffness values (k_A and $k_V\,kN/m$) for $F_{dia} = 93.9\,kN$ for the cases of $\alpha = 0.5$, 2.0 and 4.0.

same figure, **Fig. 8(b)**. Any pair of diaphragm connection stiffness values (k_A and k_V) on a limiting curve or within its bound region would satisfy the corresponding diaphragm stiffness condition being targeted.

This procedure helps in predefining the required diaphragm connection stiffness when undertaking the process for developing new innovative diaphragm connections or modifying existing ones to meet stiffness requirements. Typically, under the action of wind loads, the diaphragm is expected to be rigid and though a similar scenario of rigid behaviour can be targeted for seismic loads, diaphragm inelastic behaviour maybe unavoidable during strong ground motions and accounting for such inelastic behaviour may provide additional dissipation of seismic energy on top of that dissipated by the LFRS of the building.

Influence of Diaphragm Stiffness on Seismic Response

Using the simplified 3D numerical model of the case study MSMB, the influence of diaphragm stiffness on the response of MSMBs when subject to strong lateral loads such as those imposed by earthquakes was studied. Following from the process described for establishing diaphragm service stiffness, three further variants of the 3D numerical model were created, where they differed only in diaphragm stiffness. Numerical models B_1 , B_2 and B_3 had their diaphragms respectively classified as being on the limit of rigid, on the limit of stiff and flexible. A reference building model (B_0) where all diaphragms were classified as being perfectly rigid was also studied which portrays the typical conventional method used for the structural idealisation of diaphragms for analysis and design.

A series of 44 ground motions were applied to the weak axis of each building model except B_0 and were scaled accordingly to the design earthquake spectrum considered which corresponded to an earthquake having a 500 year return period. These ground motions were the x- and y-directional motions from 22 far-field earthquake records that have been suggested within FEMA P695 [124] for studying the collapse behaviour of building archetypes and were obtained from the Pacific Earthquake Engineering Research Centre's ground motion database. Model B_0 on the other hand, was subjected to lateral loads determined through the equivalent lateral force method described within various standards [69, 70, 93] and a method based on a constant strength design approach where a uniform distribution of seismic force over the height of the building is assumed [99].

The response of each building model was compared using data extracted from recorded nodal displacements, inter-story drifts, diaphragm connection axial and shear forces and overall diaphragm inertial forces. The following were key observations with regard to the LFRS.

- Increase in diaphragm flexibility results to a slight reduction in the maximum inter-story drift ratio, inter-story force and ductility demand for the LFRS.
- Despite the increase in diaphragm flexibility, the LFRS had a first-mode dominant response similar to that of a cantilever.
- Designing under the assumption of perfectly rigid diaphragms results in un-conservative estimates for the key performance indicators studied.

The following were key observations with regard to the diaphragms.

- Increase in diaphragm flexibility, results in significant mid-span drifts, where a dramatic increase was observed for the fourth-story.
- Collectively, with increasing flexibility, all diaphragms were in an out-of-phase response from the LFRS and indicates higher-mode participation. Furthermore, it was likely that each individual diaphragm was also influenced by higher-mode effects.
- A constant strength design approach was found to better account for the developed diaphragm inertial forces, especially at the first-story level, than prescribed equivalent lateral forces methods within the Australian and New Zealand seismic design codes (see **Fig. 9**).
- Diaphragm connection forces were significantly larger than those recorded for the reference model, where the largest forces were at the third-story level and was consistent with observations made for the greatest lateral drift and largest inertial force.

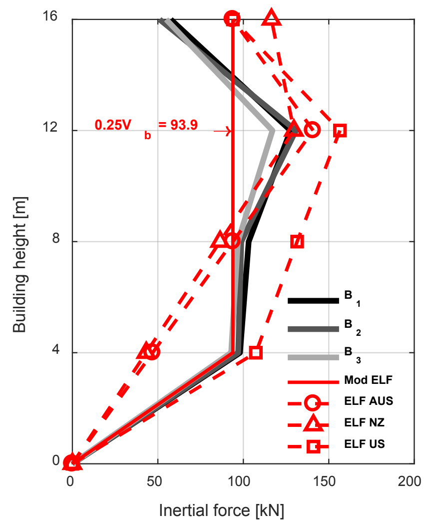


Figure 9: Comparison between observed inertial forces and diaphragm design forces estimated using different prescribed ELF methods

Performance-Based Seismic Design of Diaphragms

Understanding that current prescribed conditions for diaphragm design in MSMBs were un-conservative, two-performance based design scenarios were proposed and studied. The first performance scenario is suitable for regions of low to moderate seismicity where an elastic diaphragm response is proposed for seismic events having return periods of 500 and 2500 years. The second performance scenario which is suitable for regions of high seismicity, is focused on achieving inelastic diaphragm response as an additional mode of energy dissipation for seismic events having a return period of 2500 years while preserving an elastic response for seismic events having a return period of 500 years. Each of these performance scenarios are detailed in **Fig. 10**, which shows the idealised force-displacement responses expected for diaphragm connections as they would govern diaphragm elastic and/or inelastic behaviour. Therefore, this part of the overall study was aimed at quantifying the required force and ductility amplification to determine the potential usefulness of the proposed scenarios. However, it should be noted that further studies are required for precision.

Of the two performance scenarios, the inelastic scenario for regions of high seismicity, has two further options which explore combinations for the inelastic behaviour of diaphragm connections. The first option considers both inelastic axial and shear behaviour for diaphragm connections, whereas the second option considers preserving the elastic shear behaviour to facilitate the use of shear critical floor and/or ceiling systems such as those of composite steel-concrete.

As before, variants of the 3D numerical model were created, and were based on modifying the response of diaphragm connections in model B_1. The diaphragm connections of model B_4 was assigned to have both inelastic axial and shear response, whereas those of model B_5 were assigned to have inelastic axial response only. The fully elastic behaviour was captured by model B_1 itself.

The same series of 44 ground motions were used and in addition were scaled appropriately to the design earthquake spectrum corresponding to an earthquake having a return period of 2500 years as expected in the region for which the building was designed. The following were key observations.

- Marginal changes were observed for maximum inter-story drift, inter-story force and ductility demand of the LFRS where building B_4 performed better than B_5.
- Though LFRS retained its first mode dominant response, the diaphragms showed signs of higher mode participation.
- All connections except those at the roof level had yielded under the applied series of ground motions for both models B_4 and B_5. However, the preservation of elastic shear behaviour, resulted in an approximate 60% increase for ductility demand in axial behaviour.
- The largest ductility demand was again consistent with the largest observed diaphragm displacement and the largest developed inertial force, which were both at the third-story level.

Summary & Conclusions

To facilitate the economical use of finished and/or un-finished gravity framed modules in both present hybrid modular construction technologies and the proposed concept of a fully-modular building superstructure construction system, studying the behaviour of diaphragms is crucial. Establishing diaphragm stiffness is essential to ensure overall building stability when under the action of lateral loads.

Diaphragm stiffness in MSMBs is governed by the stiffness of diaphragm connections and the stiffness of modules themselves. A simplified method to classify diaphragm service stiffness in MSMBs was presented. This method was used to construct a range of numerical models, namely B_0 to B_5, of a four-by-four bay four-story modular steel building and were used to investigate the influence of diaphragm stiffness and strength on the seismic performance of MSMBs. Building models, B_1, B_2 and B_3, were subjected to the design level earthquakes

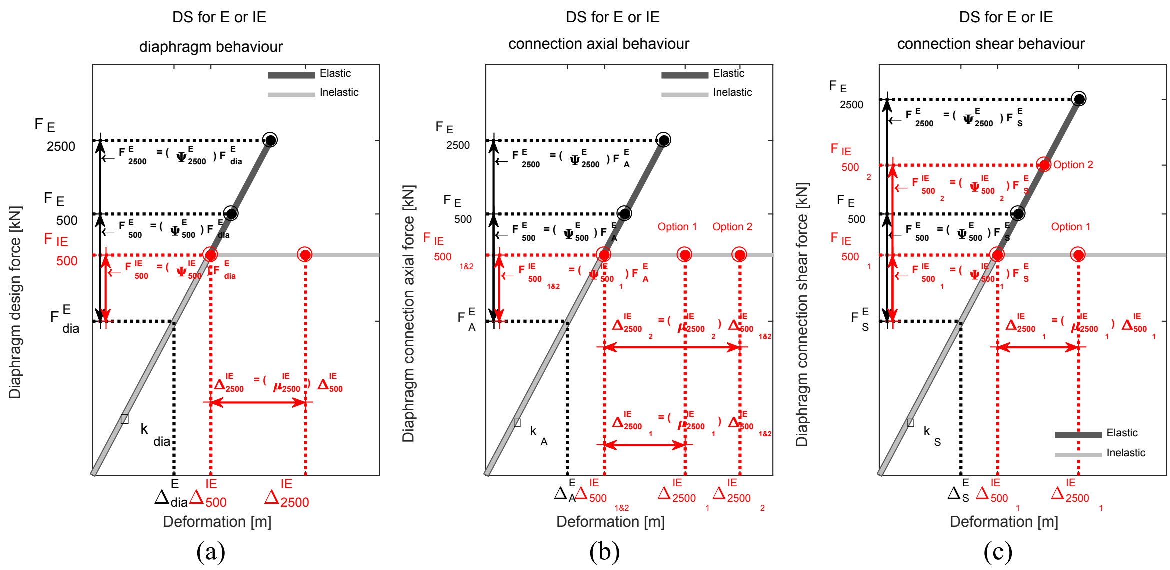


Figure 10: Performance-based design scenarios (DS) for elastic and inelastic behaviour of (a) the full diaphragm (b) diaphragm axial connections (c) diaphragm shear connections.

having a return period of 500 years using a suite of 44 scaled ground motion records considered in FEMA P695. The results were compared to investigate the influence of diaphragm flexibility on the seismic response of the building. Also, to evaluate the reserve capacity of diaphragms beyond their design level, numerical models B_1, B_4 and B_5, were subjected to seismic events having a return period of 2500 years using the same suite of ground motions. The results were used to propose two performance targets, namely, elastic and inelastic diaphragm response, through the use of force and ductility amplification factors. The following are key conclusions drawn.

- The increase of diaphragm flexibility in MSMBs results in higher mode participation and affects diaphragms displacement and their connection forces. Note that, the higher mode effects are due to in-plane module-to-module motion and individual overall diaphragm motions over the height of the building, as the response of the LFRS was observed to be first-mode dominant.
- More stringent diaphragm classification methods are required for compatibility in using current seismic code provisions for MSMBs, since prescribed seismic response modification factors seem to be inadequate.
- The observed vertical distribution of diaphragm forces in the models are better approximated by the assumed uniform distribution of seismic force over the height of the building, where it accounts for the large lower level forces than the equivalent lateral force methods prescribed within current Australian [69] and New Zealand [70] seismic design codes.
- The MSMB with diaphragms classified at the limit of being rigid (B_1) was unaffected by higher modes, however, had developed lateral displacements and forces much larger than those of the reference building model, B_0, which had diaphragms that were ideally rigid as they would conventionally be assumed.
- The allowance for inelastic diaphragm behaviour induces higher mode participation as a result of the increased ground motion intensity. This could likely be controlled through the use of appropriate seismic response modification factors.
- More detailed studies are required to establish generalised factors for the seismic design of MSMBs for use with the method of assuming uniform distribution of seismic forces over the height of buildings.

Proposed Inter-Module Connector

Introduction

As identified earlier, among the two key technical limitations other than those imposed by transportation, is the need for a high-performing easily assembled load transferring inter-module connection. Inter-module connections need not only meet structural performance requirements but also certain constructional and manufacturing requirements. Structural performance requirements essentially require inter-module connections to meet stiffness and strength requirements along with the capability of providing for additional safety through any means of reserve capacities drawn from any inherent ductility. Constructional requirements are principally the connection's ability towards simplifying and reducing on-site work thereby promoting on-site occupational safety, faster construction, reduced duration of environmental disturbances and reduced on-site related emissions. Though structural and constructional needs fulfilment are by far the most critical, the simple yet cost-effective manufacture of connection components is also a modest concern which however is easily addressed by adopting mass manufacturing techniques.

Nevertheless, a distinction needs to be made with respect to whether an inter-module connection would be part of a modularised gravity framing system or the LFRS. Inter-module connections that are part of a modularised gravity framing system transfer vertical loads through one module column to the next, whereas lateral loads can be 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 a coupled load transferring mechanism. 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 or is for both gravity framing and the LFRS. The latter is greatly expected for the proposed ideal CBS or fully-modular building superstructure construction system for MSMBs.

Therefore any proposed concept should be versatile to transfer vertical loads, be it axial compression or tension, and lateral loads, be it inter-story shear forces to be transferred within itself or accommodate additional attachments to facilitate diaphragm force transfer preserving diaphragm stiffness.

Methodology

The first step was to survey literature to identify key performance requirements for inter-module connections. The outcomes were principally a set of structural and functional/constructional requirements, along with manufacturing requirements.

The second step was to survey literature and identify the current state-of-the-art with respect to inter-module connections available in the public domain and critically review their capabilities against the established performance requirements from the previous step. This not only assists in the bottom up approach to concept development where flaws of an existing system are understood and incremental changes suggested, but also the top down approach, where the foundational needs for an entirely new concept is laid for a quantum improvement.

The third step was to suggest incremental changes on existing connections and propose entirely new concepts for inter-module connectivity. The principle focus was on the latter since suggesting incremental changes for existing systems requires full commanding knowledge of those systems.

The fourth step was to perform a preliminary assessment on overall functionality and structural conformance via simplified kinematic and finite element models.

The fifth step was to create simplified cost-effective prototypes of the finalised concept using ABS or ASA plastic to assess its actual functional behaviour.

The sixth step was to manufacture and/or fabricate the finalised prototype using the most suitable grade of steels for subsequent characterisation of its actual real-life mechanical and functional properties.

Model development and kinematic checks were done using the software AutoDesk Inventor, whereas preliminary finite element analyses were undertaken using the software ANSYS.

Outcomes

Reviewing the current state-of-the-art

Following from **Table 1** and the identified performance requirements from the survey of past literature, it is inferable that the current state-of-the-art for inter-module connectivity is commonly achieved through the use of bolted or welded assemblies that have several un-integrated components and require laborious on-site work for assembly.

The conducted review process is described below, where a hypothetical type-b inter-module connection, as shown in **Fig. 11**, is considered as the generic demonstrative example. It should be noted that this generic connection is assumed purely for demonstration and not as an actual solution for inter-module connectivity. Furthermore, it is assumed that all connection systems would have access to assembly line mass manufacturing technologies capable of achieving reduced unit costs.

Firstly, structural needs fulfilment was assessed based on whether a connecting system could provide the following.

- S1. Axial tension resistance in elevation or the vertical plane of the structure, which essentially governs column-to-column axial force transfer.
- S2. Axial and shear resistance on plan or horizontal plane, which essentially governs diaphragm force transfer to the LFRS.

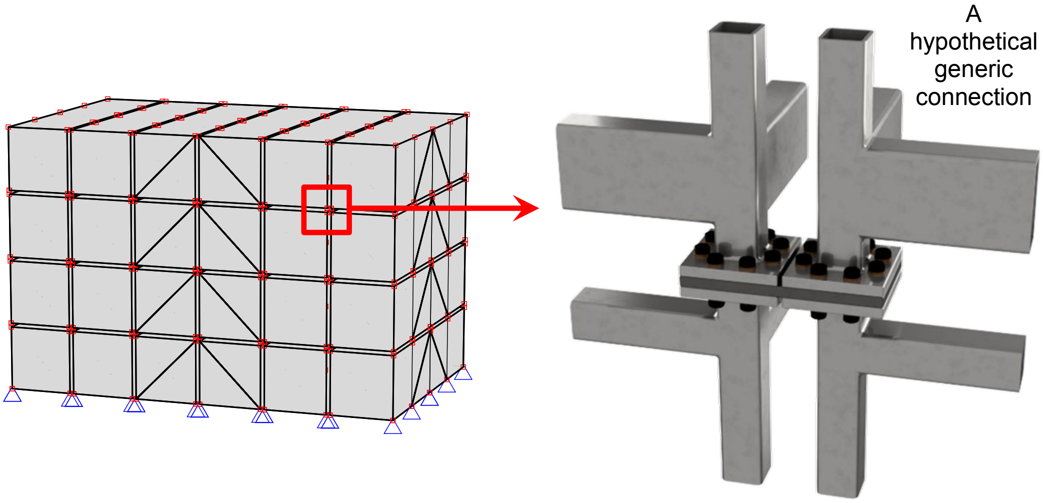


Figure 11: The generic connection assumed for demonstrative purposes

When considering the generic connection of **Fig. 11**, 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, and hence both S1 & S2 structural performance criteria are satisfied by the generic connection.

Secondly, the manufacturing needs fulfilment was assessed based on the complexity of manufacturing the parts that would form a connection including its attachment to modules, and therefore considers the following.

M1. Number of unique parts that form the connection that requires separate manufacturing.

M2. Complexity of each unique part as a function of the complexity in its manufacturing process. The least intensity weightage of 1.0 was given to the forming of plates and forging of bolts, threaded rods, pins and screws. Other specific methods/processes such as casting was assigned a weightage of 2.0 and the need for any simple machining was assigned 3.0, whereas complex machining processes such as milling were assigned 4.0.

M3. The need and complexity of post-manufacturing integration of parts to form the connection. The complexity of post-manufacturing component integration was based on the need for either simple assembly, fastening or welding. The assigned weighting factors were respectively 1.0, 1.0 and 2.0.

M4. The final number of unique parts after integration, where it is expected that there would ideally be a vertical connector and a horizontal connector.

M5. The complexity in pre-attaching the final integrated connection components onto modules, based on the need for either fastening, welding of endplates or angled sections, welding of the key connection components, drilling or cutting module elements or requiring length-wise welding. The assigned weighting factors were respectively, 1.0, 2.0, 2.0, 3.0 and 3.0.

As before, when considering the generic connection of **Fig. 11**, it comprises of column end plates, a transfer plate and relevant nuts, bolts and washers, hence requires the forming of the plates (1 x 1.0), forging of nuts, bolts and washers (1 x 1.0) and the machining of each component as per requirements such as the drilling of holes on plates (1 x 3.0). Therefore, apart from having three unique components, the degree of component/manufacturing complexity equates to five. Furthermore, 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. However, this generic system requires the end plates to be pre-attached via welds onto the columns of modules, hence the pre-attachment complexity criterion results in a value of two as per the assigned weights.

Finally, constructional/functional needs fulfilment was assessed based on the onsite effects relating to assembly and overall building form, and considers the following.

C1. The connection system has self-aligning or self-locating geometric features.

C2. Inter-module connectivity can be engaged remotely without requiring direct access externally or through modules

C3. The amount of time and effort required to engage vertical and lateral inter-module connectivity, based on whether the connection system functions through 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. 4**), where the weighting factors used for any vertical or horizontal connector insertion, mechanism operation, fastening, welding, pre/post tensioning, concreting were 1.0, 1.0, 2.0, 3.0, 4.0 and 5.0 respectively.

C5. The amount of tools required to engage connectivity, where the weighting factors considered for driving a mechanism, fastening, welding, pre/post tensioning and concreting were respectively, 1.0, 1.0, 2.0, 3.0 and 4.0.

C6. Modules can easily be demounted

C7. Reduces non-usable space between modules.

Focusing on the demonstrative example, the generic connection of **Fig. 11** 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 level modules adjacent to each other, 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.

Likewise, a similar assessment was conducted for each identified connection system and has been presented highlighting whether the established performance requirements were satisfied, partially satisfied or requires additional modifications to satisfy as shown in **Table 2**. 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.

<u>Proposed Concepts for Inter-Module Connectivity</u>

Having reviewed the current-state-of-the-art with respect to inter-module connectivity, three basic directions for concept development were identified keeping in mind the need to satisfy the identified performance requirements. The following were the key few that were explored for achieving vertical inter-module connectivity.

1. Connection incorporated with a driven mechanism.
2. Connection incorporated with a gravity assisted mechanism.
3. Connection that utilises pre- or post-tensioning.

Of these three, the driven mechanism type connector was favoured for further development. This connector features an internal unit that houses a mechanism which relates an applied torque to linearly translate a set of pins that would engage with the external unit once lowered in place (see **Fig 12**). Vertical load transfer in compression is via the bearing of both internal and external unit surfaces and the vertical load transfer in tension is via the pins (see **Fig 13(a)** and **Fig. 13(b)** respectively). Vertical plane shear forces are transferred through the pins and the bearing of surfaces on both the external and internal units (see **Fig 13(c)**). Horizontal load transfer in axial tension and/or compression and shear is achieved through a transfer plate held in position by the internal unit (see **Fig. 13(d)**). The greatest limitations for this concept are the need for precise manufacturing and therefore the lack of being capable of handling large tolerances that are typical in construction practices. Though module manufacture can achieve the required complimentary levels of precision since it would be in a factory environment, on-site construction activities, on the other hand, at present, may

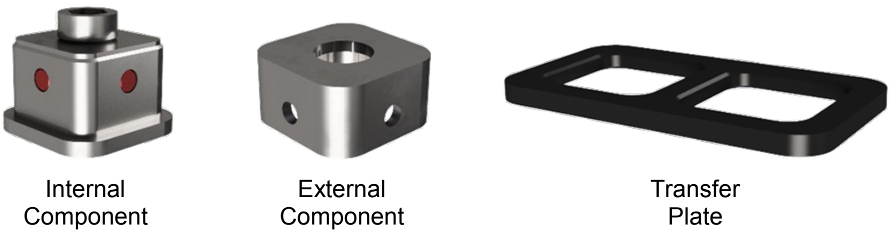


Figure 12: Proposed connector concept having a driven mechanism

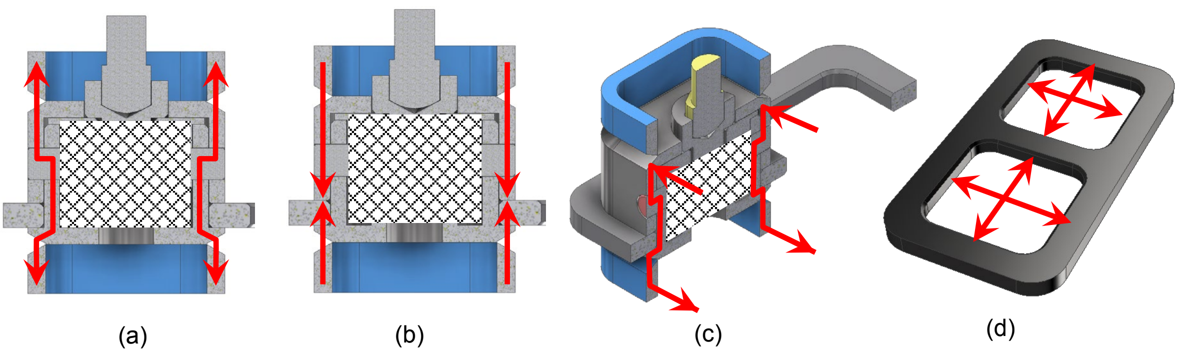


Figure 13 Expected load paths when the connection is under (a) tension, (b) compression, (c) shear and when the plate is under (d) axial tension and/or compression and shear.

not be capable of achieving such levels of precision. Hence, the use of fully-finished modules may not be realised since on-site adjustments would be inevitable and therefore access to structural frames would be a necessity. However, it is not unlikely that a single stack of modules could easily be assembled without difficulty despite tight manufacturing tolerance controls. The analogy follows that if the vertical elevations of all foundational anchor bolt nuts are precisely located through the surveying process using equipment such as the total station, and if module manufacture is as precise as connection manufacture and undergo no plastic deformation upon transport and on-site handling, then the vertical assembly of modules would conform to the tight tolerance limits enforced by the connections. But, achieving module-to-module lateral connectivity would prove to be the most challenging, and hence focusing on allowing for methods that can facilitate larger tolerances within this regime could prove beneficial and may improve the overall viability of the connection. Therefore, conventional solutions maybe adopted to overcome this barrier, where instead of a simple transfer plate insertion, the plate may require to be fastened through oversized holes or incorporate other means of securement such as grouting. Nevertheless, it is expected that with the onset of construction automation, the construction industry is likely to soon reach levels of manufacturing precision.

Conformance towards Established Performance Criteria

As described in the previous section, the proposed concept is capable of vertical plane axial tension and compression resistance including vertical plane shear resistance. The placement of the transfer plate caters to the need for horizontal plane axial tension and/or compression including shear resistance. Therefore both S1 & S2 structural performance criteria are fulfilled.

Though the connection has only three final off-the-shelf components, its manufacturing stage not only requires the casting of the overall internal unit housing and the external unit, but also requires the forming of plates, forging of pins and the machining of components that would make up the mechanism. However, despite the manufacturing stage being relatively complex, post-manufacturing component integration requires only a simple assembly of the manufactured components and the finished units requires only to be welded on to the respective ends of module framing columns or beams (see **Fig. 14**). Therefore, in overall the proposed concept can modestly satisfy manufacturing needs.

With regard to the constructional needs fulfilment, the proposed connector is superior to most other inter-module connectors in practice. The incorporation of a mechanism enables the connection to be engaged remotely without requiring direct access and also with ease without much effort and requiring only a single drive tool. Furthermore geometric detailing at the edges of both the internal and external units enables self-location within a tolerance of 2 mm. Moreover, the mechanism is such that assembly and disassembly are accomplished with relative ease and hence the system is easily demountable. Therefore, when focusing on the number of on-site operations to engage a type-b inter-module connection using the proposed connector, when upon having placed and secured two base level modules adjacent to each other, the transfer plate is lowered in place prior to the lowering of the next level of modules (see **Fig. 15(a)**). Upon the upper level modules being lowered, the drive tool is inserted and the connections are engaged one after the other (see **Fig. 15(b)**). The overall outcome is that the proposed connector may likely facilitate the fastest on-site assembly of any MSMB.

Table 3 shows the comparison of the proposed connector against the identified performance requirements and based on the evaluated final scores for all identified connectors found within available literature, the average score among all correspond to approximately a 67% fulfilment in addressing the established performance requirements, whereas the proposed connector achieves a percentage fulfilment of 86%.

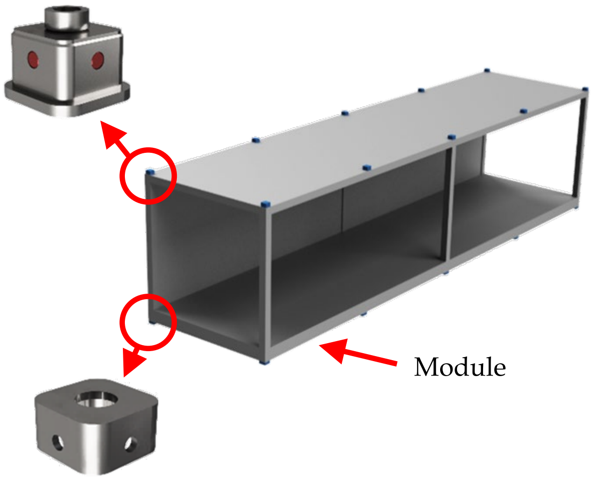


Figure 14: The locations of the external and internal units on a module.

Table 2: Comparison of existing systems 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 [78, 80]	■	■	□	■	▣	■	■	■	□	■	■	■	■	■
ATLSS [103, 104]	■	■	▣	□	■	▣	□	■	□	■	▣	■	▣	□
Annan [52]	■	■	■	■	■	■	□	□	□	□	□	□	□	■
Lawson *et al.* [12, 74]	■	■	■	■	■	■	□	□	□	■	■	■	▣	■
Farnsworth [105]	■	■	▣	□	■	▣	□	■	■	▣	□	▣	▣	■
VectorBloc™ [106-108]	■	■	▣	□	■	▣	■	■	□	■	■	■	▣	■
Hickory [8]	■	■	□	□	■	▣	□	■	□	□	▣	▣	□	■
Styles *et al.* [110]	■	■	■	■	■	■	■	□	□	■	▣	■	▣	□
Gunawardena [42]	■	■	■	■	■	■	■	□	□	■	■	■	▣	□
Choi *et al.* [111]	■	■	■	■	■	■	□	□	□	■	■	■	▣	■
Robinson [62]	■	■	□	□	□	▣	■	■	□	■	■	■	▣	■
Buro Happold [62]	■	■	▣	□	□	▣	■	■	□	■	■	■	▣	■
Chen *et al.* bolt assembly [112, 113]	■	■	■	□	□	■	□	■	□	■	■	■	▣	■
Chen *et al.* prestress assembly [114]	■	■	□	■	□	□	■	□	□	□	□	□	□	■
Deng *et al.* [115]	■	■	▣	□	□	■	▣	■	□	■	▣	■	▣	■
Deng *et al.* welded cover plate [116]	■	■	▣	■	□	▣	□	□	□	▣	▣	■	□	■
Doh *et al.* [117]	■	■	■	▣	■	■	■	□	□	■	▣	■	▣	■
Lee *et al.* [118]	■	■	■	■	□	■	▣	□	□	■	▣	■	▣	■
Sharafi *et al.* [119]	□	■	■	▣	■	■	▣	□	■	■	■	■	■	■
Sanches *et al.* [120]	■	■	□	□	□	▣	□	■	□	▣	□	▣	▣	■
Yu *et al.* [121]	■	■	■	□	■	■	■	■	□	▣	■	■	□	■
Generic (**Fig. 7**)	■	■	■	■	■	■	■	□	□	■	■	■	▣	□

□	Requires modifications ($0 \leq$ weighted score (WS) < 0.34)
▣	Can partially meet requirements ($0.34 \leq$ WS < 0.67)
■	Can meet requirements ($0.67 \leq$ 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

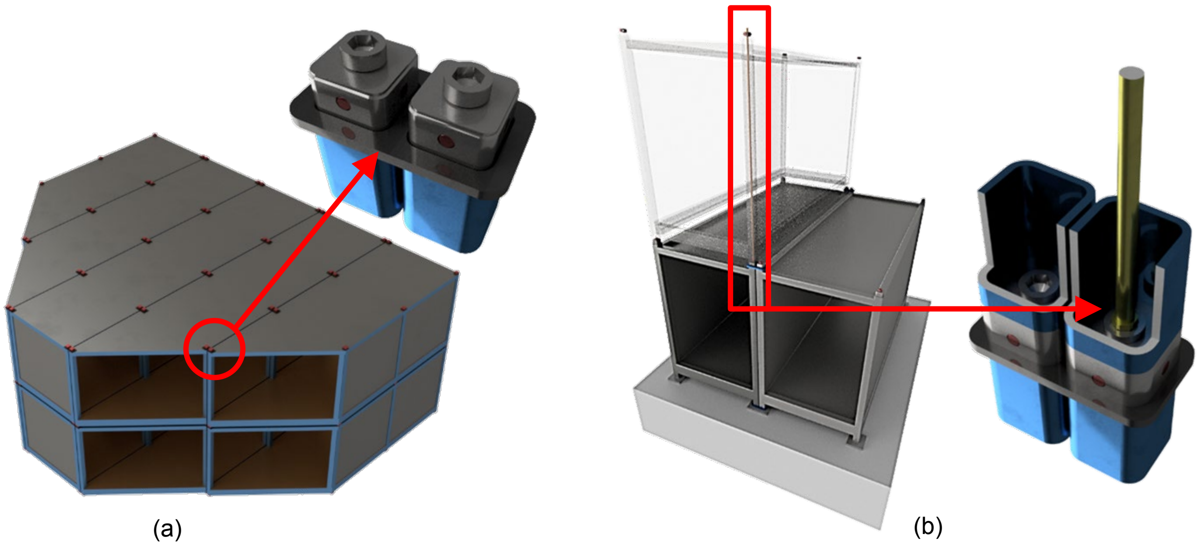


Figure 15: (a) Transfer plater insertion (b) drive tool lowered and torque applied to engage connectivity.

Table 3: Comparison of the proposed connector against established 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
Proposed Connector	■	■	□	□	▣	■	■	■	■	■	■	■	■	■

□	Requires modifications ($0 \leq$ weighted score (WS) < 0.34)
▣	Can partially meet requirements ($0.34 \leq$ WS < 0.67)
■	Can meet requirements ($0.67 \leq$ 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

Preliminary Structural Performance Assessment

Having established that the proposed connector is functionally superior, it is therefore required to establish that the connector be designable to meet any desired structural performance requirement, and therefore be scalable. Furthermore, given that the overall goal is to achieve a fully-modular building superstructure construction system for MSMBs with the specific target of achieving the modularised construction of mid- to high-rise buildings, it therefore becomes paramount to make use of structurally efficient hollow sections than the typically used cold formed open sections for modular construction, which tend to limit construction to low-rise buildings if without additional conventionally built structural systems. Furthermore, such light-weight cold formed steel modules are typically of the continuous bearing type (see **Fig. 1**) and therefore limit architectural freedom as well as the capability to achieve large open spaces. It is therefore considered in this dissertation that structural hollow sections are more suited for discrete column connected configurations such as the selective bearing form (see **Fig. 1**) and that cold form steel sections would be best suited for use alongside other complimentary materials (such as cross-laminated timber or light weight concrete) for flooring, ceiling, roofing and/or walling systems. On this note, it is assumed that the proposed connector would have to be compatible so that it can be attached to standard structural hollow section sizes, where for simplicity, square hollow sections were selected. **Table 4** shows typical structural square hollow sections made of grade 350L0 steel and their estimated nominal capacities in axial compression (N_C), axial tension (N_T), moment section (M_S) and shear (V_V). The proposed connector was first designed to suit a 100 x 100 x 9 square hollow section and the expectation is to have superior capacity than those of the column. It would then follow that the connection would be scalable to exceed the capacities of larger section sizes as well.

Table 4: Key nominal capacities of SHSs per AS1163 [125]

SHS	N_C [kN] Effective Length [m] 3.0	3.5	4.0	N_T [kN]	M_S [kNm]	V_V [kN]
100x9	643	521	420	1049	34	307
150x9	1422	1322	1211	1678	86	493
200x9	2122	2056	1978	2311	163	680

Analytical Assessment using Prescribed Methods

The proposed connector, for vertical connectivity, requires the design of three critical components, which are, (1) The external unit, (2) Internal unit and (3) pins.

When considering the pins, under both vertical plane axial tension and compression, they would be in shear. Therefore undertaking a design based on the AS4100 for nominal capacities [72]

$$V_f = 0.62 f_{yp} n_s A_p = 0.62 f_{yp} n_s \pi \frac{d^2}{4}$$

$$M_p = f_{yp} S = f_{yp} \frac{d^3}{6}$$

The number of shear planes (n_s) as a result of the proposed system is 1.0, therefore the nominal shear and moment capacity will be governed by the diameter of the pin and the grade of the material.

When considering the external unit, under both vertical plane axial tension and compression, its critical cross-section would be that which is at the elevation of the pins. Furthermore, being that the connection would function as a short column, its compression capacity would be considerably larger than the framing column of similar cross-section dimensions to which it will be attached to. Therefore, undertaking a design based on AS4100 [72] for nominal capacities.

$$N_c = \alpha_C k_f A_n f_y$$

$$N_T = min(A_g f_y \, , 0.85 k_t A_n f_u)$$

If the external unit is similar in dimensions to the column to which it will be connected, then its section properties are comparable to standard square hollow sections mentioned in AS1163 [125], therefore, k_f for standard sections being considered is 1.0 and α_C would effectively be 1.0 as well since the modified slenderness of the unit would always be <10 and the unit's height would typically be <100 mm. k_T is also taken as 1.0 since under tension the unit will be loaded symmetrically and the resultant force will pass through the centroid of the section.

On the other hand, the internal unit is based on the principle of telescoping sections, however the clearance is set to manufacturing tolerances. The considered external dimensioning for the internal unit is based on the selected standard size for the external unit and the expected clearance. It is therefore expected that the compression and tension capacity of the internal unit could be determined adopting the methods prescribed in AS4100 [72]. However, they would be smaller than those determined for the external unit unless compensated by allowing for a thicker wall section. Moreover, restrictions may apply with regard to the wall thickness of the internal unit if it were to house a mechanism within it.

Fig. 16 shows the comparison of the nominal axial force that can be applied considering for four pins (tension or compression) as a result of the nominal shear capacity of a single pin for grade 8.8 and 16 mm diameter, the nominal axial compression and tension capacities for the external unit of grade 350L0 and of section 100 x 100 with varying wall thicknesses ranging from 9 to 5 mm, the nominal axial compression and tension capacities for the internal unit of similar grade and expected section sizes as determined from its external unit pair, the relevant bearing capacities for the different thicknesses, the relevant tearing capacities for the relevant thicknesses considering an end distance of $1.5d_f$ =24 mm and the tension and compression capacities of a framing member of section 100 x 100 with varying wall thicknesses where it is assumed that the member is pinned at ends and of length 3 m.

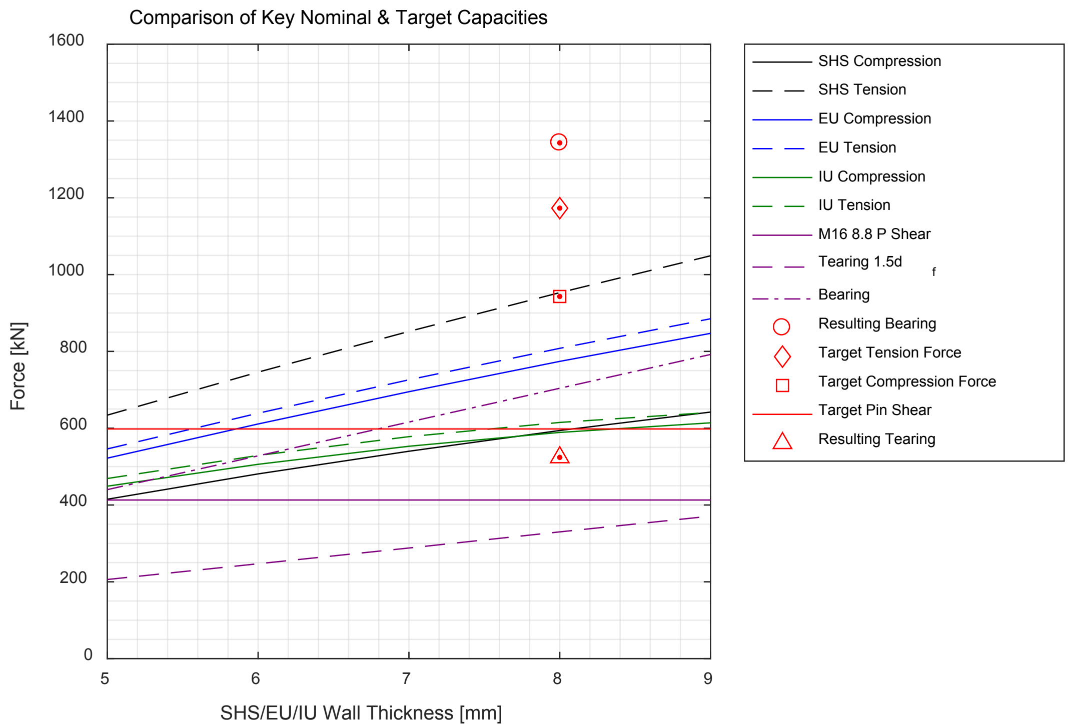


Figure 16: Comparison of key nominal capacities of 100 x 100 square hollow section (SHS), complementary external unit (EU), complementary internal unit (IU) and 16 mm diameter grade 8.8 pin (P) and respective bearing and tearing, along with targeted and resulting values for the overall connector of wall thickness 8 mm and higher grade pins for complementary use with a 100 x 100 x 9 SHS.

Preliminary Finite Element Analysis

This section details the preliminary finite element work undertaken for the proposed connector concept. Model development was undertaken using the software Autodesk Inventor, through which 3D model files were generated and imported into ANSYS workbench. The base material was selected as structural steel and the default properties were used for this preliminary analysis and the values are shown in **Table 5**. At this stage each individual component was studied rather than the complete assembly. **Table 6** lists out the different components and the assumed boundary conditions, whereas **Table 7** lists out results obtained for (1) the external component when under tension, compression and shear, (2) the internal component when under tension, compression and shear, (3) the pin when under shear and (4) the transfer plate when under tension, compression and shear.

Table 5: Considered material properties

Material Property	Value	
Density	7850	kg/m³
Young's modulus	200	GPa
Poisson's ratio	0.25	
Shear modulus	80	GPa
Yield General	350	MPa
Yield Pin	580	MPa

Table 6: Boundary conditions used for external unit (EU), internal unit (IU), pin (P) and transfer plate (TP), where the application of displacements were at the yellow regions and support conditions being a mix of fixed and friction-less supports at violet/blue regions.

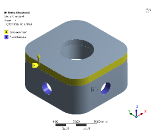
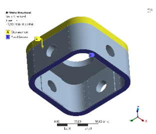
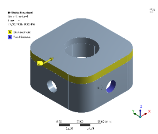
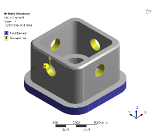
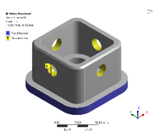
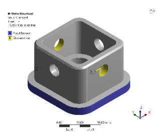
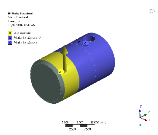
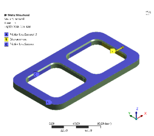
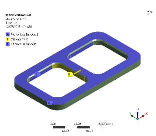
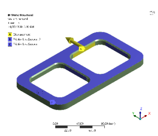
	Boundary Conditions		
	Tension	Compression	Shear
EU			
IU			
P	-	-	
TP			

Table 7: Sample results obtained for each key component under tension (T), compression (C) and shear (S).

	Displacement [mm]	Max Equivalent Von-Mises Stress at mid-plane [MPa]	Force Reaction [kN]
EU - T	0.0204	350	288
EU - C	-0.0226	350	270
EU - S	0.0178	350	87
IU - T	0.0415	350	288
IU - C	-0.0410	350	284
IU - S	0.0278	350	75
P - S	0.0074	580	46
TP - T	0.0446	350	12
TP - C	-0.0148	350	172
TP - S	0.0404	350	8

Prototyping and Assessment of Actual Functionality
Upon finalising dimensions of the key connector components and the complementary square hollow section to which the connector will be attached, an analysis of the kinematics of the mechanism housed within the internal unit was undertaken. The software Autodesk Inventor was used for this purpose. Upon verifying the smooth functionality of the mechanism via the software, prototyping was undertaken where connector components and the mechanism were 3D printed in Acrylonitrile Styrene Acrylate (ASA) plastic. Upon verifying the actual functionality of the mechanism using the 3D printed prototype, which was based on the set manufacturing tolerances, the actual connector and subsequently the test specimens were fabricated. **Fig. 17** shows the actual connector being subjected to a functionality check and **Fig. 18** shows the remote operability check on a test specimen.

Summary & Conclusions

This section established performance criteria for inter-module connections and compared existing inter-module connection technologies against those established criteria. Through this evaluation, it was found that the current state-of-the-art for inter module connectivity is mostly achieved through bolted or welded assemblies requiring considerable on-site work. Though these systems can be made to satisfy structural demands, they require furthermore modifications to meet constructional needs. Therefore, alternative solutions were proposed and among those it was found that a mechanised connector was the most suited. The proposed mechanised connector was assessed against the established performance criteria where it met all constructional needs and additionally some manufacturing needs as well. A preliminary structural performance assessment and assessments on functionality and remote operability have been demonstrated. It is believed that the proposed connector would be the most ideal for MSMB construction.

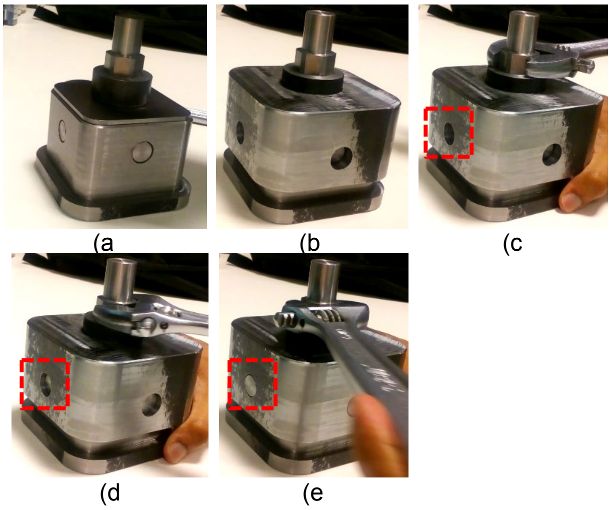


Figure 17: Portrayal of the actual system functionality, (a) internal unit alone, (b) external unit lowered, (c) no engagement, rotation at 0°, (d) partial engagement, rotation at 60°, (e) full engagement, rotation at 120°.

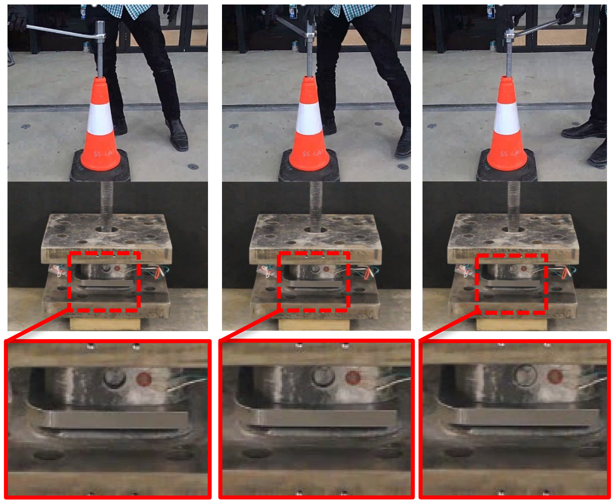


Figure 18: Remote operability check, where the test specimen is being engaged from a height greater than 4 m.

Highlights on conducted experimental work

Introduction

Upon having verified the functionality of the prototype connector and its expected structural behaviour, the proposed connector was opted for experimental verification and proof of concept validation. Therefore, a series of static load tests were planned for determining the factor of safety in design and to evaluate the actual load bearing capacities and deformability when under axial tension, compression, shear and combined tension and shear. These mix of forces will be seen by the connector if it were part of the LFRS of a MSMB and would therefore be useful for subsequent numerical model calibration and use for further parametric studies.

The first series of tests were designed to assess the tension and compression behaviour of the connection including the load at mechanism failure whereas the latter was to understand the shear behaviour of the connector including its combined tension shear interaction. Key properties required for evaluation under these applied loading scenarios are, (1) stiffness, (2) strength, (3) ductile capacity and (4) failure modes.

Test specimens were fabricated to suit the different loading cases considered, where for connection axial behaviour, the setup was analogous to a tensile coupon test setup where the connection would be gripped and pulled apart, whereas for shear, a more elaborate setup was required, since the study of combined axial and shear interaction was of interest and therefore was needed to be accommodated. Linear variable differential transformers (LVDT) were used to measure relative movement between concerned points during the tests and global stress distributions were captured using digital image correlation techniques such as through the VIC-3D system from Correlated Solutions Incorporated. Local stresses at specific stress critical locations were determined through the use of bonded strain gauges of a general purpose 3 element 45^{o} rosette type. However, neither of these techniques could capture the state of stress in the mechanism nor the internal unit and therefore a calibrated finite element model is essential for optimising the design of those components.

Displacement trends during the initial stages of loading are vital to identify the presence of any slack or slippage in the connection due to the tolerances present in the overall system. Failure modes would have to be investigated as well and can also be used to validate finite element model predictions. The MTS 1 MN universal testing machine (UTM) was found to be adequate to carry-out tension, compression and pure shear tests, whereas an additional actuator having a minimum capacity of 250 kN was sought for the combined shear and tension interaction tests.

The results provided herein, relates to the tension compression tests carried-out so that the connector could be made viable for use in gravity frames of MSMBs.

Methodology

The first step was to fabricate specimens suitable for the load cases being tested and have them prepared or fitted for attaching relevant measuring devices. Surfaces for strain gauge bonding were appropriately cleaned and a speckle pattern was formed for the image correlation system. Material coupons were also made for establishing the material behaviour for later use within finite element models for further studies.

The second step was to gather information on standard loading protocols and rates of load application as deemed appropriate for the load case/cases being considered. Typically, up to the theoretical yield, loading would be based on the method of force-control where load increments would be based on the appropriately factored theoretical yield limit. Once, the region of the yield load is reached, load application is based on the method of displacement-control where incremental displacements are applied to the system based on the appropriately factored theoretical yield displacement limit.

The third step is to process the relevant data and compute the key parameters being sought.

Outcomes

Axial Behaviour of Proposed Connector

Test Setup Description

The external and internal components of the proposed inter-module connector were welded on to plates that could be attached via bolts to a gripping assembly, through which tension and compression was applied to the overall system by the MTS 1 MN UTM. LVDTs were attached on to opposite sides of the plate to which the external unit was welded, and the movable arms were made to rest on angle elements fit onto the plate to which the internal unit was welded. The arrangement of LVDTs on opposite sides may nullify any residual effects caused by bending due to any fabrication related misalignments and the average of all feeds were considered for establishing the movement of the centroid of the connector. Furthermore, since only two specimens were manufactured, it was decided that the specimens would be subjected to multiple cycles of monotonic loading safely within the elastic range prior to loading till failure. However, it is of special interest, that when under compression, a load of 280 kN is applied and released, which simulates a stack of 5 modules of 4 m in height and width and 16 m in length (in relation to a 4 m grid interval) carrying a total story-wise gravity load of 7 kN/m^2, which can also be interpreted as having a stack of 10 similar modules carrying a total story-wise gravity load of 3.5 kN/m^2. It is expected that upon load release and inspection, the connection remains functional. **Fig. 19** shows the test setup.

Applied Loading

The considered loading was of a non-standard load protocol and was formulated to not only mimic the successive placement of modules but also to assess the performance of the mechanism after each load step.

Furthermore load was applied at 56 kN increments for the first five cycles to a maximum of 280 kN and at 112 kN increments for the remaining cycles till failure. The 56 kN load increment value was based on a 7 kN/m^2 load acting within an interior column tributary area of 8 m^2 derived from having considered modules of 16 m length, 4 m width and 4 m height. The load increment change to 112 kN, for the remaining cycles beyond the fifth was due to the failure of the mechanism having occurred within the fifth cycle. **Fig. 20** shows the applied protocol.

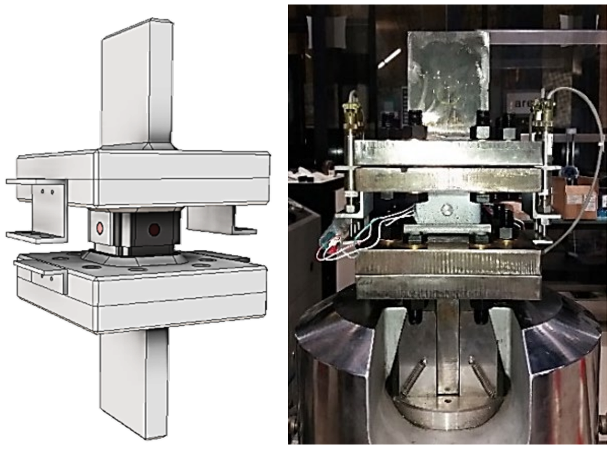


Figure 19: The test setup for tension compression testing of the proposed connector along with the location of LVDT mounts.

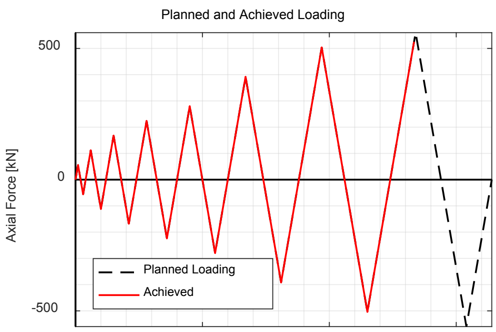


Figure 20: Applied loading where for the first 5 cycles, the load increment was set at 56 kN and for the remainder it was 112 kN.

Results

Fig. 21 shows the force displacement plot obtained for the connector under the applied loading. The force measurement was from the load transducer of the MTS 1 MN UTM and the displacement measurements shown is the average of those obtained from the arrangement of LVDTs. An idealised multi-linear fit for the observed data is also shown which depicts the expected static-monotonic tension response and the descriptions below are in conjunction with this fitted multi-linear curve.

A direct noticeable observation from the force-displacement plot is that under compression, the connection functioned as expected in bearing mode and in tension the response was satisfactorily ductile as well. Furthermore, with regard to the functionality of the mechanism, upon completion of the fourth loading cycle, the connection was verified to have behaved linear-elastically and the mechanism was fully functional with smooth retraction and engagement. The fourth loading cycle saw to the application of a maximum tension and compression force of 224 kN. However, upon the end of the fifth loading cycle, it was verified that the mechanism had yielded and failed, and despite significant effort to retract the pins, no considerable movement could be achieved. A potential cause for this failure was identified and the necessary rectifications for an updated configuration have been implemented for the overall connector for a more robust response and a delayed onset for mechanism failure. From the idealised fit, the load at mechanism failure is estimated to be approximately within the range of 250 kN (248.5 kN as shown in **Fig. 21**). The initial stiffness, in tension, prior to mechanism failure was determined at ~347 kN/mm and was at 138 kN/mm for post mechanism failure response, where a ~60% reduction is noted. The vertical movement of the connection at mechanism failure was established as 0.7 mm. Furthermore, all proceeding cycles were noted to have increasing levels of slippage where for the seventh cycle it was noted to be within an idealised range of 0.8 to 0.9 mm. It can be related that this movement could potentially be due to the influence of the post yield behaviour of the components that make up the mechanism.

It is further noticed within the seventh cycle that a clear deviation in tension stiffness occurs and is likely due to the yielding of the external or internal unit of the overall connector. The post external and/or internal unit yield stiffness was estimated at 50 kN/mm and the slippage experienced on the eighth cycle approximates to an idealised range of 2.1 to 2.2 mm.

The ultimate tensile strength noted for the connector was at 525 kN, where the corresponding vertical displacement was ~7.7 mm. The observed mode of failure was due to tearing of the external unit (see **Fig. 22**). Moreover, It should be noted that the simplified design approach adopted following prescribed conditions within AS4100 [72], yielded a nominal tearing capacity of 525 kN (see **Fig. 16**) when considering the engineering stress-strain values of the underlying material used and 560 kN if true stress-strain values are used. Hence, it can be claimed that the expected outcome was achieved.

When considering the compression phase of loading, up to the sixth cycle, the determined compression stiffness averaged at 6370 kN/mm. The proceeding cycles, due to having resulted in the yield of the external and/or internal unit, influenced an early initial gain in compression stiffness prior to achieving bearing through-out the whole section and thereby subsequently picking up to approach the initial average compression stiffness estimate.

Summary & Conclusions

This section covered the tension and compression testing of the proposed connector. The connector was found to have behaved as expected and achieved an ultimate strength in tension as analytically predicted/designed. However, it is of further interest to verify the actual compression capacity of the connector. The connection response in tension was satisfactorily ductile as well. Therefore, it has been demonstrated that the connector can achieve 50% of its intended framing column member's (100 x 100 x 9 SHS) nominal tensile capacity (1049 kN) and is capable of achieving compressive strengths that are 100% of the framing column member's (100 x 100 x 9 SHS) design section capacity in compression (944 kN).

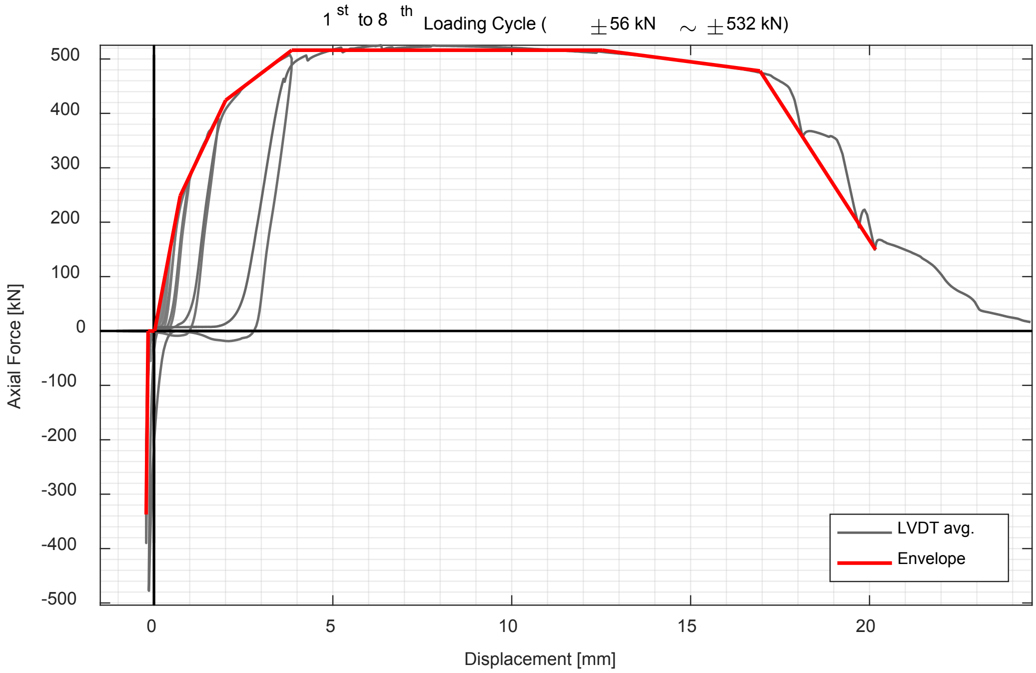


Figure 22: Force-displacement plot for the connector under applied tension compression loading cycles.

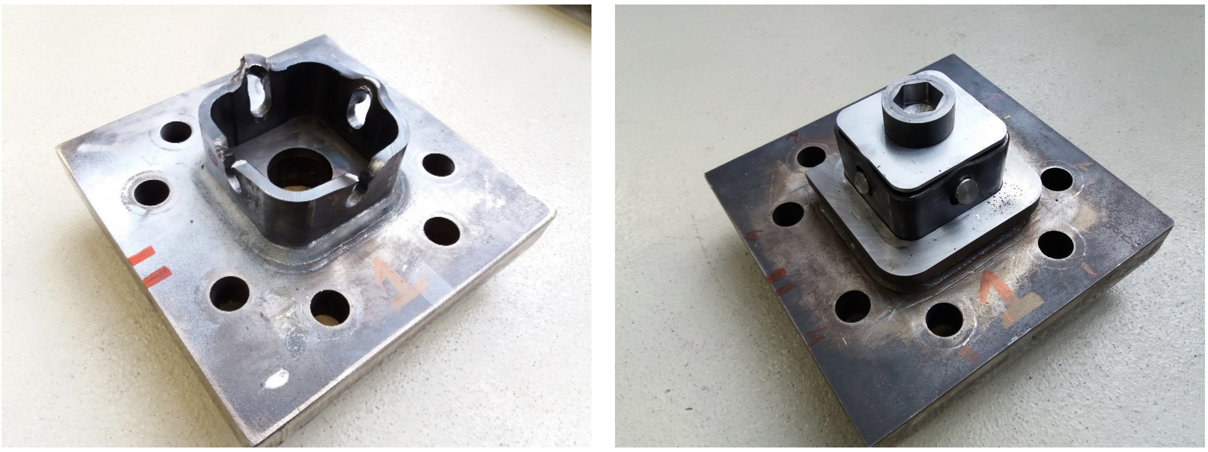


Figure 21: The external and internal units after testing, where tearing failure and its onset are visible for both components including bending/shearing of the pins.

Dynamic load effects during module transportation - UOM

Introduction

During the course of road transportation of the modular building unit (MBU), vehicular vibrations on the truck-trailer may cause damage to components that are attached to the unit. The amount of dynamic loading depends on many parameters including the size and weight of the truck, suspension system of the truck as well as the nature of road profile. The rougher the road the higher are the vertical accelerations of the truck. In order to predict the vertical accelerations of the truck and of the secondary attachments of the truck, we express the truck-road dynamic system mathematically as a 2-dimensional Pitch-plane model (see **Fig. 23**). An MBU is assumed to be rigidly attached to the truck chassis and the chassis is represented by a rigid beam (sprung mass) whereas the wheels of the truck are represented by blocks (un-sprung masses). Suspension system of the truck is represented as a spring and a damper element connected in parallel.

Road profile is derived from the power spectrum of its displacement data. Road roughness spectra are available in their idealized forms in International Standards (ISO) 8606. Road profile is a vertical displacement graph with the distance travelled plotted on its x-axis. A lot of research is available on modelling the correct road profile from its spectrum. Stationary Gaussian process has been used in the current study to model the road profile from ISO-8606 road spectra.

After expressing the road-vehicle system mathematically, 5 parameters are varied to understand their effect on vertical accelerations in the secondary modular connections. The parameters are identified as;

1. Location of the centroid of the weight along the chassis length
2. Gross weight of truck along with Modular building unit
3. Vehicle traveling speed
4. Suspension stiffness ratio of rear axle to front axle
5. Damping present in the secondary modular attachments

Observations

Based on this parametric study, a secondary attachment (Component and its mount) inside an MBU has been expected to experience an acceleration as high as 32 m/s^2 in a vertical direction (see **Fig. 24**). This value of acceleration has been predicted to occur at least once every 100 km of road stretch with 95% confidence. Apart from this the study showed that;

1. Dynamic amplification increases with the lowering of damping, as expected.
2. The peak response acceleration decreases with increasing the level of loading on the truck-trailer meaning that conditions on a lightly loaded truck-trailer tend to be more onerous.
3. As the centre of mass is shifted towards the front of the truck-trailer, the response acceleration in that part of the truck-trailer is lowered accordingly.
4. As the stiffness of the suspension at the rear of the truck-trailer is increased above that of the suspension at the front, the response acceleration at the front of the truck would increase.
5. The response behaviour of the truck-trailer has been studied for two different truck-trailer velocities (10 m/s and 20 m/s). A higher velocity of travel has been found to generate a higher level of vertical acceleration.

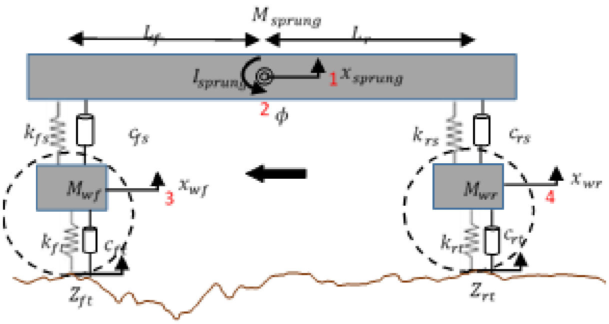


Figure 23: Mathematical representation of the truck road system.

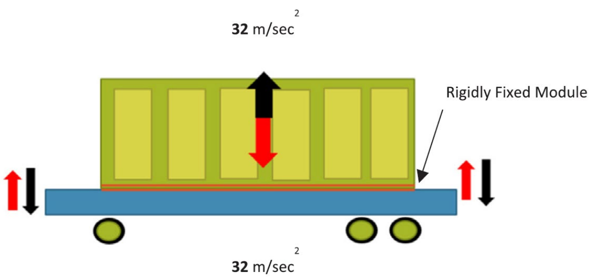


Figure 24: A schematic representation of the experienced acceleration.

Conclusions and recommendations

This report presented the outcomes of a multi-institutional collaborative research project between Swinburne University of Technology, Melbourne University and the industry partners AECOM, Bluescope, Multiplex, Hassell and the Victorian Building Authority (VBA). The study included performance requirement of modular buildings under service/extreme loads and to propose an innovative structural connections for modular connection.

Particularly, a systematic study was presented to cover the behaviour of diaphragms in multi-story modular buildings and to quantify the essential characteristics required for inter-module connections. Not only structural needs but also manufacturing and construction requirements were discussed in details. Brief descriptions of existing inter-module connecting systems that are available in both literature and the public domain as well as a critical review against the identified performance requirements were also presented.

A newly-developed concept for inter-module connectivity was then proposed. A preliminary assessment on overall functionality and structural conformance via simplified kinematic and finite element models was performed. Model development and kinematic checks are done using the software AutoDesk Inventor, whereas preliminary finite element analyses are undertaken using the software ANSYS.

Upon having verified the functionality of the prototype connector and its expected structural behaviour, the proposed connector was opted for experimental verification and proof of concept validation. Therefore, a series of static load tests were planned for determining the factor of safety in design and to evaluate the actual load bearing capacities and deformability when under service and ultimate loads. The loading represented the forces generated in the connector when it served as part of horizontal and vertical load resisting systems within a modular building. Finally, the study was extended to quantify the dynamic loads applied to the modular units during transportation.

The outcomes of this comprehensive study provides quantum improvements on the current modular construction industry through fast on-site assembly, in-life adaptation to service/extreme loads, post-life disassembly, and affordability. This will assist in the future development and application of fully-modular superstructure construction systems for multi-story modular buildings.

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