A Review on Seismic Performance Analysis of High Rise Modular Steel Construction (MSC)

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ABSTRACT

The construction industry has tried out a variety of trends in its field to bring out innovative, economic, efficient and sustainable infrastructure to meet the growing demand. One such development is the off-site manufactured modular steel buildings. The practice reduces the construction period as well as reduces wastage of resources. It was extensively used for low rise structures earlier, but due to increasing urban construction demand the practice is preferred nowadays in high rise structures too. For the high rise structures the lateral stability needed to be well looked into as there may arise a mass irregularity, structural irregularity, discontinuity etc. Psychological acceptance of such construction practice by the public is also not assured as they are not well aware of the advantages and use of the practice. And hence there is a need to conduct detailed and thorough investigation on its contradiction part to seismic performance. The modular construction consists of different structural systems and load transferring mechanisms. The integration of many materials and elements to modular structures are also discussed in various papers. But regarding lateral force resistance of its structural and non-structural components only limited research is conducted. Further research is required. The aim of the study is to provide a collective critical review on individual units or components of the structural system and their effects contributing to seismic resistance.

Keywords: Modular steel construction, High rise modular structures, Lateral force resisting systems, Offsite construction, Modules

1 INTRODUCTION

These days the construction industry is on its way to phase changing developments. Researchers look up to these with utmost interest as they are trying to transform the construction industry to a sustainable sector. The paper here discusses the construction practice of high rise modular steel construction (MSC). Over the past, the system existed in low to mid rise structures with little knowledge of its stability contributing factors. But with increasing demands of mankind and availability of limited resources it was proved that the modular steel buildings (MSBs) had the potential to meet the demand efficiently and economically in high rise structures too. Though they provide a promising future to the construction industry in case of high rise structures the earthquake resistance behavior need to be well studied. MSC usually comprises of – off-site manufactured volumetric modules and on-site assembly. As they are mainly prepared in factory conditions their negative impact to the environment is reduced to a wider extent. The MSB can also be efficiently constructed if the buildings are with repetitive architectural plans and structural layouts. The construction practice stands out to be more effective than traditional practice and hence recently the technique was adopted for construction of hospitals, hotels, classrooms and dormitories etc. These buildings are produced in "modules" that when put together on-site, reflect identical design intended and specification of the most sophisticated site-built facility without compromise. One of the example of MSC made at time of recent crisis was the post-disaster hospital that could accommodate 1000 patients constructed in Wuhan, China, aiding in the fight against the COVID-

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19 virus. This structure in Wuhan was made in just 10 days. There are also lots of MSB constructed in India as well as across the world. Some examples of such construction in Kerala are the Polachirakkal H. S School (Nelliyampathy), Avitis Hospital (Nenmara) etc. This construction practice is gradually taking up the construction sector and in the near future it is expected to be more in demand and practice. All these modular structures consist of different structural systems and load transferring mechanisms. And also various connection forms arise in these structures. All these play a significant role in lateral force resistance and it needs to be analyzed well. The further discussion on the paper details more of it. The MSC practice is argued to have more benefits than conventional building construction because the whole working process is speedy, flexible, environment friendly and economic. There is a faster return on investment, that is, the schedule of completion of the work is much faster. At the same time site and building work could be completed. There is an increase in work efficiency. The practice reduces labor, financing and supervision costs. And the module assembly is independent of weather condition unlike the conventional construction process. Since the modular units are completely prepared in a factory controlled setting, they exhibit improved quality and durability. There is also improved air quality since there is no moisture in framing materials as they are made out of dry materials. Each modules are built in such a way that it can independently withstand travel and installation requirements. Also there is flexibility in use; that is, based on later change in usage pattern they can be relocated or refurbished minimizing demand of raw materials as well as amount of energy expended to create a new building. The entire building can be recycled. The construction and demolition of such structures are low waste generating. And the materials used for construction are also minimal compared to the usual construction practice. Hence the practice could be in total considered efficient and sustainable. The limitation of MSC is that these buildings have limited customization, though they have a variety of designs, there is a limit on dramatic changes to shape or look. The cost and transportation difficulties increase if sites are at far off places. There may also be restrictions in the area of modules for its easy transportation and installation. Since they are not much popular among the populace the knowledge about it or its efficiency is unknown to them. Zoning regulations and psychological marketplace factors may restrict buyers or builders the thought of MSB.

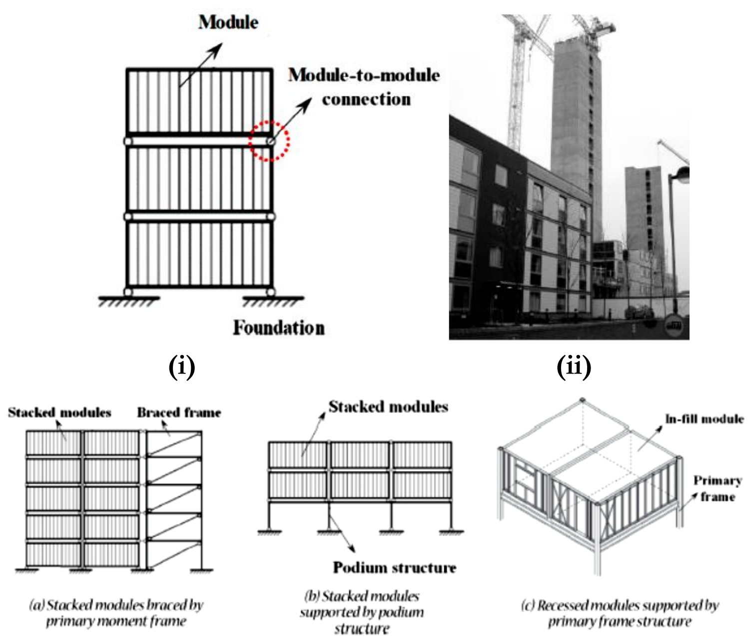
2 LITERATURE REVIEW

2.1 Structural system

The different kinds of module classification based on load transferring mechanism are the continuously supported, frame supported, and non-load bearing modules as shown in Figure 2.1. *Deng et al.* briefs in their review paper that in the continuously supported modules the loads are transferred through side walls. Here the steel studs forms the wall around and is important in compressive resistance. In case of frame supported modules, the columns are either at corners or at intermediate points.

Fig. 2.1. Classification of modules in MSC (continuously supported, frame supported and non-load bearing modules respectively) (Deng et al., 2020) [6]

The transfer of loads takes place from edge beams to the posts. Hence the corner posts require high compressive resistance. So the corner posts are preferred to be structural hollow sections to obtain a smooth building elevation and excellent compression, torsion, and bending behavior. Currently this type of module is widely used. Lastly the non-load bearing modules, or pod-like modules, as the name mentions they are unable to transfer loads and are supported by a floor. Some examples of such modules are staircase, bathroom, or kitchen. Structural systems are also classified into three types based on the lateral-force transferring mechanism - stacked module, module-moment frame hybrid and module-concrete core hybrid structures. They are designed to satisfy various height requirements for buildings. In stacked module structure the gravity and lateral loads caused by wind and earthquake are transferred by the side walls for the continuously supported module, or by the inter-module connection for frame supported module. The stacked module structure is suitable for low-rise buildings comprising no more than three stories and with a regular plane layout. However, the stacked module structure can be built higher by using an incorporated lateral force resistant component and rigid module-to-module connections (shown in Figure. 2.2 (i)). The module-moment frame hybrid structure combines stacked modules with a primary steel or concrete moment frame, to improve the lateral force resistance of MSC (shown in Figure.2.2 (ii)). The stacked modules can be supported by a braced frame to thereby resist the lateral force together. They could also be supported by a podium frame creating a podium structure as seen in supermarket or bottom car parking. Also, the modules can be recessed in the primary frame. This structural form is also called the "modular in-fill construction method. In a module-concrete core hybrid structure there is a concrete core, around which modules are arranged (as shown in Figure. 2.2 (iii)). The concrete core efficiently resists the lateral force, and has been widely adopted for high-rise MSC worldwide. High rise MSC requires not only adequately stiffened modules to form the lateral force resisting systems, but also requires a high-performance connection system to ensure efficient load transfer systems both horizontally and vertically.



(iii)

Fig. 2.2. (i) Stacked module structure; (ii) Module-concrete core hybrid structure; (iii) Module-moment frame hybrid structure (Deng et al., 2020) [6]

2.2 Module layouts

Shi et al. studied the seismic behavior of high-rise MSCs with various module layouts. In their study five 3D high-rise MSCs with various module layouts were considered (shown in Figure. 2.3). Seismic analyses were carried out in terms of these five models through response spectrum and elastic-plastic time-history analyses.

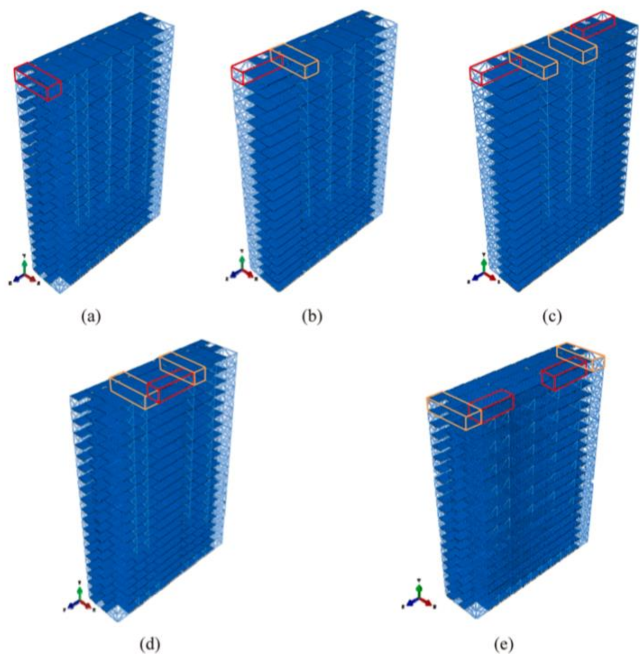


Fig. 2.3. Layout of structures: (a) Parallel stacked modules (C1); (b) One end staggered modules (C2); (c) Both ends staggered modules (C3); (d) Intermediately staggered modules (C4); and (e) Vertically staggered modules (C5). (Shi et al., 2020) [8]

From results it was observed that all had minimal variation in structural performance except C3. For it design should be according to torsional irregular structure and its influence to higher modes need to be assessed. Also the authors mentioned that the vibration period of the first three modes is large and decreases gradually, and the fundamental period increases in the order, C2 < C3 < C1 < C4 < C5. The stiffness of C2 is the largest and that of C5 is least. When the modules are staggered at one end, the fundamental period and second period are close to each other, which indicates that the lateral stiffness of the two main axes of the structure are consistent. From the observation (as shown in Figure. 2.4) it was known that the inter-story drift ratios (IDRs) of constructions with modules staggered at one end are the least and those of constructions with modules staggered at both ends are the highest along the X-direction while those of constructions with parallel stacked modules are the highest along Z-direction. The X-direction deformation presents the characteristics of bending deformation while the Z-direction presents the characteristics of shear deformation, which reveals that the stiffness along the X-direction is greater than that along the Z-direction. The MSC in which the intermediate modules are staggered exhibits essentially the same displacement along the X and Z directions. The MSCs with vertically staggered modules have a more uniform distribution of the overall IDRs along height. Owing to the vertical staggering of the modules, the stiffness values of adjacent layers are inconsistent, which causes the IDRs along the Z direction to fluctuate. Structural deformations considering various module layouts show that

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staggered layouts (C2–5) can solve the problem of inconsistent bidirectional stiffness in C1, and improve the phenomena of insufficient Z-direction stiffness and non-uniform distribution of IDRs.

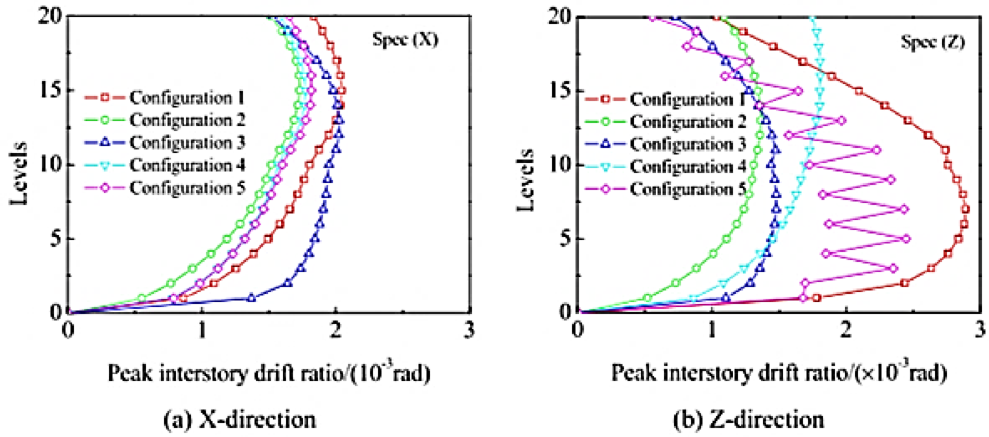

Fig. 2.4. Height-wise distributions of peak IDRs under seismic response spectrum. (Shi et al., 2020) [8]

2.3 Connections

In MSBs there are a cluster of different units for forming the complete structure and hence one of the main factor guaranteeing its structural integrity and stability is its connection. The connections are the critical factor contributing to the capability of building to withstand load. Horizontal and vertical connectivity arises in these structures. The different connections are:

2.3.1 Inter-module connection

In inter-module the types of connection arising is beam-beam and column-column connections. Many researchers had proposed various mechanical fasteners like bolts, shear keys, threaded rod, tie plates, etc., at the inter-module joints. In beam-beam connection floor beams of upper modules need to be tied into ceiling beams of lower modules. In column-column connections the upper and lower columns are connected using vertical rod, plugin bars, or pretension strands. And in order to enhance the shear force resistance and rotational stiffness between these connections short segments like plug-in device, shear key or tenonwere are incorporated. *Lacey et al.,* (2017) reported that bolted connection is preferred over site welding. A gap is usually provided between the floor and ceiling beams, allowing for external access to inter-module connections and for services to pass between the beams. But *Deng et al.,* (2018) highlighted in their study that this will lead to indirect uplift load transferring when subjected to lateral forces, such as wind and earthquake. So as a better alternative their paper proposed an innovative bolted connection with welded cover plate (shown in Figure. 2.5), which can meet the architectural design demand and with significantly better seismic behavior. The proposed cruciform bolted connection performed better ductility and energy dissipation capacity than the previous beam-to-beam bolted connection. The average ductility coefficient and energy dissipation coefficient were improved by 14.1% and 46.5%, respectively. It was observed that the reinforced specimens maintained more than 80% of the maximum moment at an IDR of 0.04 rad. The average initial rotational stiffness was improved by 18-25%.

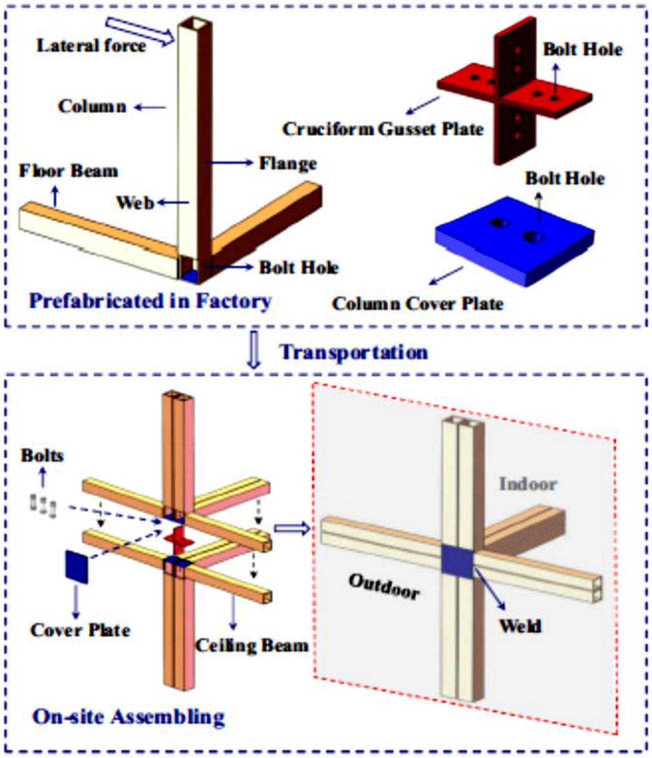

Fig. 2.5. Cruciform bolted connection (Deng et al., 2018) [7]

Apart from this the recent paper by *Lacey et al.* discusses the need to determine shear force slip behavior in these connections and their work suggests an alternative by use of a new post-tensioned bolted steel connection. This consists of a shear key combined with a post tensioned tie rod which is located inside of the hollow steel sections that form the module columns (as shown in Figure. 2.6). This inter-module connection exhibited greater initial load-slip stiffness and it was determined that the slip load can be effectively controlled by varying the bolt preload and faying surface slip factor. Sand blasting the faying surfaces increased the slip factor, which gave a greater slip resistance. And increasing the bolt preload significantly increased the slip load. Also it was reported that increasing the contact area resulted in a small increase in the slip load, but was not that significant contributing to the accuracy of slip.

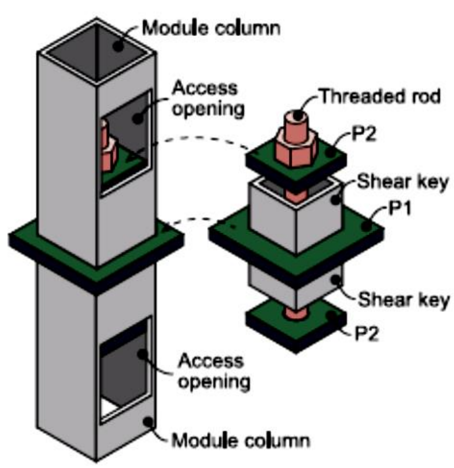

Fig. 2.6. Post tensioned vertical inter-module connection (Lacey et al., 2019) [2]

2.3.2 Intra-module connection:

These connections occur within the module. It involves use of both welded and bolted connections. The column to beam bolted connection includes single web plates, double angle cleats, and bolted end plates. *Srisangeerthanan et al.* reported that intra-module connections may have less influence on the overall seismic performance of MSC, as it is completed off-site manufactured. However, from *Deng et al.* work it can be concluded that the intra-module beam-to-column connection has a significant influence on the seismic performance of the module-to-module connections, thereby affecting the overall seismic performance of MSC. Various practices are discussed on this by researchers but still works are at its infancy stage regarding their contribution to seismic performance of structure and providing a better alternative to these connections.

2.3.3 Module to frame/concrete core connection

In module-to-frame connection the traditional practice of embedded steel anchors and welds are recommended. According to CECS 334–2013 cover plate and high strength bolts are required for connecting modules with frames (as shown in Figure. 2.7 (a)). Choi et al. demonstrated a possible bolted module-to-concrete core connection by embedding stud bolts and gusset plate, as shown in Figure. 2.7 (b). But further detailed studies are required to know its seismic aspects or resisting properties.

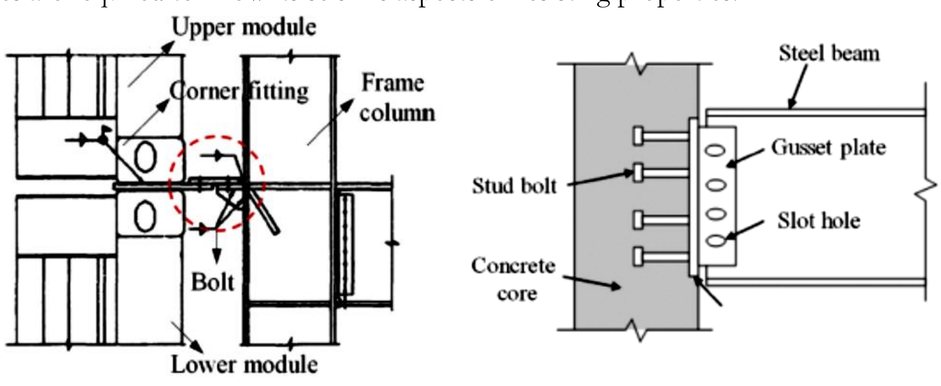

Fig. 2.7. (a) Module-to-frame bolted connection; (b) Module-to-concrete core bolted connection (Deng et al., 2020) [6]

2.3.4 Column to foundation connection

Structures located in areas of high lateral load require appropriate connection with foundation to avoid overturning. The foundation used for MSB can be in situ or precast concrete footings, bored concrete piles, augured steel piles, or some combinations. And the modules are connected to the foundation by chains, cables, keeper plates or welding to concrete or steel piles, or large mass concrete footings. Each connection type has associated disadvantages including tensioning requirement for chain and cable. Base plates may be incorporated in modules and fixed to cast-in anchors, or welded on site to accessible cast-in plates. Park et al. developed an embedded column connection (Figure. 2.8 (a)), as an alternative to the traditional cast-in or post-fixed steel bearing plate. This connection was developed to ensure best use of the full column strength and provide good ductility. According to the suggested model the four individual columns of the module meet at the joint, and these columns are welded to an end plate, which efficiently transfers forces and moments to the foundation. The columns and the welded end plate are then placed at the recess of the foundation and connected with mortar. As a result, the columns are not connected to each other and there is a gap. Thus, the plastic moment capacity of the section is obtained by summing the plastic moment capacity of the individual unit columns. Further various tests were conducted with the model to ensure its stability and the results concluded that embedment depth played a significant role in the behavior. It was observed that if sufficient depth is not provided lead to pull out failure. And the shear studs between the column and mortar constrained the separation of the interface, which leads to more brittle failure of the connection compared to specimens without shear studs. The shape of the end plate did not significantly contribute to the connection behavior in resistance to lateral loads. The other suggested module-to-foundation connection from Technical specification for modular freight container building (CECS 334–2013) is shown in Figure. 2.8 (b). In this suggested method anchor bolts are used to connect the precast foundation and connecting corner fitting.

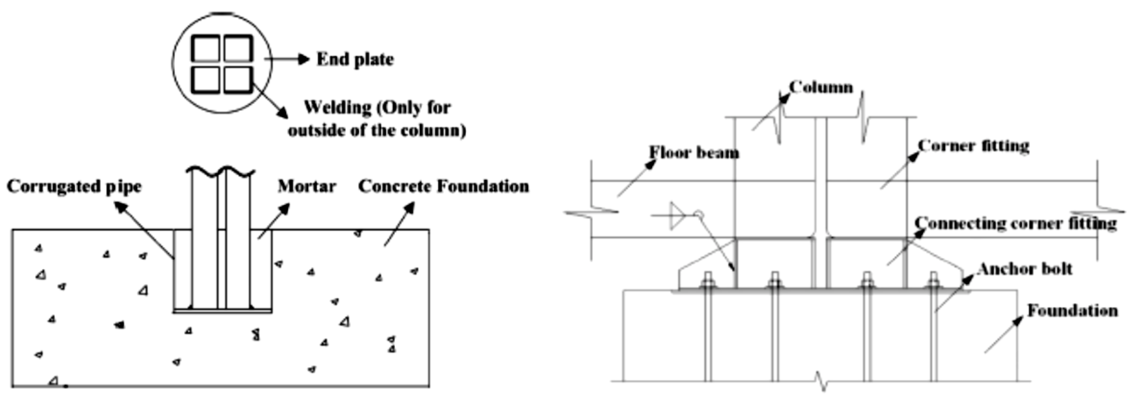

Fig. 2.8. (a) Column-to-foundation embedment connection for interior column of modular unit (Park et al., 2016) [9]; (b) Corner fitting connection (Deng et al., 2020) [6]

2.4 Seismic improvement alternatives

In seismic analysis of any structure the major concern is lateral force acting on the structure. Considering this in MSBs, various lateral force resistant components like steel plate shear wall, braces etc., were used in MSCs. *Robert G. Driver* and *Hassan Moghimi* conducted cyclic loading tests on steel plate shear wall. They conducted their experiment with 3 concepts - minimizing the size of steel plate shear wall; minimizing number of pieces of steel plate shear wall used for modular structure and using large bay width. Tests were done in it with and without fish plate. It was found that the minimized number of pieces showed sufficient out-of-plane stiffness during construction but the vertical splice used in the structure created significant erection and plumbing challenges. Whereas in case of large bay width it exhibited reliable performance but when subjected to higher forces infill plate tearing occurred [13]. So it is evident that the steel plate shear wall has high initial stiffness, significant strength and good ductility but the disadvantage of flat panel is that it is prone to elastic buckling under lateral force which is accompanied by loud noise. Usage of stiffeners solves this problem but the approach is costly and time consuming. To provide more economic and efficient solution *Hong et al.* proposed a double skin steel panel system for MSC. Corrugated steel plates were welded to this, to prevent the premature buckling of steel plates. The test results on the material also reported that the material exhibited higher initial stiffness and higher energy dissipation capacity. The study mentioned that the steel panel reached the yield point before the yielding of the frame thereby showing favorable seismic performance. Later on from studies it was analyzed that corrugated steel panel shear walls (CSPSW) were more advantageous over latter from seismic performance assessment. Tests on CSPSW with and without openings were also done and the results indicated that the initial stiffness of CSPSWs was reduced by the opening or slit in the infill panel, whereas the energy dissipation capacity improved significantly. *Dai et al.,* proposed of providing a steel strip around opening for strengthening the openings which made the structure more in favor of seismic performance even when the openings are provided. Regarding usage of braces *Annan et al.,* from their observation on braced steel module emphasized that it is vulnerable to the bending of the column segment between the ceiling beam and floor beam, whereas in case of regular frame the out-of-plane buckling of the brace occurs. Both specimens demonstrated stable and ductile behavior up to a drift ratio of 3.1%. *Sultana et al.,* expanded the latter work and drew attention to the adoption of shape memory alloy (SMA) braces in the steel module. The authors researched on the matter and asserted that the maximum residual IDR was reduced by up to 98%, which was attributable to the re-centering capability of the super-elastic SMA braces, resulting in a reparable module unit. Later they conducted seismic performance analysis of modular steel-braced frames using SMA bolts in vertical module connection. The capacity provided by these bolt were 40% more than that of high strength bolt. From the results of seismic analysis of frame with SMA bolt the authors pointed out that there was a significant reduction in residual drift at vertical joints. The authors also mentioned that though there was an increase in IDR, it was controlled by the yielding of braces and thus exhibited improved seismic performance of the frame. [10]

Another components of MSC discussed by *Deng et al.* in their work are group columns and steel stud walls. These serve as lateral-force resistant components for the stacked module structure. In MSBs there exist three types of group columns in the structure, they are – double column, special-shaped tri-column and four posts group column. Whereas steel stud wall is wall which is made of cold-formed steel (CFS) tubes or channels sheathed by the oriented strand board/cement particle board/calcium silicate board/gypsum board is the crucial component for transferring the vertical and horizontal force for the continuously supported module. It has been identified that the cover board makes a considerable contribution to the load bearing capacity and stiffness of the steel stud wall. And the steel stud wall is prone to weld tearing fracture owing to its relatively thin CFS member, making it difficult to guarantee the quality of the weld. Regarding the seismic performance of group column and steel stud wall a very limited research is available and more studies need to be conducted to analyze its stability to withstand lateral force (Figure. 2.9).

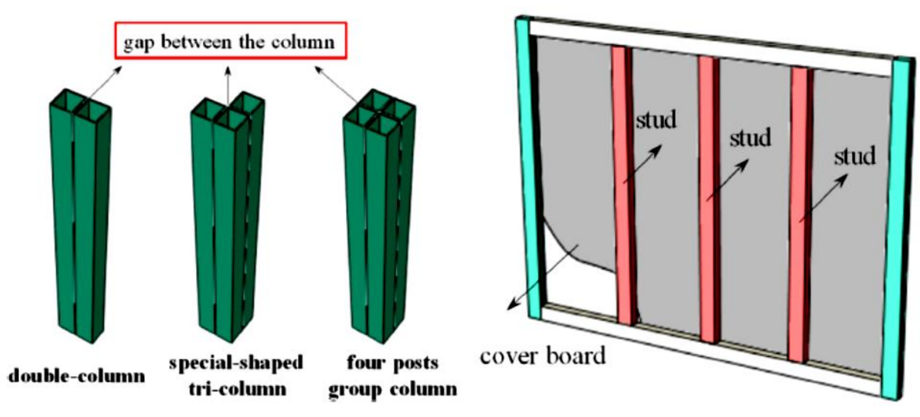

Fig. 2.9. Group columns and steel stud wall in modular buildings (Deng et al., 2020) [6]

3 CONCLUSION

Advancement in construction practices are equally as important as advancement in technology, techniques or materials used. When time is a constraint without compromising with cost and efficiency the construction practice discussed is of relevance. Due to increasing infrastructure demand and limited availability of area, mankind is switching on to construction of high rise structures. Also MSC has many advantages over the traditional practice. So psychologically the practice can catch the attention of the public if detailed and thorough investigation on its contradiction part to seismic performance is cleared. And this can turn out to be a promising sustainable and economic construction practice in the near future. This innovative construction method may shape the future of the construction industry. The paper discusses the collective review of various studies on individual units or components of MSB and their effect contributing to seismic resistance.

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REFERENCES

Andrew William Lacey, Wensu Chen, Hong Hao, Kaiming Bi (2020), "Effect of inter-module connection stiffness on structural response of a modular steel building subjected to wind and earthquake load", *Engineering Structures*, 213, 11062

Andrew William Lacey, Wensu Chen, Hong Hao, Kaiming Bi, Forrest James Tallowin (2019), "Shear behaviour of post-tensioned inter-module connection for modular steel buildings", *Journal of Construction Steel Research*, 162, 105707

Andrew W Lacey, Wensu Chen, Hong Hao and Kaiming Bi (2017), "Structural Response of Modular Buildings – An Overview, *Journal of Building Engineering"*, Vol.16, 45-56

C.D. Annan, M.A. Youssef, M.H. El Naggar (2009), "Experimental evaluation of the seismic performance of modular steel-braced frames", *Engineering. Structures*, 31, 1435-1446

C. D. Annan , M. A. Youssef and M. H. El Naggar (2009), "Seismic Vulnerability Assessment of Modular Steel Buildings", Journal of Earthquake Engineering, ISSN: 1363-2469, 1065-1088

En-Feng Deng, Liang Zong, Yang Ding, Zhe Zhang, Jun-Feng Zhang, Feng-Wei Shi, Li-Ming Cai, Shu-Cai Gao (2020), " Seismic performance of mid-to-high rise modular steel construction – A critical review", *Thin Walled Structures*, 155, 106924

En-Feng Deng, Liang Zong, Yang Ding, Yun-Biao Luo (2018), "Seismic behaviour and design of cruciform bolted module-to-module connection with various reinforcing details", *Thin Walled Structures*, 133, 106-119

Fengwei Shi, Haipeng Wang, Liang Zong, Yang Ding, Junsheng Su (2020), "Seismic behaviour of high-rise modular steel constructions with various module layouts", *Journal of Building Engineering*, 31, 101396

Keum-Sung Park, Jiho Moon, Sang-Sup Lee, Kyu-Woong Bae, Charles W. Roeder (2016), "Embedded steel column to foundation connection for a modular structural system", *Engineering Structures*, 110, 244-257

Papia Sultana and Maged A. Youssef (2020), "Seismic Performance of Modular Steel- Braced Frames Utilizing Superelastic Shape Memory Alloy Bolts in the Vertical Module Connections", *Journal of Earthquake Engineering*, ISSN: 1363-2469, 628-652

Papia Sultana and Maged A. Youssef (2018), "Seismic performance of modular steel frames equipped with shape memory alloy braces", Bull Earthquake Engineering.16:5503–5527

Pezhman Sharafi, Mina Mortazavi, Bijan Samali, Hamid Ronagh (2018), " Interlocking system for enhancing the integrity of multi-storey modular buildings", *Automation in Construction,*85,263-72

Robert G. Driver and Hassan Moghimi (2011), "Modular Construction of Steel Plate Shear Walls for Low and Moderate Seismic regions", *Structures Congress*, 758-769

Ruoqiang Feng, Liu Shen, Qiu Yun (2020), "Seismic performance of multi-storey modular box buildings", *Journal of Construction Steel Research*, 168, 106002

Shuaike Feng, Zhongxiang Liu, Xeujen Zhou, Zhengxing Guo (2020), " Seismic performance of curved haunched connections in modularized prefabricated steel structures", *Journal of Constructional Steel Research,* 172, 106188

Sung-Gul Hong, Bong-Ho Cho, Kyung-Soo Chung, Ju-hyuk Moon (2011), "Behavior of framed modular building system with double skin steel panels", *Journal of Construction Steel Research*, 67, 936-946

Sriskanthan Srisangeerthanan, M.Javad Hashemi, Pathmanathan Rajeev, Emad Gad, Saman Fernado (2019), "Review of performance requirements for inter-module connections in multi-story modular buildings", *Journal of Building Engineering,* 101087

Xiao-Meng Dai, Yang Ding, Liang Zong, En-Feng Deng, Ni Lou, Yang Chen (2018), "Experimental study on seismic behavior of steel strip reinforced CSPSWs in modular building structures", *Journal of Constructional Steel Research*, 151, 228-237

Y.S. Chua, J.Y. Richard Liew, S.D. Pang (2020), " Modelling of connections and lateral behaviour of high rise modular steel buildings", *Journal of Construction Steel Research*, 166, 105901

Zhihua Chen, Jiadi Liu, Yujie Yu (2017), "Experimental study on interior connections in modular steel buildings", *Engineering Structures*, 147, 625-638