DESIGN AND STATIC BEHAVIOR OF BEAM-TO-BEAM-TIED CONNECTION FOR MODULAR STEEL BUILDINGS

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Abstract. *Modular steel building(MSB) is the high-end prefabricated building product with outstanding advantages of high assembly rate and environmental friendliness. Specially, the connections between modules are critical parts that can strongly influence the overall structural stability and robustness. This study presented an innovate MSB connection design that has the intermediate plug-in device and beam-to-beam bolting system as horizontal and vertical connecting respectively. Detailed connecttion and features for MSBs were introduced. Then static behaviors of the different position connection were investigated through static monotonic loading tests, including one direction corner connection and two direction inner connection. Effect of diagonal stiffener was discussed trough experimental tests. Results showed that gaps formed between upper and bottom columns can influence the deforming patterns and bending demand distributions at each unit joints.*

Keywords: Modular steel building, Plug-in device, Beam-to-beam-tied connection, Static uniaxial loading test, Diagonal stiffener.

1 INTRODUCTION

Modular construction provides a new way of building based on factory-made units that are installed and connected on site to creat functioning modular building [1]. The discrete modular units usually form a self-supporting structure in its own, and are generally built in the factory to reach a fully fitted state that completed with floors, lighting, plumbing, heating, etc. before they are delivered to site for installation[2]. The assembly line construction mode in manufactory can effectively reduce the time cost and waste, and ensure the high quality control and accuracy of construction at the same time. The modular constructions are found being used in North American, Japan, and in parts of Europe[3], with the application generally in low rise houses, and some high rise buildings like apartment buildings, student residences and hotels[4].

Modular steel building (MSB) systems differ significantly from the traditional onsite counterpart in terms of detailing requirements and method of construction[5]. And then the "unit-prefabricated onsite-assembled" construction method leads to different structural requirements from traditional structures, especially on the connection designs[6, 7]. Traditional frame structure generally features the continuous single column concept that has one or multiple beams connected to with moment connection or joint connection[8]. While in MSBs, the whole structure has many sub-structures and each structural unit has its own frame system. Then at the connecting region, there would have many small beams and columns meet together which creates new challenges on the structural design. As in Fig.1, the corner joint has 2 columns-4 beams, side joints have 4 columns-8 beams, and inner joint has 8 columns -16 beams construction.

MSB connections are structurally important, as they can strongly influence the overall structural stability and robustness of the assembly of modules. Annan proposed a horizontally and vertically separated connection solution that has partial welding between lower and upper modular columns as the vertical connection, and field-bolting on the shop-welded angles between the floor beams[5]. Then he also discussed the effect of direct welding between strings and floor beams on the structural design of modular structures[2]. Park introduced a unit connection that utilize the cross shaped plate installed at column flange and then bolted to the beam web, and an embedded steel column-to foundation connection for a modular structural system[9]. Fathieh once performed seismic evaluation on modular steel buildings[10], during which the inter-modular connections were simulated by adding additional vertical short column and horizontal beam. And Bae developed the details in the beam-to-column joints in unit modular system through basic experiments and theoretical analysis, to help developing the high -rise frame unit modular system[11].

Present designs of MSB connection are generally made at two ends of module columns in the form of horizontal or vertical connecting plates. Access for these attachments has to be made externally to the modules, and sometimes can pose practice difficulties for module arrangements. Then to solve this problem, this paper proposed a new beam to beam modular connecting method and the static performance of the corner connection and edge connection was analyzed, which results could be used to guide the real structure and connection design for modular steel buildings.

2 DETAILS OF THE NEW BEAM TO BEAM MSB CONNECTION

The compositions of the new beam-to-beam-tied connection for MSBs are given in Fig.2. The connection had two effective connecting parts, which are the plug-in device to transfer the horizontal forces and the long stay bolting system at beam ends to tie the upper and bottom modular beams together. The modular beams and columns are all made of cold formed rectangular steel tube and the small beams and columns are connected through welding.

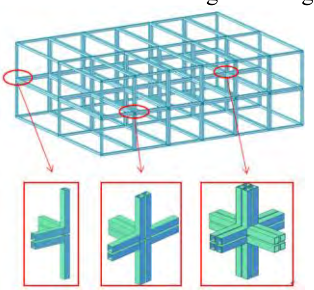


Fig 1. Connection features in MSBs

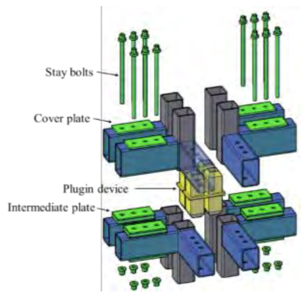


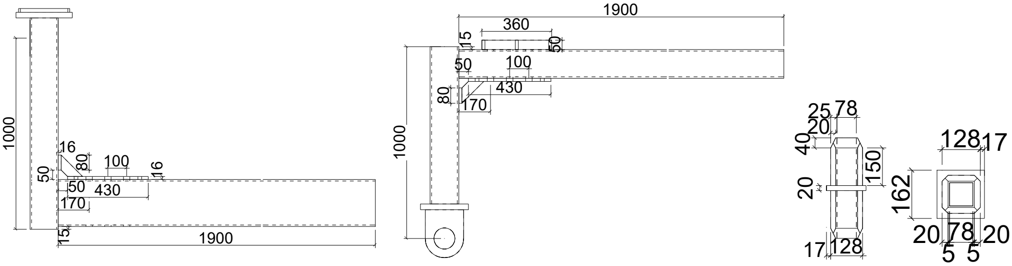
Fig. 2 Beam-to-beam-tied connection for MSBs

In this MSB connection, no additional welding process are needed at the construction site. Each well-built unit will be transported to the working site and lifted to the position right above the designed location. Put the plug-in devices to the top ends of bottom modular columns, then align and insert the bottom ends of upper modular columns to the four plug-in devices. The plug-in unit is made of cast steel that has two square tube pieces connected to both sides of an intermediate plate. The tube pieces have their outer dimensions being the same as the inner size of modular columns, with a shrunken end to help the alignment and to allow for installation error. Then the upper and bottom unit will be clasped together along the horizontal direction. Due to the lack of vertical linking mechanical, the plug-in unit itself is not able to resist the pull-up force. And this deficiency is then compensated by the long stay bolting system at beam ends. In traditional inter-modular connection, there often have side plates welded or bolted to the beam or column sides which requires additional construction space between adjacent modular unit. But generally, the intermediate space cannot be too large or allowed for architecture and structural consideration, thereby inducing difficulties for modular installations. While in this connection design, the long bolt can be installed from inside of the modular units, and there only has plate thickness gap between upper and bottom beams. The unit connection has the moment resisted only by the welded beam section, then to strength this region, a pair of diagonal stiffeners were added and both stiffened and unstiffened connections were all studied here.

3 EXPERIMENTAL STUDY

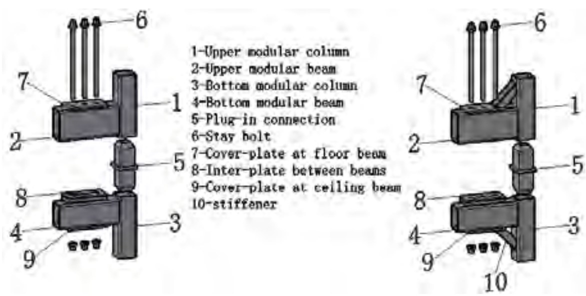
3.1 Description of test specimens and test setup

The different position designs in MSBs, the corner connection （T shape）and edge connection （Cross shape）, were studied. Dimension of test specimens were given in Fig3 and Fig4. Then to explore the working mechanism and effect of connection in different position and the key investigated parameter was the effect of diagonal stiffener.



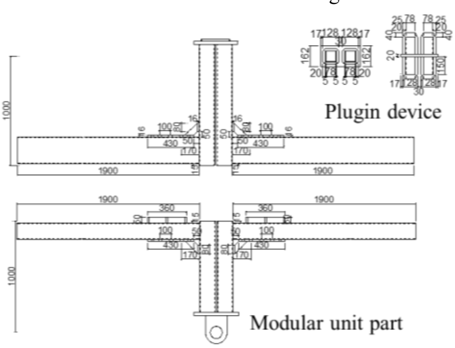
(1) Upper modular part (2) Bottom modular par (3) Cast plug-in unit

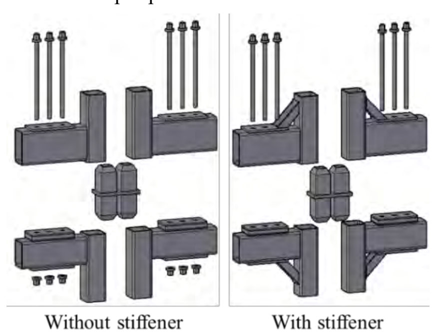
(a) Major dimensions



(b) Specimen types

Fig.3 Detail information of T shape specimens





(a) Major dimensions (b) Specimen types

Fig.4 Detail information of Cross shape specimens

Totally 4 monotonic loading tests were performed, with the specimen information in Table.1. All the specimens were made of Q345 steel and took the groove fusion welding for those welds. The diagonal stiffeners were connected through fillet welding with wire ER50-6, and similar to practical process, only appearance inspections were performed to ensure the quality.

Table 1 Specimen information

Specimen	No.	Ceiling beam	Floor beam	Modular column	Stiffener thickness	Stay bolt	Axial force ratio
T-Shape	S1	150×150×8	150×250×8	150×150×8	None	24	0.2
	S2	150×150×8	150×250×8	150×150×8	10	24	0.2
Cross-Shape	SC1	150×150×8	150×250×8	150×150×8	None	24	0.2
	SC2	150×150×8	150×250×8	150×150×8	10	24	0.2

All those experiments were performed in structural lab at Tianjin university, with the test setup given in Fig.5. The connection adopted column end loading method that had beam ends and bottom column ends pin constrained to simulate the inflection point boundary.

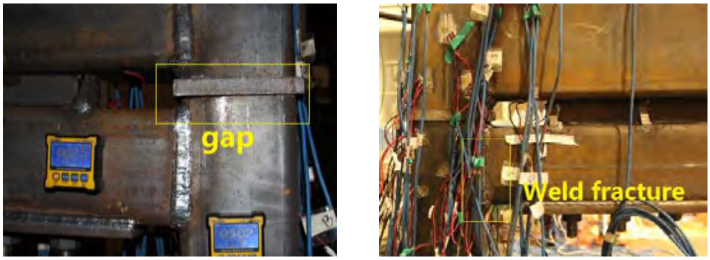
（a）The corner connection （T shape） （b）The edge connection（Cross shape）

Fig.5 Test setup

Two monotonic static loading tests of T shape connection (S1-S2) and two monotonic static loading tests of Cross shape connection (SC1-SC2) were performed to verify the safety of different positions design and to understand the practical load bearing performance . Totally two specimens were tested in each connection: one is the base test that has the modular beam welded directly to the modular column, and the other one is the strengthen connection that had two pair of stiffeners added to the inner side of upper and bottom unit joints, as in Table 1. Other member dimensions are the same for the two specimens.

3.2 Results of static uniaxial loading test

Specimen S1 is the unstiffened connection. As the lateral loads went up to 89.8kN and the loaded displacement reached 45mm, there had visible gap between the bottom column and plug-in device,(Fig.6(a)). Then as the increase of lateral load, the gap got widened. When the lateral displacement of top column end reached 78.7mm (lateral load was 111.5kN), a huge sound was heard and test was terminated. A weld fracture was observed at the welded joint between ceiling beam and bottom column(Fig.6(b)).



(a) Gap at plug-in device (b) Weld fracture failure

Fig.6 Failure mode of S1

Compare to S1, specimen S2 had diagonal stiffeners to strengthen the unit joint, as shown in Fig.7. When the loading displacement reached 31.4mm (load reached 128.8kN), turning point was witnessed at the load-displacement curve, and the specimen entered its elastoplastic stage. When the lateral displacement reached 51.9mm, the lateral load went up to 162.6kN and a gap was observed between the upper column and plug-in device, but no strength reduction was presented. When the lateral load got to 199.4kN, the weld between diagonal stiffener and cover-plate had brittle fracture with a huge sound and a sudden drop at lateral strength(Fig.7).

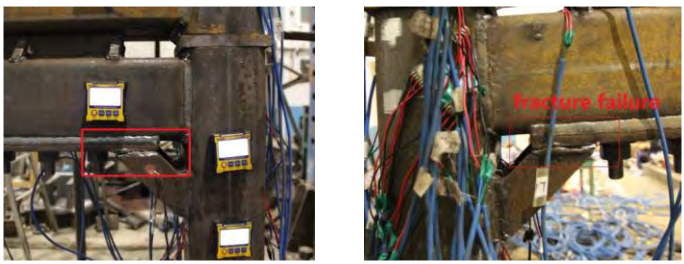
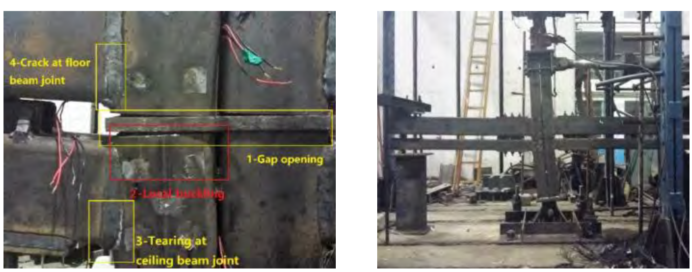


Fig.7 Failure mode of S2

Specimen SC1 is the regular inner connection without any stiffened measures. As the lateral load reached 128 kN, gap opening began to show up between two modular columns and the intermediate plug-in device due to the relatively independent construction. As the lateral load rose, the gap continued to open up. The gap led to the uneven compression transferred from the intermediate connecting device to the bottom modular column, and then led to the slight local buckling behaviors at the top end of bottom modular column. As the lateral displacement reached 88 mm, a sudden huge sound was heard and an obvious tearing crack happened at the ceiling beam column joint. As the increase of loading, the tearing at bottom unit joint continued to grow and propagated upward and the lateral strength kept on decreasing. When the lateral displacement reached 132mm, crack failure happened at the upper floor unit joint with dramatic decrease at the lateral strength and the test ceased. Failures at joint region were given in Fig.8.



(a) failures at joint region (b) Deforming state at the end of test

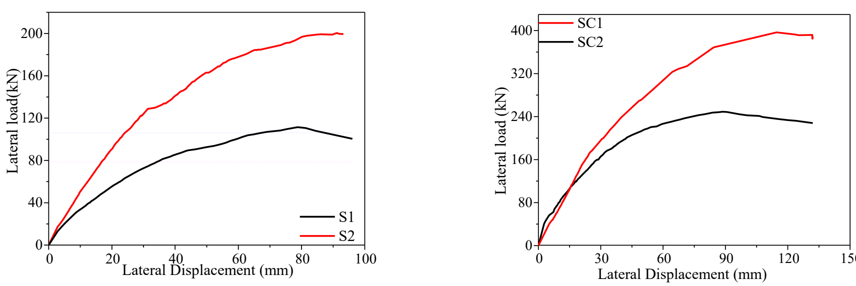
Fig.8 Failure mode of SC1

Member dimensions of Specimen SC2 are the same as SC1 but with diagonal stiffeners welded at both top and bottom unit joints. Then due to the strengthened construction, the whole connection presented a larger lateral bearing stiffness than the unstiffened SC1. At a lateral displacement of 25mm, gap opening was also observed at the joint region between upper and bottom modular parts, accompanied with slight stiffness decrease at the lateral force displacement relations (Fig.9(a)). This specimen presented steady strength increase till the loaded displacement reached 64mm. At this moment, a local inward extrusion deformation can be observed at the compressed bottom joint, which also accompanied with a second decrease on specimen strength-displacement relation. When the lateral load got to 398kN, a huge sound was heard and brittle facture happened at the weld between right bottom stiffener and column flange (in tension state at this moment). Then test stopped, and corresponding strength loss and huge deformation demand during stiffener failure also led to crack at the weld of bottom unit joint. (Fig.9(b))

(a) failures at joint region (b) Deforming state at the end of test

Fig.9 Test results of SC2

Fig.10 gives the lateral load versus displacement relations, which indicated that for both specimens, the lateral load kept increasing before failure happened. And the vertical stiffener can effectively help strengthen the connection and protect the unit joint to improve the bearing capacity.



(a) S1 and S2 (b) SC1 and SC2

Fig.10 Load displacement relation

4 CONCLUSION

In this paper, a new MSB connection design was put forwarded. The connection had the plug-in device to transfer horizontal loads and beam to beam bolting as the vertical connecting. Then the MSB connection needs no additional welding process at the construction site thus had excellent installation convenience. To understand the mechanical properties in corner and inner connection, 4 static uniaxial loading tests were conducted on the T and Cross shaped MSB connection under monotonic loadings. The following conclusions are made:

(1) The proposed MSB connection was superior to traditional connector plate and single bolt connection on the erection convenience. The beam to beam bolted connection can be accessed through infilled wall, and structural members are needed and the gap between adjacent modules can be enough small without considering the working access.

(2) In T-shaped MSB connection, both static loading specimens failed with fracture happened at unit joint welds. Then the weld at unit beam-column joint was the critical part that needed special care to ensure the weld quality and connecting ability. The connection consisted of two joint units, then under lateral loading, gap would be formed at the intermediate plug-in device and could lead to different bending rotation extents between the upper and bottom unit joints. In Cross-shaped MSB connection, specimens in monotonic loading tests all failed with tearing at the tension side of bottom joint or local extrusion deformation at the compression side of bottom column. The MSB connection allowed separate panel zone deformation between upper and bottom units, with the major column inclination and joint rotational deformation happened at the bottom units.

(3) Results showed that the vertical stiffener can effectively strengthen the connection and help the composite load transferring between assembled joints.

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