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Full-scale seismic performance test of a two-story modular frame

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Abstract

In this paper the cyclic behavior of the modular steel-braced frame is studied by full-scale experiment and the finite-element analysis computer program of SAP2000. Seismic performance of the modular system was a main concern in this paper. Evaluation of the lateral stiffness, strength, deformation and failure modes for long direction of modular system was conducted. The analysis model is based on the bending ultimate strength of each section. Same cyclic load history was applied at the computed modeling until it failed and conducted again with conversion to the hinge for the failed points. For the evaluation of the seismic performance, we set lateral strength standard as the point at 0.01 radian after entering plastic zone. As the evaluation standard, lateral strength of the modular system at Drift 1.55% level was the criteria and the lateral strength at that point was 487.1 kN. And the validity of the analysis model with SAP2000 was verified by comparing with the experimental results.

Keywords: full-scale test, modular building, seismic performance

1. Introduction

1.1 Purpose of Study

The common cast-in-place concreting, utilizing mainly wet-cast retaining wall systems, fails to ensure more precise concreting in the quality of the work and poses problems from an eco-friendly construction point of view. Modular construction, on the other hand, involves the putting together in factories of all structural members, facility systems, internal and external materials, etc., enabling wide ranges of benefits, including shorter construction, better quality, lower cost, and more environmentally friendly construction. The demand for such mass-produced modular system is increasing despite the sharp slowdown in the domestic and international construction industry.

The modular approach, however, can invoke doubts about the structural performance of the structures as they are built with fast and easy sealing to connect the units that are dry cast. Verification of the system's structural integrity, therefore, is essential. The challenge has duly inspired over the years a number of studies on the subject.

This study proposed to conduct a full-scale experiment for the modular system that is to be actually used to erect a dormitory building. The experiment would involve the verification of the system, based on comparison of the previous studies and theoretical examinations against the assessment of lateral resistance performance and computational analysis data. The study aimed to recognize the efficacy of the computational analysis model based on the lateral resistance performance assessment and the structural analysis program. Assessment of the lateral resistance performance, currently lacking more definite regulation, was intended to be made using the resistance past developing a plastic rotation of 0.01 rad after entering the plastic zone.

1.2 Methods and Procedure

To assess the lateral resistance performance of modular systems, cyclic lateral loading plans were established and executed using a two-storied life-sized model of stackable modules system. Subject to the interlayer displacement angle, a total of 11 cyclic loading was performed covering the drift 0.25% - 4%. For each cycle, the specimen's dynamic behavior was examined, and the relationship was analyzed between the interlayer displacement angle and load applied. Based on the data, understanding was sought of the structural performance of the modular system.

Further, the SAP 2000 program was used to obtain computational structural analyses which were then compared against the experimental values. The comparison intended to find out whether the properly modeled computational structural analysis can substitute experiments using actual loading application.

2. Experimental Design

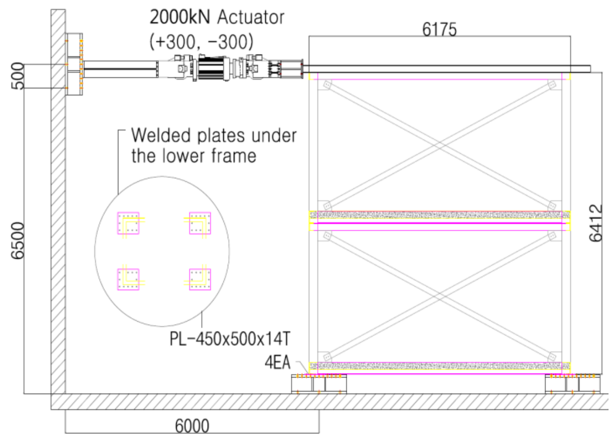

Fig.1 - Size and Layout of Modular Specimen

The life-sized modular block specimen used for the experiment was 6175 mm (length) X 3470 mm (width) X 6412 mm (height). Its arctangent (layer displacement divided by height) was defined as the angle of rotation. The protocol was established such that two cycles of loading were applied for each drift until reaching the rotational angle of 0.04 (or a 4% drift). The loading was provided by two actuators, each 2000 kN-class. The transfer of the actuator loads was planned by using a beam bolted to the top of module.

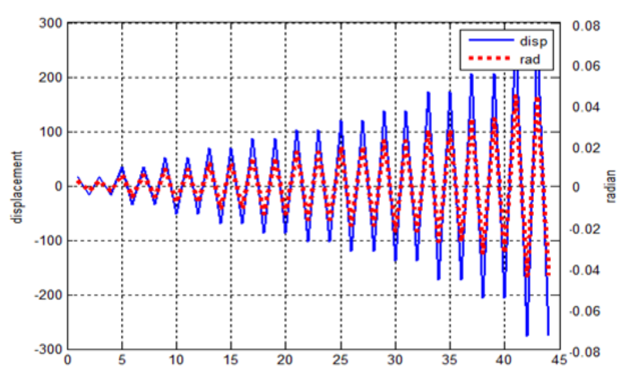

Fig.2 - Loading Protocol

3. Results and Analysis

3.1 Total Behavior under Cyclic Loading

Upon the completion of the last loading reaching the 4% drift limit, one additional loading was provided for each direction while the actuators' maximum displacement standing at ±292 mm (approx. a 4.5% drift). For the study, the initial stiffness of the modular system used, seemed to be governed by the stiffness of the bracing member. After the yielding of the bracing system, the resistance behavior was observed in the modular frame's lateral stiffness.

Until reaching the drift of 2.0%, the behavior of the modular frame took place in the elastic zone which looked more linear. From the drift of 2.5%, however, a decrease in the lateral stiffness was observed in the modular frame due to the local buckling of the top and bottom beam. When reaching the drift 4.0%, the slope of the envelope curve approached zero, which showed the frame's lateral stiffness had become extremely insignificant.
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4. FEA (Finite Element Analysis)

The finite element method was used to carry out the structural analysis of the modular block system and to compare its results against the experiment's to determine the accuracy of the FE analysis. To this end, the SAP 2000 program was used.

Table 1 - Lateral Strength of Each Member in FEA

	M_p (kN·m)	M_n (kN·m)	Width-thickness ratio		Λ_p	Λ_p	Slenderness
MC2 (□ - 200 X 100 X 9)	104.3	104.3	Flange	9.11	27.8	34.7	Compact
			Web	20.2	60.0	141.4	Compact
MBT1 (□ - 250 X 100 X 6)	75.2	60.8	Flange	16.7	13.4	22.6	Non-compact
			Web	39.7	13.4	22.6	Compact
MBG1 (□ - 150 X 100 X 9)	37.4	30.5	Flange	16.7	9.4	24.8	Non-compact
			Web	23	93.3	141.4	Compact

The structural analysis performed was linear elastic. Based on an assumption that each member's reaching the flexural strength will lead to their respective yield, at which point hinging was added to further the analytical process. The aforesaid process was repeated for the purpose of the analysis.

The process of structural analysis demanded the flexural strength of each member, which necessitated separate calculation. Table 1 lists the member-specific flexural strengths obtained by the equation for lateral buckling strength per Korea Building Code (KBC). With the top and bottom beam thickness being 6 mm, i.e., non-compact section, local buckling was foreseen prior to the manifestation of the plastic moment strength.

A moment frame, the beam-column was considered a rigid welded connection. For the analysis, the brace member was determined as the hinge on both ends for meshing.

5. Assessment of Seismic Performance

As shown in the envelope curve, the modular specimen exhibited an elastic behavior while the lateral resistance was being mostly endured by the bracing up until about 0.55% of drift. From the bracing's yield point on, the plastic zone was entered gradually, where the entire modular system taking over the lateral resistance.

To assess the modular block's lateral resistance performance, such performance was intended to be captured at a 1.55% drift, i.e., the point at 0.01 radian after entering the plastic zone as established earlier.

As illustrated in Figure 3, the modular system's lateral resistance at the drift of 1.55% was represented as approx. 487.1 kN. This value is intended by the study as the system's seismic performance for the experiment.

Figure 4 compares the lateral load curve per yield point obtained by the FEA against the envelop curve plotted by the experiment using a life-sized modular block. The computational analysis delivered a value of approx. 521 kN for the drift of 1.55% which served as the reference point for seismic performance assessment. The accuracy was calculated to be 93.5% (i.e., experimental value divided by analytical value x 100). The error was deemed to have resulted from the analytical assumption made of the joint having an infinite Young's modulus, from the eccentric load that applied during the experiment, and from other factors.

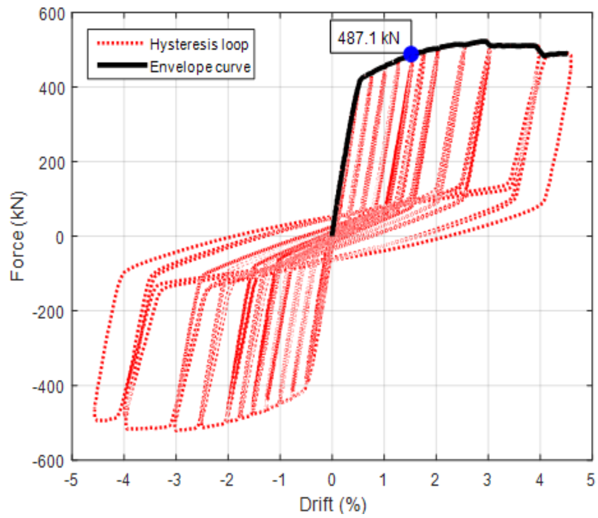

Fig.3 - Modular System's Lateral Resistance At 1.55% Drift

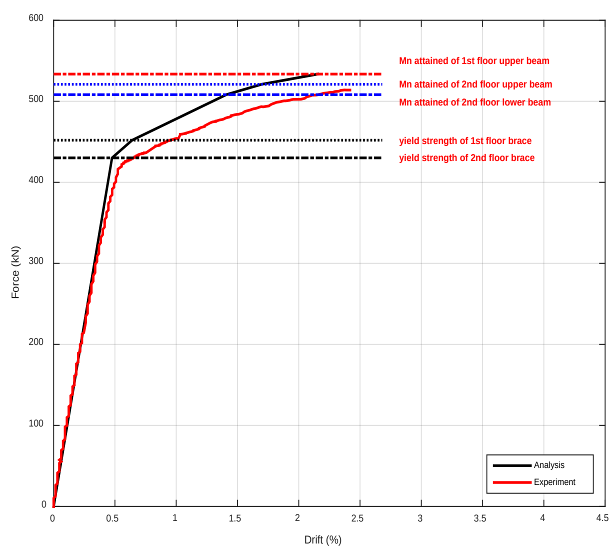

Fig.4 - Comparison between Envelope Curve and Analytical Results

Examination of the data obtained for each main yield point showed, the initial yield by the bracing had taken place at an approximately 0.5% drift for both the analysis and experiment, while the beam's initial yield had occurred at about a 1.4% drift during the analysis and about a 1.6% during the experiment, with the results of similarity. Such accuracy and similarity shed light on the potential efficacy of the modular system modeling used for the study, in the future endeavors for developing experimental modular specimens.

6. Conclusion

This study conducted a full-scale experiment on a two-storied modular block that was to be actually used in the erection of a dormitory building. Based on the previous research findings and theoretical studies, assessment was made of the specimen's lateral resistance performance. Verification was achieved through comparison between the computational analytical data and the experimental data.

The results showed, the yield by the second-story brace came first at about a 0.55% drift (interlayer displacement angle), followed by the yield of the first-story brace at the drift of 1.0%. With both layers, the top beam's local buckling took place at the drift of 1.75%, while at the drift of 2.5% the first-story bottom beam experienced additional local buckling. When the second-story bottom beam edge underwent a partial failure in the weldment at a 4.0% drift, a mechanism was identified that the bracing's yield was followed by a decrease in the lateral stiffness of the modular frame.

For seismic performance assessment, the reference point was established at the lateral resistance past 0.01 radian following the entry into the plastic zone. Using such reference point, the experimental modular system's lateral resistance at a 1.55% drift was considered to be its seismic performance. The results showed the lateral resistance at the drift of 1.55% was approximately 487.1 kN.

According to the results of computational vs experimental data comparison, the seismic assessment reference point of 1.55% (drift) had attained the FEA value of approx. 521 kN, thus delivering an accuracy of 93.5% (i.e., experimental value divided by computational value X 100). The error was deemed to have resulted from the analytical assumption made of the connection having an infinite Young's modulus, as well as from the eccentric load that had applied during the experiment and other factors.

The comparison of the data obtained for each main yield point found out that the initial yield by the bracing had taken place at an approximately 0.5% drift both during the FE analysis and experiment. A similar result was obtained for the beam's initial yield which had occurred at about a 1.4% drift during the analysis and about a 1.6% during the experiment. With similar results obtained across the experiment and FEA, it is opined that the modeling that was used for the study offers potential efficacy for the future development of modular building systems.

7. References

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