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An Analytical Study on Rotational Capacity of Beam-Column Joints in Unit Modular Frames

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***Abstract*—**Modular structural systems are constructed using a method that they are assembled with prefabricated unit modular frames on-site. This provides a benefit that can significantly reduce building construction time. The structural design is usually carried out under the assumption that their load-carrying mechanism is similar to that of traditional steel moment-resisting systems. However, both systems are different in terms of beam-column connection details which may strongly influence the lateral structural behavior. Specially, the presence of access holes in a beam-column joint of a unit modular frame could cause undesirable failure during strong earthquakes. Therefore, this study carried out finite element analyses (FEMs) of unit modular frames to investigate the cyclic behavior of beam-column joints with the access holes. Analysis results show that the unit modular frames present stable cyclic response with large deformation capacities and their joints are classified into semi-rigid connections even if there are access holes.

***Keywords*—**Unit modular frame, steel moment connection, nonlinear analytical model, moment-rotation relation, access holes.

I. Introduction

A modular system is a kind of industrialized houses construction systems which deliver modular units and connect them at a construction site. Modular units constituting a modular system can be classified as four-sided modules and open-sided modules depending on the lateral force resisting mechanism. Four-sided modules resist external loads with braces and bearing panels installed on a side. On the other hand, open-sided modules carry forces using unit modular frames which consist of beams, columns, and joints, like steel moment resisting frames. Modular frames normally consists of hot rolled steel members, such as square hollow section columns and channel beams, that are bolted together [1]-[4].

As unit modular frames are delivered to a construction site, it is general to drill an access hole at a beam-column joint in order to connect adjacent modules with bolts. As a beam-column joint of the unit modular frame is the most important element that carries and distributes external loads, the strength and stiffness of a joint have great effects on stability of the entire structure system [5], [6]. This study carried out FEM analyses to evaluate effects of an access hole which is required for fast erection of unit modular frames.

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II. FEM Analyses of Unit Modular Frames

A. Description of FEM Analyses

Fig. 1 shows an analytical model considered in the study. The length of long sides in a unit modular frame is approximately 6.3m while the length of short sides is approximately 3.2m. The height of unit modular frame is 3m. Beams and columns are made of steel channels and square hollow sections, respectively. A beam and a column are welded at a joint which is modeled with an assumption that welds have sufficient strength to avoid brittle failures. Bolt holes with 18mm diameter are drilled on the beam flange and the end plates of columns on the top of the unit modular frames. In addition, an access hole provided for bolted connection is located at the webs of a column that is parallel with the short side of unit modular frame.

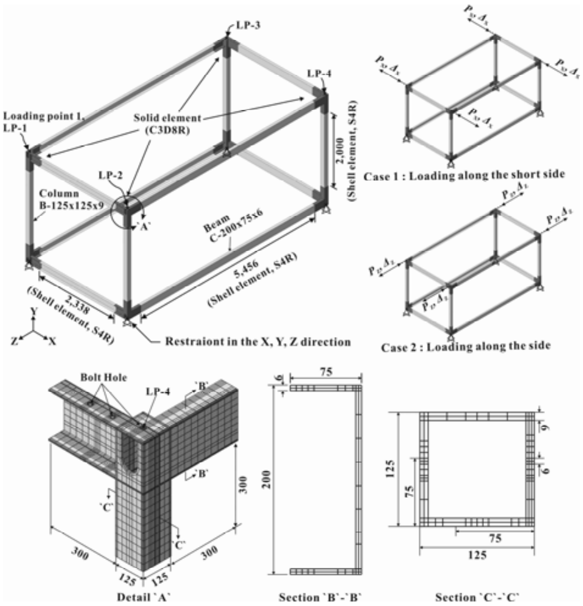


Fig. 1 Detailed boundary conditions and geometry of a FEM model

One of the common structural analysis programs, ABAQUS 6.10.1 [7] is used to conduct finite element analyses of unit modular frames. For beam-column joints, C3D8R solid elements are used while beams and columns are modeled by S4R shell elements that are capable of capturing their elasto-plastic behavior with predetermined material stress-strain relation.

For boundary conditions, pinned supports are located at the bottom of columns. Displacements along a side of a beam are imposed to four loading points at the top of a column. The analysis models are displaced in both short side (Axis-X) and long side (Axis -Z) directions.

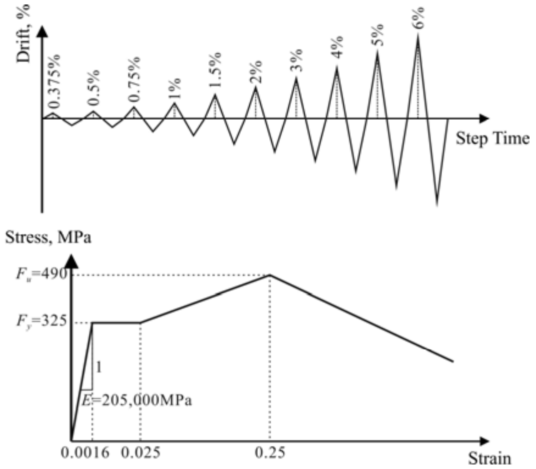


Fig. 2 Loading protocol and material property

Fig. 2 shows a loading protocol and the stress-strain curve of SM490 steel. Displacements are applied up to 6% of story drift ratios, referring to the loading protocol presented by AISC [8]. Elastic modulus and Poisson's ratio of the material, SM490 are 205GPa and 0.3, respectively. Strain hardening after the yield strength (F_y) and strength and stiffness degradation after the nominal tensile strength (F_u) are considered.

B. Result of FEM Analyses

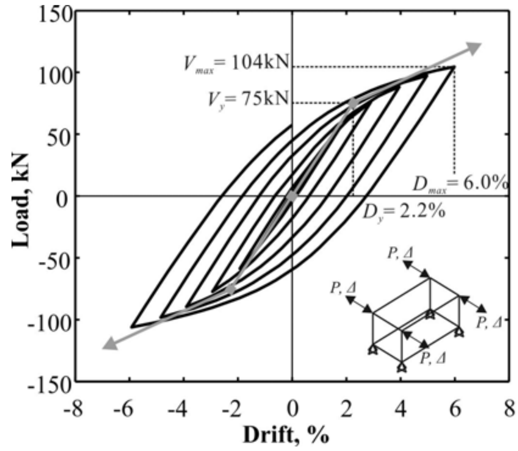
Two FEM analyses are carried out in accordance with the loading directions: Case 1 (loaded along the short side) and Case 2 (loaded along the long side).

The load (V)-drift ratio (D) curves along loading directions are shown in Fig. 3. Both analysis results do not show strength and stiffness degradation until 6% drift ratios are applied, which indicates stable hysteretic behavior. In this study, a yield point is defined as a point where an elastic line with the slop of the initial stiffness is crossed with a tangential line with 1/3 slop of the elastic line.

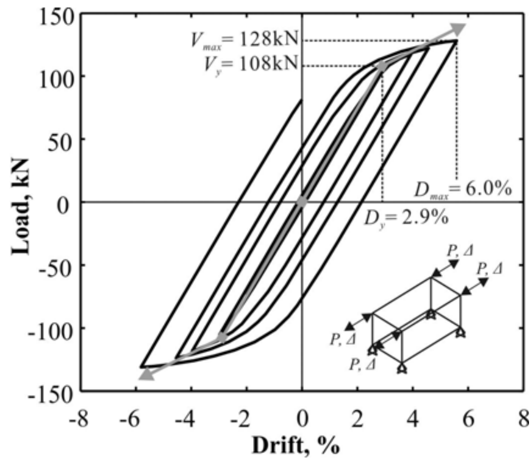
The maximum load of the Case 1 is 104kN while the Case 2 reaches to 128kN. The yield load of the Case 1 and 2 models are 75kN and 108kN measured at 2.2% and 2.9% drift ratios, respectively. It is shown that stiffness and strength of unit modular frames in the Case 1 are relatively small, compared to the Case 2.

Fig. 4 presents deformed shapes and distribution of Von Mises stresses of a joint at 6% drift ratios. Stresses are increased from the center to the end of a beam which is parallel to a loading direction. The maximum stress is found near the beam-column joint. A material yield is measured at a web of the column and top and bottom flanges of the beam.

For the Case 1, stresses are concentrated around access holes in the joint. As a result, distortion of horizontal stiffeners, relatively large shear deformations at a joint and local buckling of the beam flange are found. For the Case 2, there is no significant deformation found around access holes although the yields at the joint and the beam flange are measured. At each joint, symmetric stress distribution and deformations are found.

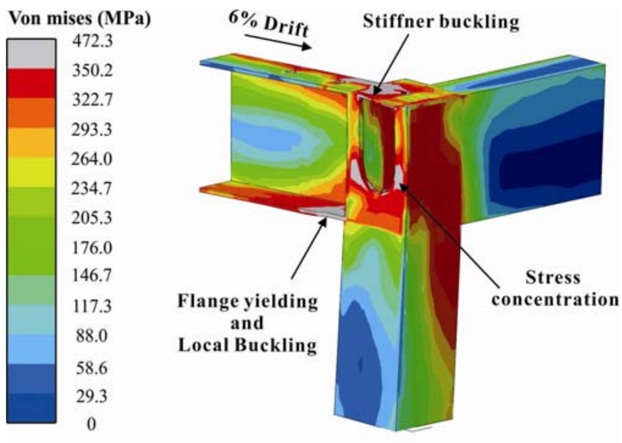


(a) Case 1

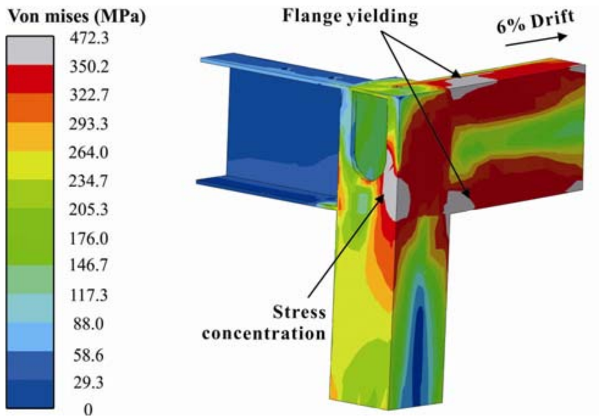


(b) Case 2

Fig. 3 Cyclic response of an open-sided module



(a) Case 1



(b) Case 2

Fig. 4 Deformed shapes and stress contour at 6% drift

III. Evaluation of Rotational Capacity of Beam-Column Joints

Since there is no criterion in defining the classification of beam-column joints of a unit modular frame in Korean Building Code (KBC2009) [9], this study classifies beam-column joints based on Eurocode 3 [10], which classifies joints according to their strength and stiffness, as shown in Table I. For the classification by stiffness, a joint is divided into a rigid joint, semi-rigid joint and nominally pinned joint, comparing the elastic rotational stiffness ($S_{j,i}$) of the joint with the flexural stiffness (EI_b/L_b) of a beam. For the classification by strength, a joint is classified as a full strength joint, partial strength joint and nominally pinned joint, comparing the flexural strength of the joint with the plastic moment (M_p) of a beam or column.

TABLE I
Classification of Joints on Eurocode 3

Strength		Stiffness	
Condition	Type	Condition	Type
$M_j \geq M_p$	Full Strength	$S_{j,i} \geq 25\dfrac{EI_b}{L_b}$	Rigid
$0.25M_p \leq M_j < M_p$	Partial Strength	$0.5\dfrac{EI_b}{L_b} \leq S_{j,i} < 25\dfrac{EI_b}{L_b}$	Semi-Rigid
$M_j < 0.25M_p$	Nominally Pinned	$S_{j,i} < 0.5\dfrac{EI_b}{L_b}$	Nominally Pinned

The bending moment diagram of a unit module frame is as shown Fig. 5 (a) when a lateral force P is applied at its top. The moment applied to every joint can be calculated as

$$M_j = M_b = -M_c = \frac{PH}{2} \tag{1}$$

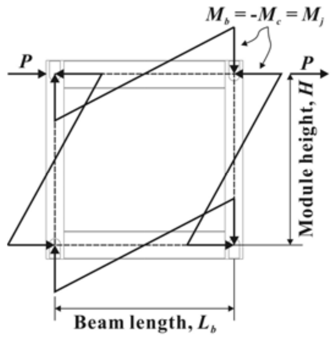
where H is the distance between the center of the top and the bottom beam as the height of the unit module.

The rotation of each member can be calculated through the longitudinal displacement distribution of the cross-section of the beam and the column which are connected to the joint as shown in Fig. 5 (b). Therefore, the relative rotation of the joint can be defined by difference in rotation between members as (2)

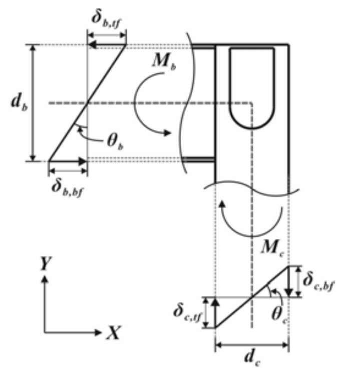
$$\theta_r = \theta_b - \theta_c = \frac{\delta_{b,tf} - \delta_{b,bf}}{d_b} - \frac{\delta_{c,tf} - \delta_{c,bf}}{d_b} \tag{2}$$

where θ_b and θ_c are, respectively, rotations of the beam and the column, $\delta_{b,tf}$, $\delta_{b,bf}$, $\delta_{t,tf}$, and $\delta_{t,bf}$ are longitudinal displacement occurring in the top and bottom flange of the beam and the column, respectively, and d_b and d_c are the depth of the beam and the column.

The moment-relative rotations of the joint along loading directions are shown in Fig. 6. In the figure, the gray line refers to the elastic rotational stiffness and two dotted lines are reference lines that can classify joints by their stiffness according to Eurocode 3. The elastic rotational stiffness is 1,780kN ·m/radian and 2,235kN·m/radian and the maximum flexural moments ($M_{j,max}$) are 39kN·m and 48kN·m of the Case 1 and 2, respectively.



(a) Moment diagram



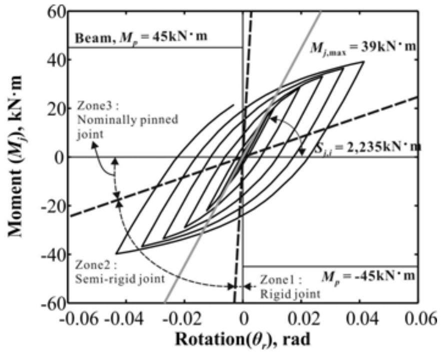
(b) Calculation of rotaion

Fig. 5 Determination of moment and relative rotation

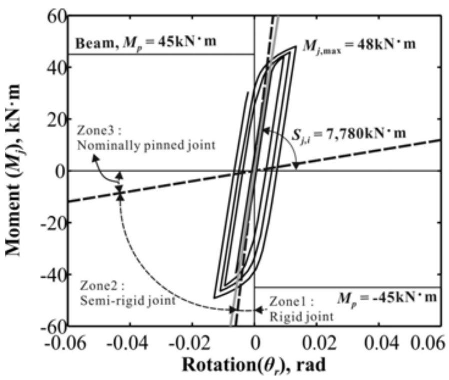
When displacements are imposed along the short side direction, sectional losses due to an access hole lead to reduce strength and stiffness of the joint. The elastic rotational stiffness of the Case 1 is 2.7 times that of the beam while that of the Case 2 is 20 times that of the beam. Both joints are classified as semi-rigid joints according to joint classification by stiffness defined in Eurocode 3.

To classify joints according to strength provided in Eurocode 3, the maximum flexural moment and the plastic moment of the beam in the Case 1 and 2 are compared. The maximum flexural moment of the joints obtained from the finite element analyses of the Case 1 and 2 are 87% and 106% of the plastic moment of the beam, respectively. The joint of the Case 1is classified into a partial strength joint while the beam-column joint in the Case 2 is considered as a full strength joint.

In conclusion, for the Case 1, relatively large inelastic deformations happen at the joint before plastic hinges are formed at the beam section. On the other hand, the beam-column joint in the Case 2 develops sufficient strength within elastic behavior until the beam member experiences plastic deformations. However, the design flexural strength is decided as the smallest value among plastic moment, lateral buckling strength and local buckling strength according to design of an ordinary steel structure. The long side directional beam is classified into a non-compact steel section of which the strength is generally governed by local buckling and its design flexural strength is 38kN·m. On the other hand, the design flexural strength of the laterally unsupported short side direction beam is 24kN·m that is determined by the lateral buckling strength. If the design flexural strength rather than plastic moment of the beam is considered, the joints in both Cases provide sufficiently strength, compared to the design flexural strengths of the beam.



(a) Case 1



(b) Case 2

Fig. 6 Moment-relative rotation relations of joints

The nominal flexural strength of a semi-rigid joint in an ordinary moment resisting steel frame presented in KBC2009 shall be designed to carry the less of 50% of the plastic moments of a connected beam and column. According to the results of analysis, the maximum flexural moment of a joint by each loading direction meets the nominal flexural strength design requirement as it is bigger than 50% of the plastic moment of a beam, which is 22.5kN·m.

IV. Conclusion

This study conducts FEM analyses to evaluate the effects of access holes at beam-column joints of unit modular frames on its rotational capacity. According to the analysis results, stiffness and strength of unit modular frames are weakened when a web with access holes is controlled by the shear compared to a web without an access hole. However, there are stable cyclic behavior up to 6% story drift with noticeable reduction in stiffness and strength.

Beam-column joints of the unit modular frame are classified according to Eurocode 3. For the joint classification by stiffness, the Case 1 and 2 are classified as semi-rigid joints which can be designed similar to those of an ordinary moment resisting steel frame. Also, the joints in unit modular frames meet the design requirements of nominal flexural strength prescribed in the KBC2009.

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