Finite Element Analysis on Seismic Response of Novel Joint in Prefabricated Modular Steel Buildings: A Review

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Abstract - Prefabricated modular generation promotes off-site production of modules and on-site assembly through enhancing the construction efficiency, safety and productivity. However, the joining of individual modules needs special connections which provides fast installation and robustness enough to ensure structural integrity. The restrictions on the overall dimension and weight of the module components for lifting and transportation provides a need for develop a more efficient structural module system that is lightweight and fast to install. Joint plays an important role in structural behaviour and load transferring in modular steel structures. In the beginning the conventional joints are prepared by connecting plates bolted with many numbers of nut and bolts and also by the use of welding. In this study, an innovative novel joint is introduced and analyzed under different loading conditions using ABAQUS software. Novel joint is a type of bolted joint providing tenon-gusset plate as horizontal connection and long beam bolts as vertical connection. A single novel joint can support upto eight modular units.

Keywords- modular steel structures, novel joint, tenon-gusset plate

I. INTRODUCTION

Modular creation includes prefabricated room-sized volumetric devices which might be generally completely geared up out in manufacture and are mounted on-site as load-bearing building blocks. Their number of major benefits are, Economy of scale in production of a couple of repeated units, Speed of installation on-site, and improved quality and accuracy in manufacture. Potentially, modular steel structures also can be dismantled and re-used, thereby correctly preserving their asset value. The modular construction has lots of application in construction industry which includes hotels, pupil residences, army accommodations, and social housing, in which the module dimensions are compatible with production and transportation requirements. **(Lawson R.M. et al., 2012)** describe the blended use of modules, panels, and metal frames to create extra adaptable constructing forms **[3]**. Steel modular units may be built specially in types. They are load-bearing modules, wherein hundreds are transferred via the facet partitions of the modules and Corner-supported modules, wherein hundreds are transferred through side beams to nook posts. MSB interconnections has fantastic importance of their structural balance and robustness. **(Annan et al., 2009)** proposed a horizontally and vertically separated connection, wherein the lower and top modular columns are partly welded to shape the vertical connection and the shop-welded angles are field-bolted to the ground beams to shape the horizontal connection **[11]**. Subsequently, they also mentioned the impact of direct welding among the strings and the ground beams at the structural layout of modular structures. There are unique styles of connections used to attach those modules collectively. A connection named novel joint and their manufacture and evaluation are mentioned on this paper. **(Chen et al., 2017)** evolved a plug-in connection device that might join modular structures horizontally and vertically on the same time **[6]**. The check results confirmed that the beam–beam connection reduces the shear deformation on the corner of the module. The consequences of finite detail modeling display that the upper and lower intramodular connection shows an independent mechanical behavior. Novel joint is a kind of bolted joint imparting tenon-gusset plate as horizontal connection and long beam bolts as vertical connection. A single novel joint can assist upto 8 modular units.

II. INTERMODULAR CONNECTIONS

The prefabricated steel modular structures may be built specially in types. First kind is load-bearing modules, wherein loads are transferred via the facet partitions of the modules and the opposite kind is Corner-supported modules, wherein loads are transferred through side beams to corner posts. Mostly corner supported connections are used because of their higher structural overall performance-to-weight ratio and better flexibility in architectural format plan for steel modular units**. (Chua et al., 2020)** founds that the corner supported modular devices are designed to face up to the gravity loads while an independent reinforced concrete middle wall system is wanted to resist to the lateral

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forces **[7]**. In high-rise modular steel structures, the modules are clustered round a middle or stabilizing system. The unique functions of the selected modular systems to be properly understood by the design team at early stage so that the detailed design conforms to the limits of the particular system and should be clearly conveying to all labours for safe and easy construction. For tall buildings, the benefit of connecting the modules influences the rate of production and the rigidity of the inter-module connections influences the general balance of the construction. The modular steel structures include separate modular units stacked up vertically and horizontally. For corner supported modular systems, the modules are linked to each other on the corners, even though they also can be linked via floors or along the edge beams. Due to the geometric constraints in which a couple of beams and columns meet on the connecting areas in addition to the obstruction of partitions or walls and inner finishes, the connections are to be built. In the past, modular metal constructing connections are evolved with light-weight C-phase beam individuals or simplified frames and additionally very restricted and limited information are determined on improvement of joint for HSS individuals, connection association and structural overall performance of complicated types of joints observed via way of means of its simplification with spring connector**. (Annan et al., 2009)** proposed a welded joint for modular steel connection and investigated the seismic overall performance via way of means of experimental observations **[11]**. According to (Lawson et al., 2007), single bolt joints for angle section column and square hollow section column. Upper and lower module column are linked with a single bolt. The bolt may be mounted directly (for angle section column) or via an access through hole (for square hollow column). However, those styles of joints can't be used for center columns in which extra beams are gathered as clusters and required them to joint with columns. This connection hassle will restriction the plans of modular steel construction. Other styles of joints have been evolved to clear up this hassle. **(Chen et al., 2017)** evolved beam-beam joints for square hollow column which introduces a cast plug-in-device is ready among the top and lower square hollow columns **[6]**. Long beam bolts penetrate the beams of upper and lower module and join the beams. Also, plug-in connections with bolts can be used for the inter-modular connection for H-section. These joints may be followed for center columns, the connecting bolts are set on beams and feature conflicts with inner end and different mounted systems. Also, **(Khan et al., 2020)** proposed a new and efficient kind of joint named novel joint specially for pre-fabricated modular metal structures **[1]**. In the case of novel joint, it connects beams and columns by the usage of bolts and gusset plate. The steel modular units linked via way of means of joints are proven in figure 1 **(Chua et al., 2020) [7].**

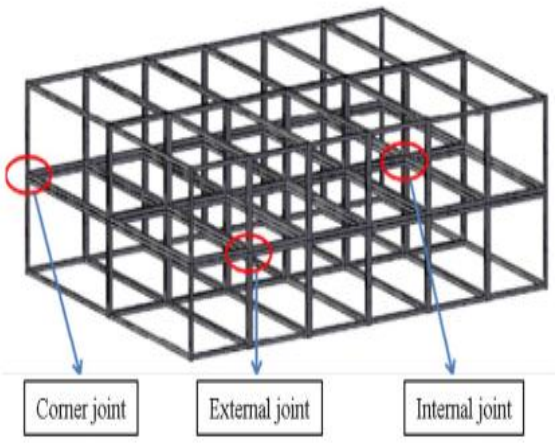

Figure 1: Steel modular interconnections (Chua et al., 2020)

III. NOVEL JOINT

Novel joint is a kind of bolted connection that's linked vertically via lengthy beam bolts and slotted-in tenons and horizontally via way of means of intermediate gusset plate. Novel joint may be assist 8 modular units at a time. Bending moment as uplift pressure is implemented at the top of the column, the disturbance is produced and gap being producing among the top and lower elements of the connection. As the distance among floor beam and gusset plate continues growing, the floor beam continues bending and faces bearing stresses towards beam bolts. With the slow boom of uplift pressure, the motion of column towards tenon will increase which exerts shearing pressure at the column bolts. Novel joint may be built without or with the presence of stiffeners. Generally, stiffeners are welded with beams and columns. The hollow steel section columns, floor beams, ceiling beams, cover plates (CPs) on beams, long beam bolts and stiffeners in line with Chinese requirements have been made from Q345B steel while, the plug-in device became crafted from ZG35 steel material. The columns and beams have been welded via way of means of groove welding while stiffeners via way of means of fillet welding with twine ER50-6. Novel joint includes three lengthy beam bolts along vertical path to attach floor beams and ceiling beams and bolts along horizontal path to attach columns with connection device or plug-in device. An exterior corner novel joint is shown in figure 2 **(Khan et al., 2020) [1]**.

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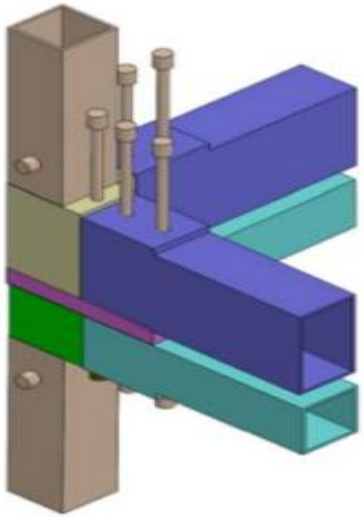

Figure 2: Novel joint (Khan et al., 2020)

IV. MATERIAL PROPERTIES

(Khan et al., 2020) states that a stress-strain curve which indicates a bi-linear behaviour with strain hardening became described for the steel substances is used for the novel connection **[1]**. In the elastic material behaviour, poison's ratio and modulus of elasticity "Es" have been described. The stress-strain curve in figure 3 shown below **(Yan et al., 2015) [4].**

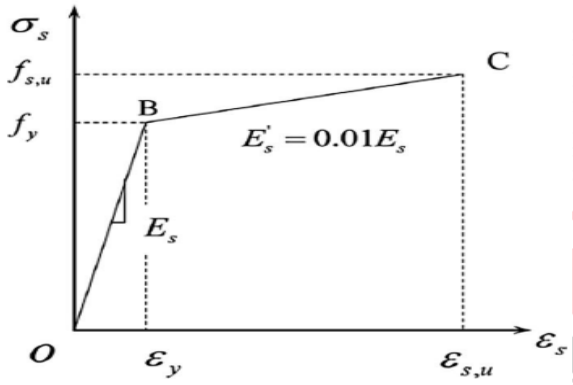

Figure 3: stress-strain curve of steel in connection (Yan et al., 2015).

In the plastic material behaviour, material's yield strength "fy", ultimate strength "fu" and strain values for corresponding strengths have been described in line with the values given from the test results as enlisted in Table 1 **(Chen et al., 2017) [6].**

Structural component	Thickness (mm)	Yield strength f_y (MPa)	Ultimate strength f_u (MPa)	Elongation in % age
Column, beam plate	8	425	575	30
Stiffeners	16	350	510	26
Cast plug-in device	–	330	350	22.5

Table 1: Material properties (Chen et al., 2017)

V. FINITE ELEMENT MODEL

(Khan et al., 2020) develops a finite element model of novel joint by using a software, ABAQUS/standard (ABAQUS/CAE 2013) [1]. For more accurate and reliable FE results, static-general step system with computerized stabilization and viable least increment size became selected for appearing each static and quasi-static analyses on novel joint. Accordingly, the bolt nuts and heads have been modelled round and collectively with bolt shank at the same time as the threads at the bolt shank and nuts have been neglected. The gap among the bolt shank and bolt hole became left out to keep away from modelling complications. The flanges of beams and cover plates have been modelled collectively to reduce the contact pairs for surfaces. Detailed FE Model for FE evaluation of detailed model of novel joint, hexagonal structured mesh controls have been implemented on all structural components. All components which include bolts, columns, beams, connections have been meshed with 8-node linear brick, reduced integration, and hourglass control element type (C3D8R). The correct choice of mesh density i.e., high-quality, more high-quality or coarse mesh for every issue of joint became carried out via way of means of evaluating the load– displacement curves of each FE (for every mesh density) and check. As received from the consequences of non-linear static evaluation, load–displacement curves have been overrated with coarsely meshed joint even as more high-quality mesh led to underestimating the results in comparison to test results. The connection region, bolts and bolt holes have been modelled with high-quality meshes for higher simulation of stress concentrated region. In bolt-hole contact application, bolts have been taken into consideration as master surfaces. Meshing is done with an element size of 30 mm for columns and beams and 10 mm for joint and bolts which gives more accurate results with the experimental findings. The interaction among columns and connection, beams and connection, columns and bolts and beams and bolts have been furnished with surface to surface with finite sliding and "hard contact" withinside the normal direction, however withinside the tangential direction as "penalty friction". The hard contact formula interaction in ABAQUS indicates that interacting surfaces will share pressure only in the time that they are in contact. If they may be separated from each other, no pressure could be transferred among the surfaces. In ABAQUS the penalty friction formula permits slip among or extra contacting surfaces (bolts with beams, cover plates) relative to each other. The friction coefficient suggests the frictional pressure amongst interacting surfaces. This kind of hard contact and penalty friction formula permits the relative movement of the additives and avoids them from penetrating in every different. To discover the correct value, special observe became carried out on three different values of friction coefficient i.e., 0.2, 0.3 and 0.4. The FE

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evaluation with friction coefficient of 0.2 led to decreasing the load carrying capacity and 0.4 growing than experimental findings. Therefore, friction coefficient of 0.3 became selected for interaction surfaces. Besides bolts that have been modelled frictionless in FE evaluation. In the exterior and interior middle connections, the adjoining columns and joints of the adjoining modular devices have been simulated with hard contact for sharing of pressure when they are in contact. In the experiment, movements have been restrained in all directions at bottom portion of the lower column, X and Z direction at top end of the upper column, at the same time as at ceiling beam and floor beam, movement in Y direction and rotation in Z direction became restrained. In ABAQUS/CAE, horizontal displacement-controlled loading of one 100 mm and axial compression pressure calculated from axial force ratio (AFR) should be given to the top portion of the upper column. **(Chen et al., 2017)** determines, with its large slenderness ratio, the modular unit column became designed with stability control, and the axial pressure ratio n (the ratio of compressive force N withinside the actual construction to the design compressive strength Nu) became normally decrease than 0.3 **[6]**. So, an axial force ratio of 0.2 became followed and therefore axial pressure is taken as 286.272 kN . The pretension load required for locating out the bolt load may be calculated via way of means of an equation,

$$P = \frac{0.9 \times 0.9 \times 0.9}{1.2} A_e f_{tv}$$

where, P= Pretension force; A_e= Effective area of bolt; f_{tv}=Tensile strength of bolt=180 MPa.

According to **(Brunesi et al., 2015)**, a refined nonlinear solid detailed FE model, accounting for the effect of friction, preload of bolts, relative slippage of additives, should properly reproduce the results obtained from the tests **[12]**. **(Renwei et al., 2021)** proposed that each one degrees of freedom on the upper and lower portion have been constrained to attain a fixed state in order that a z-direction constraint plane became set on the dual beams to simulate the out-of-plane restraint device in experiment **[2]**. The seismic reaction of novel joint may be analyzed against static and quasi-static cyclic loading.

VI. RESULTS AND DISCUSSION

(Lawson R.M. et al., 2012), investigated about the future scope and applications of modular steel structures. There are several case studies of buildings with different stories are discussed in the paper **[3]**. By using this steel modules with concrete will be an asset for the whole construction industry. Modular construction will reduce construction wastes by 10-15%. Also, it will reduce the time of construction and the noises and disturbances within the site. The number of workers required on site should be also less for modular steel building construction. According to **(Chen et al., 2017)** an innovative plug-in device and bolts for beam-to-beam connection is used **[6]**. The final results show, there will be a gap formation between the two columns due to its two-unit connection. This gap will create deformation, cracks and bending. While in the study of **(Khan et al., 2020),** finite element analysis of novel joint is performed in ABAQUS software **[1]**. The results, against lateral loads, the generated gap between the upper and lower portion of novel connection, the bearing failure of floor beam occurs. The finite element analysis results show a good agreement with the experimental results.

VII. CONCLUSION

In this paper, a study about novel connections on prefabricated modular steel structures are conducted and a introduction of finite element analysis on novel joint is conducted and following are the findings of study. As modular steel structures are assembled with room modules, the powerful joints among modules are key elements. The overall performance and reliability of the joints will have an effect on the overall performance of the structure directly. The novel connection consists of column and beam tenons even as long beam bolts fabricated from Q345B grade steel for vertical connection and ZG35 grade steel is used for plug-in device. Gusset plate is used for supplying access gap and horizontally connecting the modular units. By analyzing against quasi-static and static situations, we will decide the seismic reaction of prefabricated modular steel buildings. From these studies, the results of finite element analysis of novel joint show better load carrying capacity and stiffness than conventional steel joints. Also, the novel connection shows a good seismic resistance.

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