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Seismic performance evaluation of the ceiling-bracket-type modular joint with various bracket parameters

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ABSTRACT

In this study, the seismic performance and inelastic behavior of joints were investigated using the bracket thickness, depth, and stiffener of the ceiling-bracket-type modular system as parameters. The performances of the joints were evaluated through a cyclic loading test and the nonlinear FEA. The initial stiffness, maximum flexural strength, failure mode at the ultimate stage, energy dissipation capacity, and inelastic behavior were analyzed, and it was determined whether the strong-column/weak-beam-type mechanism occurs at the joint. The results of the analysis were compared with those of the theoretical and FE models, respectively. For the comparison of the seismic performances, the flexural strength of the joint at the 0.04 and 0.05 rad inter-story drift ratios, which exceed the plastic moment, was investigated. From the comparison results, the standard specimen had a sufficient structural performance compared to the reference model, which was a welded joint. The joint was shown to be capable of maintaining a seismic performance higher than 80% of the plastic moment, and showed strain curves pointing to a strong column-weak beam behavior. In the joints, the initial stiffness was increased with a higher bracket thickness. In addition, the maximum flexural strength showed a large change in the loading direction due to the ceiling bracket. If the number of stiffeners is reduced, the joint will have both reduced initial stiffness and reduced maximum flexural strength. The bracket-type modular building was shown to be an effective and dependable modular system for resisting seismic loads, and the energy dissipation capacity of the standard specimen was shown to be higher than those of the other modular joints

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1. Introduction

The modular structural system is a prefabricated construction method or system that consists of multiple sections called “modular units.” It has the potential to increase building production by reducing the construction time and costs. The general benefits of the system are construction time saving, cost saving, indoor construction by modularization, environment-friendly construction process, and quality control via BIM (building information management). Recently, the modular system began to be used in diverse applications, such as houses, apartments, university dormitories, and hospitals. Moreover, the modular unit development and the connection of the modular system for mid- to high-rise buildings, and the performance evaluation of the said system, have drawn the attention of a number of researchers of late [1,2].

Diverse studies have been performed of late on modular buildings, including studies on BIM-based modular project planning, development of a modular unit or a joint, structural performance assessment under a seismic load, and construction methods as well as case studies on modular buildings. The advantages of applying the BIM platform to the design and construction of a modular building are (i) the entire planning, design, shop drawing, and construction process can become more efficient; and (ii) the potential physical conflicts between the structure, mechanical, electrical, and plumbing systems can be easily identified early on in the design process [3]. The following are the types of selected studies on the development and structural performance of modular systems: (i) seismic performance comparison between steel-braced modular building frames and regular frames for the seismic design of assembled modular buildings [4]; (ii) a study on the framed modular system with its modular units reinforced with double-skin steel panels of slender thin steel plates rather than with braces [5]; (iii) a proposal of column-to-foundation connection of the modular system and a study on the hysteresis behavior for the cycle loading of the proposed connection [6]; and (iv) development of a new plug-in-type T-shaped beam-to-beam modular connection to facilitate the

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Notation

θ	Inter-story drift ratio (rad)
P	External force at the end of the floor beam
L_b	Length of the floor beam
L_c	Total length of the upper and lower column
L_{c1}	Length of the upper column
δ_t	Total deflection of a floor beam ($=\delta_b + \delta_c$)
δ_b	Deflection by P of a floor beam
δ_c	Deflection by a column's rotation
θ_c	Rotation angle of a column at the joint (rad)
$y(x)$	Deflection function of a column rotation
$E_{b(or\ c)}$	Elastic modules of a floor beam (or column)
$I_{b(or\ c)}$	Moment of inertia of a floor beam (or column)
λ	Slenderness of a column ($=\kappa L/r$)
λ_f	Width-thickness ratio of a flange ($=H/t$)
λ_w	Width-thickness ratio of a web ($=B/t$)
L	Unsupported length of a column
r	Radius of gyration of a column's section
ε_y	Yielding strain
${}_tK_i$	Experimental initial stiffness
${}_aK_i$	Theoretical initial stiffness ($=6903.68$ kN·m/rad)
${}_RK_i$	Initial stiffness ${}_tK_i$ of the specimen Ref-W
${}_BK_i$	Initial stiffness ${}_tK_i$ of the standard specimen (C200-4.5-2)
${}_fK_i$	Initial stiffness of the FE models
${}_tM_{max}$	Maximum moment (Experiment)
${}_RM_{max}$	Moment ${}_tM_{max}$ of the specimen Ref-W
${}_BM_{max}$	Moment ${}_tM_{max}$ of the standard specimen (C200-4.5-2)
${}_bM_n$	Nominal flexural strength of a floor beam ($=168.89$ kN·m)
${}_tM_\theta$	Moment (Experiment) at a drift ratio θ
M_p	Nominal plastic flexural strength ($=205.91$ kN·m)

easy assembly of modular units and structural performance evaluation of the interior joint of a modular building [7,8]. Among these studies, the studies on structural performance were mainly experimental researches such as a cycle loading test that focused on the joints and connections formed during the assembly of modular units. In the study on the construction method, studies on crane selection and site layout optimization for the efficient lifting of a modular unit [9] were performed, while in the present study, a mathematical model for optimization was proposed with the solution obtained via a genetic algorithm. There have been countless attempts by many studies to apply modular systems to mid- and high-rise buildings, thereby demonstrating via case studies that modular systems are applicable if the stability of the steel- or concrete-framed core is achieved even in a 25-story building [10]. Researches on the application of a brace or a shear wall as a resisting element have also been conducted [11,12]. Especially, for mid- and high-rise modular buildings, the seismic performance is highly important. In addition to this, practical application topics such as the demand generation [13] and application plan of the modular construction method [14] and have been discussed. Studies have also been performed on the assessment of the resistance performance of high-rise buildings in an extreme environment like fire [15], as well as on a modular dome composed of a highly filled extrusion wood-plastic composite member that is an eco-friendly material [16]. In particular, the improved modular design techniques have been combined with the BIM and 3D printer technologies, propelled by the increasing demand for modular systems, foretelling the possible emergence of new architectural engineering fields.

The modular system is a high-quality, mass-supply-friendly design method, and the structural performance of the joints can be competitive. The module size and manufacturing restrictions on onsite transport, however, have a great impact on the performance of the modular building. Modular units based on lightweight steel structures are mainly designed in hexahedral form, and depending on the force-resisting element, they are classified into the close-sided or open-sided (corner-supported) module [17,18]. Open-sided modules are mainly applied to mid- to high-rise modular buildings and resist external forces through the column, beam, and joints as well as through the general steel moment-resisting frames [10,17–19]. For this reason, the seismic performance of the modular building is evaluated as similar to that of the ordinary steel frame. The performance of the joint, however, is difficult to evaluate. There is also a substantial difference in seismic performance depending on the developed joints [18,19].

A modular building is usually constructed by manufacturing modular units at the factory, transporting them to the site, and then assembling the pre-fabricated units. Typically, box-type units are designed in a way that requires a minimal process to be completed onsite, with the onsite construction process shown in Fig. 1. As shown in the figure, modular buildings are built in the order of foundation work, unit lifting, and unit assembly. Box modular systems based on 3D steel frames are generally joined to the units via welding or with high-tension bolts. In particular, the upper- and lower-unit assemblies are connected together using a connection plate. As such, the onsite work process of a modular building includes the assembly of units in the manner shown in Fig. 1, whereas an access hole (see Fig. 2) is created and fastened with bolts using a manual wrench to increase the workability in the conventional construction method. This approach, however, lowers the job performance due to the loss of the cross-sectional area of the column, and it is difficult to assure seismic performance at the joint, thereby necessitating the preparation of a separate brace element. Besides, due to the loss of the cross-sectional area by the hole, the shape of the joint is not the same as that of a fully restrained moment connection. The modular building has a large increase in strength due to the overlapping columns and beams, but the increase in beam strength causes the steel frame to behave as a weak-column/strong-beam-type mechanism [20,21]. Steel moment-resisting frames are classified according to their inelastic capacity [19,22]. Among these, the seismic performance of the special moment frame is such that the earthquake energy is dissipated due to the bending collapse of the end of the beam, whereas the column and joint remain elastic. In other words, the "strong column-weak beam" design concept is aimed at optimizing the energy dissipation capacity of structures [19,22]. Therefore, a modular unit designed with a strong-column/weak-beam-type mechanism and with a fully restrained moment connection is advantageous for mid- to highly modular systems.

Recently, as shown in Fig. 3, a study on the joint [21] that can be assumed as a rigid joint was begun. The specimen was made of low-price SPSR400-grade steel and an SPHC-grade steel plate, and it was determined whether the 4.5-mm-thick C– and L-type bracket models satisfy the criteria for a special moment frame. In the study [19], the initial stiffness of the joints and the flexural strength at the 0.04 rad inter-story drift ratio were compared, and the necessity of conducting a further study on various parameters and inelastic characteristics was raised. Especially, it is necessary to analyze various parameters, such as the thickness and stiffener of the bracket, and to investigate the dissipated energy capacity and the failure mode in the column and beam.

Therefore, in this study, the seismic performance and inelastic behavior of the joints were investigated using the bracket thickness, depth, and stiffener of the ceiling-bracket-type modular system as parameters. The specimens were made of general structural steel SS400 [23] and SM490A [24], respectively, and the performances of the specimens were evaluated through a cyclic loading test and the nonlinear FE (finite element) method. The initial stiffness, maximum flexural strength, failure mode at the ultimate stage, energy dissipation capacity, and inelastic behavior were analyzed, and it was determined whether the strong-column/weak-beam-type mechanism occurs at the joint. The results of the analysis were compared with those of the theoretical and FE models, respectively. Also, for the comparison of the seismic performances, the flexural strength of the joint at the 0.04

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