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Steel Module-to-Concrete Core Connection Methods in High Rise Modular Buildings: A Critical Review

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Abstract: Modularization in a high-rise building is different from a small building, as it is exposed to more lateral forces like wind and earthquakes. The integrity, robustness, and overall stability of the modules and their performance is based on the joining techniques and strong structural systems. High lateral stiff construction structures like concrete shear walls and frames, braced steel frames, and steel moment frames are used for the stability of high-rise modular buildings. Similarly, high-rise stick-built buildings have concrete cores and perimeter frames for lateral load strength and stiffness. Methods for general steel-concrete connections are available in many works of literature. However, there are few modular-related papers describing this connection system in modular buildings. This paper aims to review the various research and practice adopted for steel-to-concrete connections in construction and compare the methods between stick-built buildings and modular buildings. The literature review shows that the practice of steel module-to-concrete core connection in high-rise modular buildings is like outrigger beams-to-concrete core connection in stick-built framed buildings. This paper concludes that further studies are needed in developing proper guidelines for a steel module-to-concrete core connection system in high-rise modular buildings.

Key words: steel modules, concrete core, high rise modular buildings, modules to core connection, lateral forces and seismic analysis

1. INTRODUCTION

Modular construction is gaining popularity every day as it has significant advantages over onsite stick-built construction like time savings, cost savings, less waste, safer environment, better quality, and low environmental impacts [1–3]. Modularization in building construction is not limited to low-rise buildings but is often applied to high-rise buildings. High rise building is the one that requires mechanical vertical transportation i.e., elevators for the movement of people up and down [4]. There are several high-rise modular buildings today. Australia has four of the ten tallest modular buildings in the world. Three of them used the Hickory Building System (HBS) [5,6]. HBS is used to integrate facades, core as well as shear walls of a building into the structure [6]. Similarly, the Croydon Tower of the UK is another tallest building of 44 stories and 38 stories residential tower. This was built with a combination of core and podium methods [5]. Three of the five tallest modular buildings in the world have concrete shear walls and 3D volumetric steel modules [5].

The process of modular construction varies from stick-built construction. Different ways of execution, planning, and implementation processes are required for modular construction in comparison to stick-built construction [7]. O'Connor et al. (2014) suggested twenty-one major factors in modular construction which should be implemented properly to ensure the benefits from it. These factors are called Critical Success Factors (CSF). The top five of them are CSF1- Module Envelope Limitations, CSF2-Alignment on Drivers, CSF3-Owner's Planning Resources and Processes, CSF4- Timely Design Freeze, and CSF5-Early Completion Recognition [8]. A timely design freeze ensures the designing of every modular construction component before the start of the activity. Choi et al. (2016) studied and found CSF4-Timely Design Freeze to be one of the most important factors for cost as well as schedule success of the industrial modular project. This presents the importance of design in modularization success [9]. There are various challenges in high-rise modular building construction like design guidelines, construction methods, and project management [5,10]. The lack of relevant knowledge about the structural system, cause and effect of lateral loads, and connection methods in high-rise modular construction to resist these forces are the major reasons to cause difficulty in high-rise modular building construction [11].

One of the modularization approaches for high-rise buildings is core-based. The core-based approach of modular construction means modules are grouped around the concrete walls. These cores are designed to resist the shear/lateral forces, while modules design is done to resist the gravity forces [5]. The lateral diaphragms transfer the lateral forces to the core [12]. Strong inter-module and module-to-core connections provide strength to the whole structure by balancing and resisting the vertical and lateral forces [12]. The core is made up of on-site concrete or precast concrete. Mostly, the construction of high-rise buildings uses 3D volumetric steel modules due to their sustainability, flexibility, easy connections, and a more strength-to-weight ratio [5]. A feasible method for high-rise modular building construction is the use of steel-concrete composite as it makes them durable, fire-resistant, waterproof, soundproof, and mostly, stable [11]. Few studies are done for the lateral load and its resistance performance in tall modular buildings [13]. Also, some researchers have discussed the design concepts for the high-rise modular buildings by considering the modules as vertical load bearers and concrete cores as lateral load bearers [10,14].

There are four connections used in modular construction: Intra module connections, inter-module connections, module to the frame or core connections, and modules to foundation connections [15]. Several research studies addressed inter-module connections and their importance in the integrity and stability of the modular building [16–19]. But there are a few research that focused on the attachment of steel modules-to-concrete cores in high-rise modular buildings. This paper reviews those research works and presents a clear idea of the steel modules-to-concrete core connection system. This paper seeks to review the general steel-to-concrete connection methods and compare them with modular high-rise buildings.

2. METHODOLOGY

The systematic research and review of journal papers, books, news articles, design manuals, and websites of construction and design companies are used for the research methodology. The process of review is shown in figure 1. First, the authors searched for the materials with the keywords and time frame, then the sources relevant for the literature are selected and lastly, the selected materials are reviewed.

The authors searched the journal papers using google scholar from 2000 to 2021. The search found 132 papers related to the high-rise buildings with modular construction, lateral forces and seismic analysis, connections in modular construction, and steel-concrete composite systems. Paper title having modular construction/buildings and related to design is taken as a criterion of selection. Among found papers, important papers are selected that include the use of cast in situ concrete core in modular buildings for the review. Also, a paper that best describes the steel embedment in concrete is searched and selected. Furthermore, the authors searched books or design manuals, newspaper articles, and websites of construction and design companies related to modular buildings. Overall, fourteen journal papers, one design manual, one news article, and one report that includes ideas about the steel-concrete connection system in modular construction are selected for review. Not only modular construction-related materials but the design guideline book of steel construction is also searched. Then a handbook that explains the steel construction in detail is selected for review.

The authors studied the connection process of steel-to-concrete explained in the selected materials. Connection methods in modular buildings and steel-framed stick-built buildings are compared. Relevant information was found in the handbook that discusses the joining techniques of steel beams to concrete walls in stick-built buildings. The authors compared the design factors and methods of a steel-to-concrete connection system between modular construction and stick-built construction and made concluding remarks based on it.

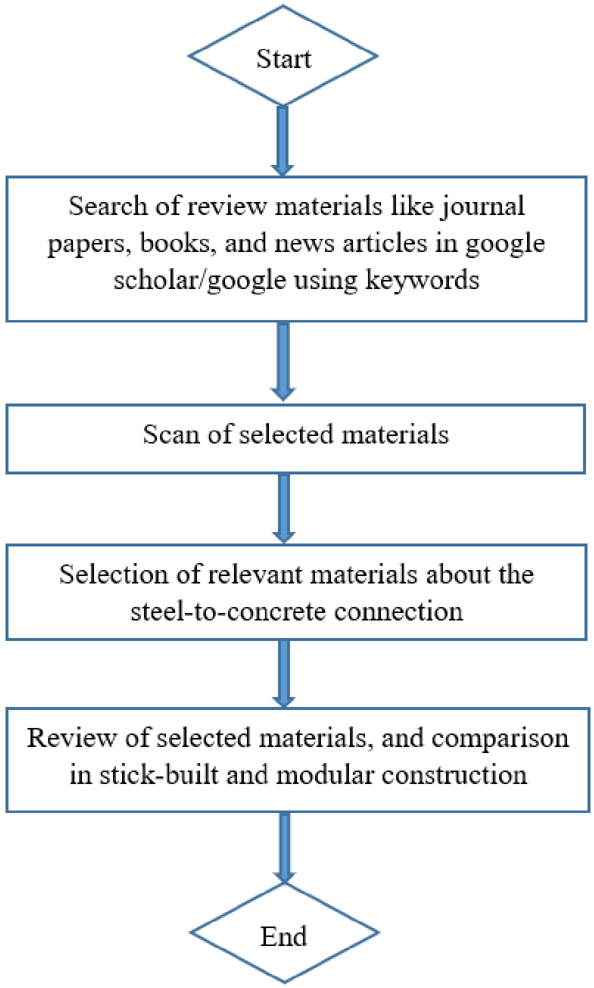

Figure 1. Flowchart of methodology

3. STEEL MODULE TO CONCRETE CORE CONNECTION

High-rise buildings require stiff structures to resist lateral loads. Conventional stick-built tall buildings are constructed using concrete cores and perimeter frames [20]. The outrigger beams are framed in between cores and perimeter columns. Similarly, modular high-rise buildings are constructed using concrete core walls and modules to balance the lateral forces [10]. The connection of steel modules-to-concrete core of modular buildings can be compared with the connection of steel beams to the concrete wall in stick-built buildings. The structural analysis provides the connection details.

3.1 Connection methods of steel beam to reinforced cement concrete core

In a tall modular building, the surrounding modules balance gravity loads while the concrete core balances the lateral loads. The interconnected modules can transfer shear forces to the concrete core. There are various ways of designing for connection between the concrete shear walls and steel beams. The steel module is a steel frame box. The beam of this module is attached to the concrete core having a steel plate embedded in it. The steel base plate used in the Croydon tower concrete core was around 400-500 mm square each and was positioned such that the modules could be attached with them within the level of 0.1mm [21].

Three connection models using Extended 3D analysis of Building Systems (ETABS) are proposed in 2019 for high-rise modular buildings [22]. One of them is the core-to-module connection. This study shows the fixed end rigid segment embedded inside the concrete wall and the steel beam attachment with the rigid segment by bolts. It demonstrates the pin-end connection of the concrete core to the module using the bolt method.

Similarly, Stora Enso published a design manual for the 3-8 story modular building system that shows concrete core bracing [23]. This manual shows the joining of a module to a concrete core with a pin settlement. Inter module connection transfers the force to the core and the overall modular building is stabilized by strong connections between the core and modules attached to it. Choi et al. (2017) have demonstrated a similar connection system of the module to the concrete core [24]. They performed a numerical analysis of a high-rise modular building and found the use of the bolted connection between the steel beam and concrete core by embedding gusset plates with stud bolts into the concrete. A gusset plate is a thick steel sheet used for joining two or more adjacent structural members when they are connecting or intersecting with each other. A gusset plate is attached with the steel plate embedded inside the concrete.

Handbook of Structural Steel Connection and Design explains the connection system of outrigger steel beam and concrete walls in the steel-framed stick-built building [20]. The book addresses the use of shear connection i.e., bolted type up to 30 story building. Shear connection transfers little or no moment from the beam to the core wall. The steel plates with shear studs are inserted in the concrete core wall, and the steel beam is attached to it using bolts. It mentions that plate is embedded during the casting of concrete that may involve slip forming and the steel beam is bolted to the stem of a steel plate. The erected steel plate or shear tab is attached to the embedded plate by welding. The details of embedment can vary for large moments like the plate can be embedded by anchoring it using an outrigger beam-like structure inside the concrete [20].

Chua et al. (2020) designed and studied the 40-story residential steel modular building having reinforced cement concrete core walls [25]. In this study, the modules are connected around the core by welding, a fixed-ended connection method. The connection is done by using steel plates embedded in the core wall and the steel angle of the module ceiling beam [25]. In the study, the core and columns are firmly connected to the building foundation. The researcher observed that the core resists 95% of the base shear.

Moreover, the Handbook of Structural Steel Connection and Design also explains the connection of steel beam-to-concrete core using moment connections in stick-built buildings of more than 30 stories. The perimeter columns are firmly connected to the core by the means of outrigger beams in tall buildings. Moment-resisting connections transfer the bending moment to the core wall and reduce the lateral deformations of the building. Moment resisting connections between the steel beam and concrete wall can be done in different ways like welding the steel beam to the embedded plate in the wall or inserting the beam inside the concrete wall [20].

3.2 Steel plate embedment

The first step of the connection method involves the steel plate embedment into the concrete core. Tensile, compression, and shear forces should be analyzed to calculate the tensile capacity, ductility, size, and the number of studs for embedment of steel plate into the concrete wall [20]. The structural engineer should analyze, design, and review the constructability process of the connection system and determine the thickness and size of the plate, the length and thickness of studs that anchor the plate, and the joining method. The design and constructability of steel plates embedment in the concrete core should be given high priority like the controlling concrete cover, clearance between concrete bars and plate, etc. [26]. The contractor must hold responsibility for layout, forming, installation, concreting, and postplacement activities [26].

3.3 Factors for connection design

The connection design requires the studying of strength, stiffness, stability, serviceability, and cyclic behavior of structural elements [20]. The strength of the connection defines the strength and stiffness of the structure. So, the design of connection elements should be done in a way to prevent failures by weld fractures. Service loads like winds, and machinery movement cause impacts in connections leading to fatigue cracking. Design should be done by analyzing the ultimate strength limit state. Moreover, one should conduct nonlinear dynamic time-history analyses using moment-rotation characteristics to understand the connection behavior of steel beams to concrete walls [20]. Generally, for the high stress caused by the low cycles of earthquake loads, the bolted connections demonstrate better performance [20].

4. CONCLUSION AND DISCUSSION

Rigid connection is important for moment resistance along with force. Welding is a more rigid connection method due to the continuous attachment of cross-section. Therefore, welding is beneficial for high-rise modular buildings as high lateral loads like earthquakes and wind acts on them. Several high-rise modular buildings were constructed, and some are under construction, but joining techniques still lack proper guidelines. This paper presents a review of steel modules connection methods to the concrete core. Here, the authors compare the connection methods of steel to the concrete wall between steel-framed stick-built buildings and steel modular buildings. The demonstration of steel-to-concrete connection by Shan et al. (2019) and Choi et al. (2017) in modular high-rise buildings show similar design concepts as explained in the handbook for steel-framed high-rise buildings. Also, the design manual of Stora Enso regarding steel modular buildings explained the connection system similar to the connection system of steel beam-to-concrete in the steel-framed buildings. These materials show how the bolt method is used to connect steel beams and concrete walls. The conclusion derived by Chua et. al. (2020) regarding the weld connection of steel-to-concrete in the modular building is like the connection method explained by the handbook.

The connection of surrounding modules to the core in high-rise buildings is the major factor in determining the stability of the building. In modular construction, all four types of connection: intra module connections, inter-module connections, module to the frame or core connections, and modules to foundation connections are subjected to vertical and horizontal loads. The design should consider more lateral forces as the height increases. Strong inter-module and modules-to-concrete core connections are necessary to transmit lateral forces to the core. Also, the concrete core should be strong enough to resist those lateral forces and transmit them to the foundation. The previous studies show the connection of steel -to- concrete in modular construction is like that in steel-framed buildings. The use of bolt connection and weld connection depends on the structural analysis and design considerations of the building elements. The joining of the steel modules -to-concrete core should be made in level and within tolerance. This applies to inter-module connections as well. The connection-induced eccentricity within the modules can cause instability. Proper connection of inter modules, and modules-to-core maintains the integrity. The design of connection like type, size, thickness, etc. of welding and bolting is the most vital in high-rise buildings as it ultimately determines the stability of the overall structure.

Further research on connection systems and joining techniques is needed to develop the guidelines that can be used by construction companies for easy and rapid modular construction in high-rise buildings. The connection of steel modules -to-concrete cores should be defined more clearly so that construction workers, scholars, and researchers can easily understand and maximize the use of modularization. Advanced computational tools and proper design guidelines should be developed for the structural analysis that determines the features of the connection process.

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