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Structural Performance Assessment of Through-Column-Type Beam-to-Column Joints

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Abstract Reinforced Concrete-Steel (RCS) moment frames consisting of reinforced concrete columns and steel beams are one of several types of hybrid structural systems which are considered as high-performing and cost-effective alternatives to traditional reinforced concrete or steel frames. A primary challenge in the design of RCS frames is the proper detailing of the connection between the steel beam and the reinforced concrete column components. Hence, much of the research has focused on the design and behavior of the composite beam-to-column joints, which are classified into through-beam-type and through-column-type categories. This study focuses on the structural performance assessment of the through-column-type joints with different detailings through experimental investigations and numerical simulation. In this research, three distinct damage patterns have been identified for the through-column-type joints and the effectiveness of proper detailing on the strength, stiffness, and toughness performance enhancement of such connections is demonstrated through experimental investigations. Moreover, the capability of the OpenSees program in simulating the structural response of the RCS frames with through-column-type joints is shown and the degrading effect of the load-cycles repetition on the connection load capacity is investigated and verified.

Keywords: *beam-to-column joints, RCS connections, through-column type, structural performance assessment, experimental investigation, numerical simulation*

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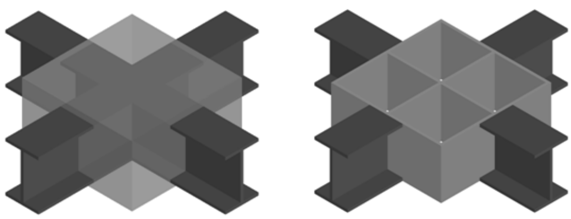
1. Introduction

Reinforced Concrete-Steel (RCS) composite moment-resisting frames that typically consist of reinforced concrete columns and structural steel beams have been commonly used in construction of buildings. RCS frame systems benefit from the strengths of concrete and steel materials and offer structural and economical advantages over traditional reinforced concrete or steel frames. Use of reinforced concrete columns can improve the stiffness and damping of the structure and also lower the construction costs compared to the use of steel columns. As well, use of steel beams can be effective in improving the energy dissipation capacity and ductility of the system, reducing the weight to be carried by the columns and foundations, and also lowering the seismic load due to reduced mass of the structure. Moreover, such structural systems are capable of having larger span size and higher construction speed [1].

One major challenge in design of RCS frames has been the detailing of the connection between the steel beam and the reinforced concrete column. In fact, application of two different types of materials complicates the performance of such composite connections. RCS connections have been classified into two main categories: through-beam type and through-column type [2]. In a through-beam-type joint (Figure 1(a)), steel beams penetrate a reinforced concrete column at the joint, while in a through-column-type joint (Figure 1(b)), the concrete column is confined by steel plates and the flanges of steel beams are replaced with transverse stiffeners at the joint [3].



(a) Through-beam-type joint **(b)** Through-column-type joint

Figure 1. Beam-to-column joints used in RCS frames [3]

The structural behavior and seismic performance of RCS beam-to-column joints have been studied by researchers, which has led to the development of some effective design guidelines. Sheikh et al. [4] summarized the results of an experimental program on the behavior of moment connections between steel beams and reinforced concrete columns. It was shown that composite beam-column connections can provide high performance in terms of stiffness, strength, ductility, and toughness, and can be considered as an attractive design alternative to structural steel or reinforced concrete. In another companion paper, Deierlein et al. [5] presented a design model and recommendations for detailing and calculating the nominal strength for composite beam-column joints. Later on, Parra-Montesinos et al. [6] proposed a deformation-based capacity design procedure for beam-column connections in RCS frame buildings located in zones of high seismicity. The effectiveness of the proposed design procedure in controlling joint deformations and damage was verified experimentally. Recently, Alizadeh et al. [1,7] reported experimental and numerical studies and showed some capabilities of RCS connections in terms of stiffness, strength, ductility, energy dissipation capacity, and application in high seismic risk zones. Ghods et al. [8], also, investigated the seismic performance of RCS connections through numerical simulation and demonstrated the desirable performance of composite systems including concrete column-steel beam in combination with steel shear wall and bracing systems.

Kuramoto [9] reported a study on the shear strength and seismic performance of composite RCS through-column-type joints. The effects of the cover plates thickness and the exitance of extended face bearing plates on the seismic performance of the connections were evaluated and some stress transferring mechanisms in such connections were discussed. Lately, Mirghaderi and Bakhshayesh Eghbali [10] and Bakhshayesh Eghbali and Mirghaderi [11] introduced a novel through-column-type joint in which the beams were connected to a vertical plate passing through the concrete column, also called as Through Plate. The effectiveness of the proposed connection detailing strategy in enhancing the structural performance of the RCS through-column-type connections was demonstrated through detailed numerical and experimental investigations.

Despite the conclusive and fruitful studies reported on the structural behavior and seismic performance of the RCS connections, in general, and the through-column-type joints, in particular, reliable design and widespread application of such composite beam-to-column connections still require systematic and detailed investigations. On this basis, the structural performance of some through-column-type beam-to-column joints with cover plates of different thicknesses and stiffened with one and two transverse stiffeners are investigated in this research endeavor on the basis of experimental findings and detailed numerical simulations.

2. Test details

In this study, through-column-type joints with cover plates of different thicknesses and stiffened with one and two transverse stiffeners, as shown in Figure 2, were designed, fabricated, and tested.

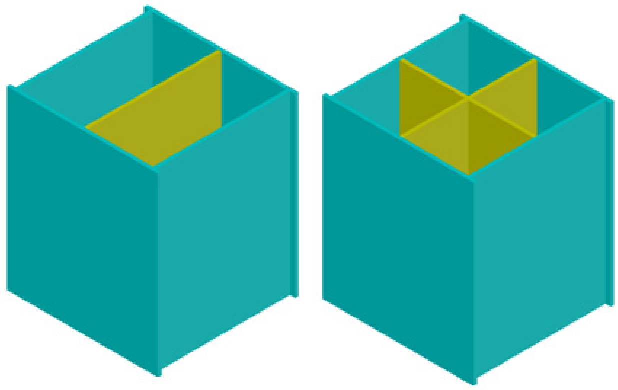


Figure 2. Through-column-type joints with one and two transverse stiffeners

A total of four joints of about ½ scale were fabricated, which simulated interior beam-to-column joint for a RCS frame. Details of the fabricated joints are shown in Figure 3. Geometrical properties of the cover plates and stiffeners of the joints are also summarized in Table 1.

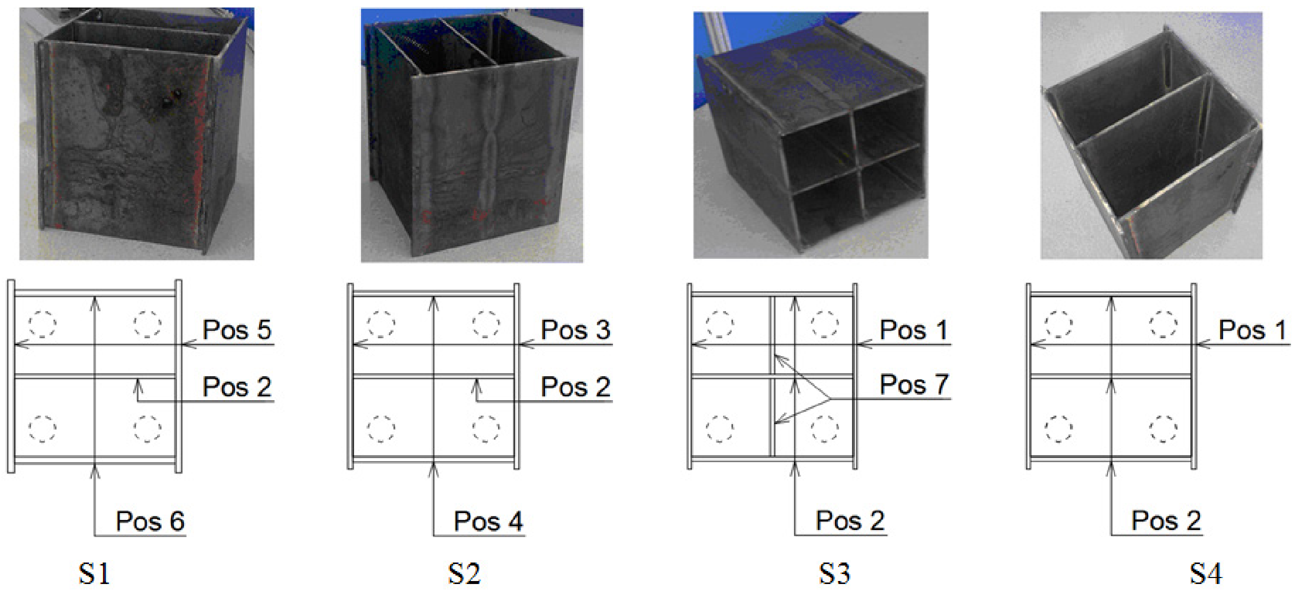


Figure 3. Details of beam-to-column joints

Table 1. Geometrical properties of cover plates and stiffeners of the joints

Specimen	Cover plate (cm)	Stiffener (cm)
S1	Pos 5: Pl 23×25×0.8 Pos 6: Pl 20×25×0.8	Pos 2: Pl 20×25×0.5
S2	Pos 3: Pl 23×25×0.6 Pos 4: Pl 20×25×0.6	Pos 2: Pl 20×25×0.5
S3	Pos 1: Pl 23×25×0.5 Pos 2: Pl 20×25×0.5	Pos 2: Pl 20×25×0.5 Pos 7: Pl 9.75×25×0.5
S4	Pos 1: Pl 23×25×0.5 Pos 2: Pl 20×25×0.5	Pos 2: Pl 20×25×0.5

Each test specimen consisted of a 20 cm × 20 cm reinforced concrete column connected to two 75-centimeter-long steel I-beams fabricated from hot-rolled IPE12 profile in accordance with the German Estahl standard. Details of a typical test specimen are illustrated in Figure 4. The longitudinal reinforcement in each column consisted of four 16-milimeter-diameter bars arranged symmetrically around the perimeter of the section in order to provide a total reinforcement ratio of 2.01%. The properties of the concrete and steel materials are tabulated in Table 2.

Table 2. Properties of the concrete and steel materials

Specimen	Concrete compressive strength (kg/cm²)	Steel yield stress (kg/cm²)	
		Beam	Rebar
S1	387	2400	3000
S2	313	2400	3000
S3	428	2400	3000
S4	402	2400	3000

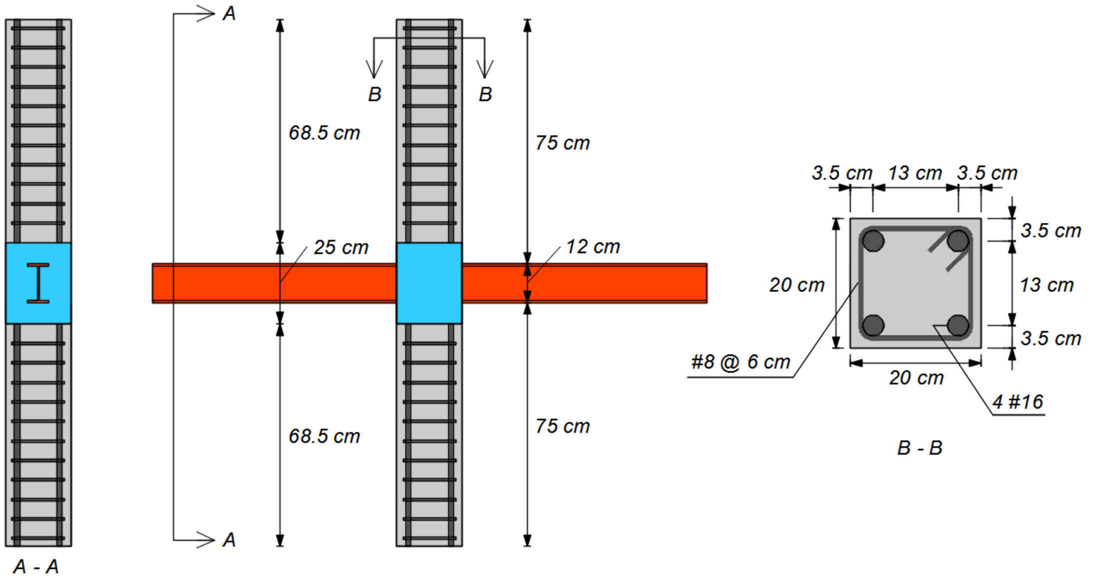


Figure 4. Details of a typical test specimen

The test setup is shown in Figure 5. Consistent with all four specimens, the reinforced concrete column was fully fixed at its lower end. The upper end of the column was fully fixed only in cases of S2, S3, and S4 specimens. In case of specimen S1, the in-plane translation as well as rotation about the longitudinal axis of the column were only restrained at the upper end of the column.

Figure 5. Test setup

Figure 6 shows the loading scheme. As shown in the figure, the beams were subjected to cyclic loading applied at their tips and the column was subjected to axial load up to approximately 10% of its axial capacity applied at its bottom. The two cyclic and the axial loads were applied by means of manual jacks.

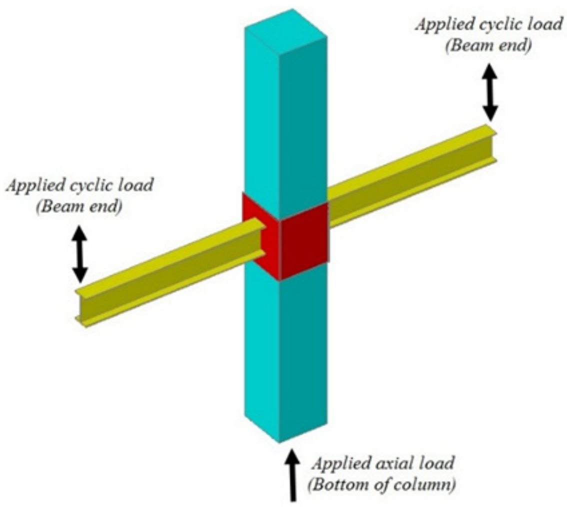


Figure 6. Loading of test specimens

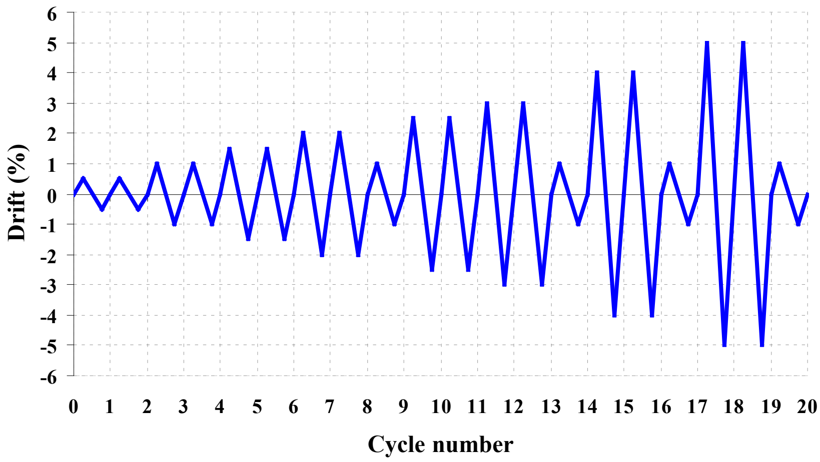


Figure 7. Cyclic loading history

The cyclic loading history is shown in Figure 7. As seen in the figure, the applied lateral displacements ranged between 0.5% and 5.0% beam drift which is defined as the ratio of the beam vertical displacement to its length. It is also noted that the loading cycle at each considered drift level was repeated twice in order to evaluate the structural performances of the specimens under repeated cycles; nonetheless, the performances of the specimens were assessed under unrepeated cycles as well.

3. Discussion of Results

3.1. Experimental Observations and Findings

In this section, the structural behavior of the test specimens is evaluated qualitatively based on experimental observations. During the experiments, the structural behaviors of the four test specimens with different designs and detailing were closely monitored in order to identify and explore the possible damage patterns which would be developed in through-column-type beam-to-column joints. The experimental observations and findings of this study are discussed in the following.

Consistent with all test specimens, diagonal as well as some flexural cracks were initially formed at 1.0% beam drift. At 2.0% drift, the column at the top support region of specimen S1 was crossed by several diagonal cracks without any significant damages; nonetheless, these cracks became more pronounced and serious at higher drifts. Figure 8 shows the damage occurred at the top support of the reinforced concrete column in specimen S1 at 5.0% drift. In specimens S2, S3, and S4, cracks spread through the column between 2.0% and 5.0% drifts, as shown in Figure 9, Figure 10, and Figure 11, respectively; however, these cracks were not significant because of their size and region which was relatively far from the joint and the supports.

Figure 8. Damage pattern in specimen S1 at 5.0% beam drift

Figure 9. Damage pattern in specimen S2 at 5.0% beam drift

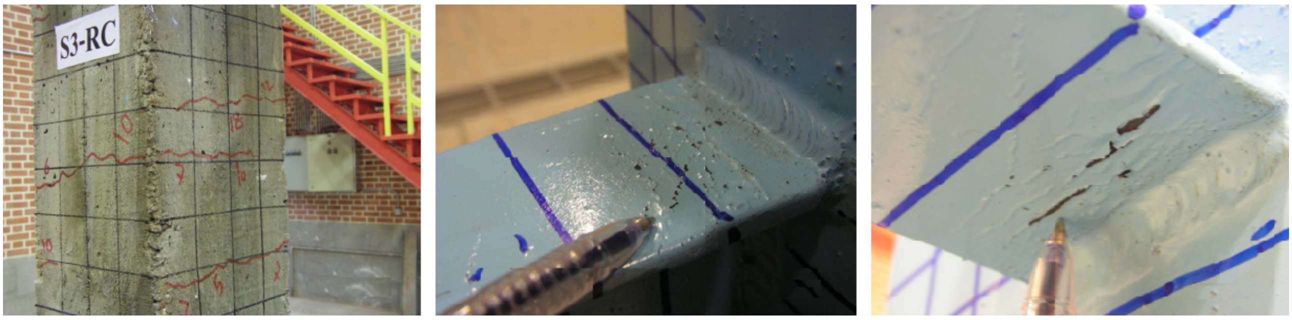


Figure 10. Damage pattern in specimen S3 at 5.0% beam drift

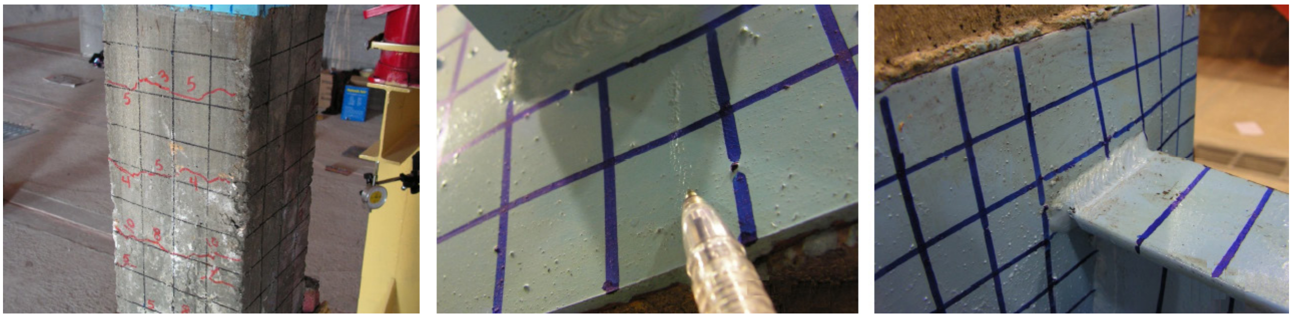


Figure 11. Damage pattern in specimen S4 at 5.0% beam drift

Figure 9 shows the warping of cover plates in specimen S2 at 5.0% drift. This damage pattern was detected at drifts higher than 4.0%. Cover-plate warping was accompanied with its separation from the transverse stiffener. This damage pattern occurred before development of plastic hinges in the beams.

Plastic hinges were desirably developed in the beams of specimen S3 in a timely manner, as shown in Figure 10. It is found that the connection details, in this case, facilitated the formation of plastic hinges and were also effective in moving the plastic hinges a short distance away from the beam-to-column connection. Formation of such yielded zones is indicative of attainment of plastic moment capacity and inelastic deformations of the beams.

As shown in Figure 11, specimen S4 suffered from the combination of two damage patterns, namely warping of cover plates and formation of beam-end plastic hinges. Nevertheless, cover-plate warping was found to be the dominant damage pattern in this experiment.

In summary, there different damage patterns, i.e. cracking of the reinforced concrete column, warping of the cover plates, and formation of beam-end plastic hinges, were identified for the specimens with through-column-type beam-to-column joints under investigation. It was found that, on one hand, application of cover plates with relatively large thickness may lower the ductility of the joint, and on the other hand, employment of relatively thin cover plates may result in introduction of other undesirable damage patterns to the joint. The experimental observations and findings of this study demonstrate that proper design and detailing of a through-column-type beam-to-column joint, e.g. addition of two crossing intermediate stiffeners and employment of cover plates with optimal thickness in case of specimen S3 in here, can prevent the occurrence of unfavorable damage patterns and also improve the energy-dissipation capabilities as well as overall structural performance of the system.

3.2. Structural Performance of the Test Specimens

This section focuses on the evaluation of strength, stiffness, and energy absorption performances of the test specimens and provides a quantitative assessment of the structural performance of the considered through-column-type beam-to-column joints.

The backbone curves of the (unrepeated and repeated) cyclic load-drift responses of the four test specimens in the positive and negative loading directions are shown in Figure 12. Despite some scatter in the depicted results, the load-drift responses under unrepeated and repeated cycles are by and large similar in case of each specimen; however, a more accurate assessment of the responses reveals some strength degradation especially at higher drifts in most cases due to application of repeated cyclic loading. In addition, it is found that the load-drift responses in the positive and negative loading directions are more or less similar in case of specimen S4, while these responses are slightly different in cases of specimens S1, S2, and S3.

Figure 13 shows the maximum strengths of the specimens under unrepeated and repeated cycles. From the figure, it is found that specimens S1, S2, and S3 possess 0.3%, 4.1%, and 4.8% higher maximum strengths, respectively, when subjected to unrepeated cycles. For specimen S4, on the other hand, the maximum strength is found to be 0.5% higher in case of repeated cycles. Moreover, it is observed that specimen S3 with the most desirable behavior, i.e. formation of beam-end plastic hinges, possessed the highest maximum strength in cases of both unrepeated and repeated cycles. Specimen S1 with the most undesirable behavior, i.e. occurrence of damage at the top support of the reinforced concrete column, on the other hand, had the lowest maximum strength among the test specimens. From the figure it is also evident that specimen S2 had a better strength performance relative to specimen S4.

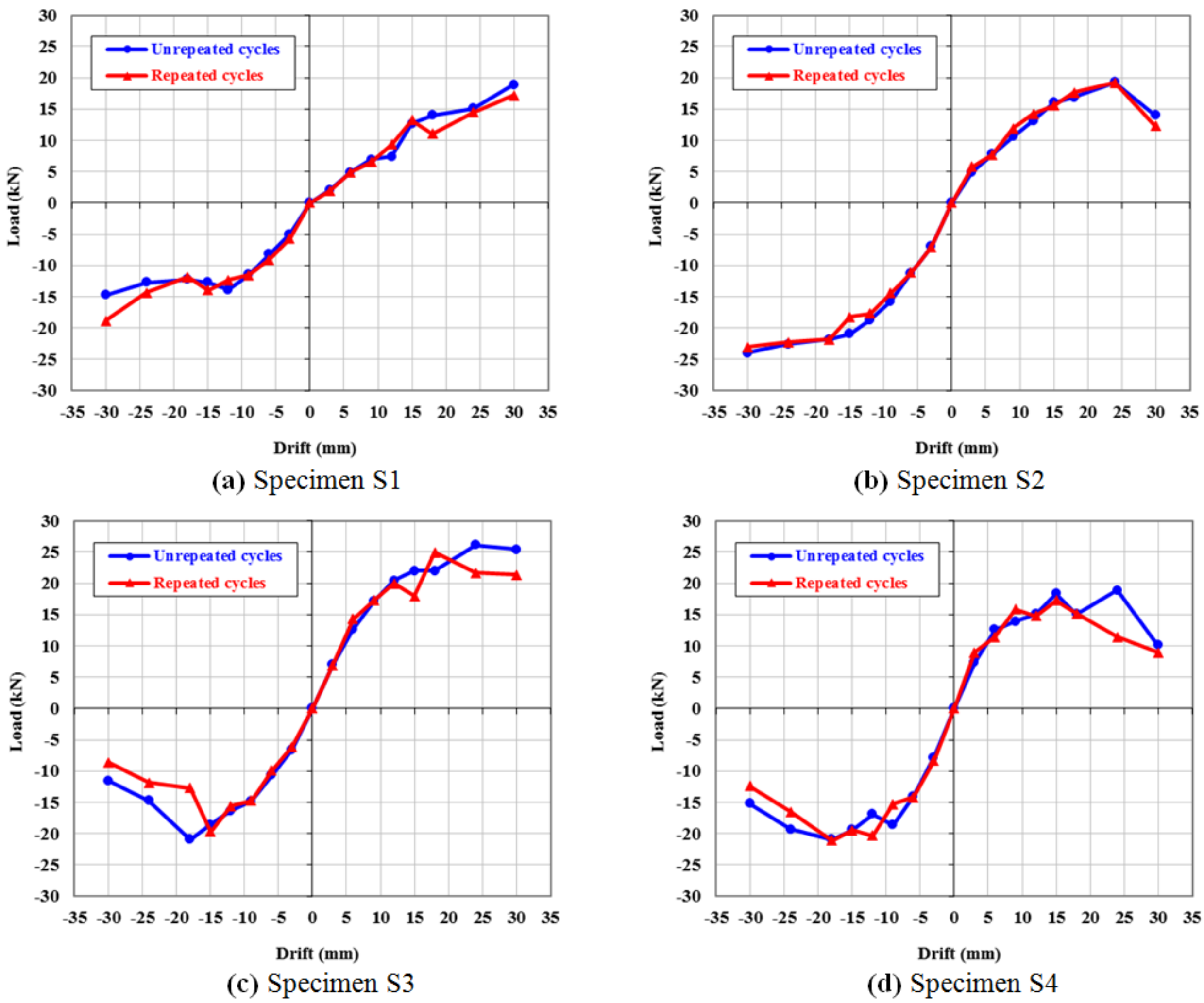


Figure 12. Load-drift curves of the specimens

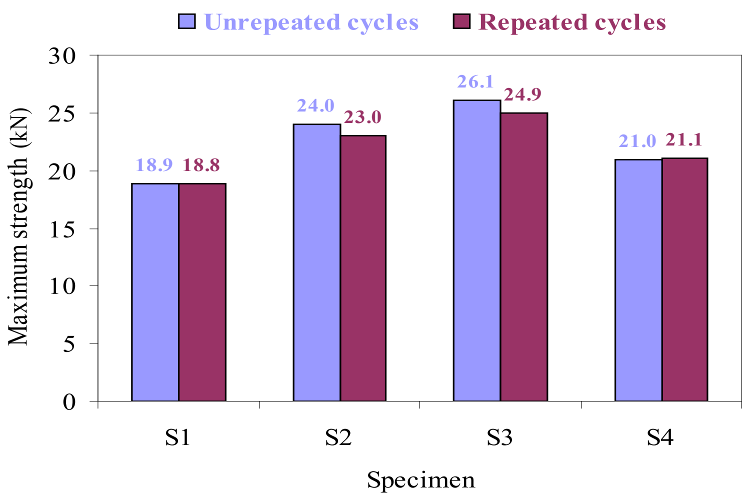


Figure 13. Maximum strengths of the specimens

The performance of stiffness of the test specimens under unrepeated and repeated cycles is shown in Figure 14(a) and Figure 14(b), respectively. Assessment of the results reveals that the specimens have fairly similar stiffness performances in both unrepeated and repeated loading cases and no significant discrepancy is detected. From the figures, the stiffness of specimen S1 with the lowest initial stiffness does not vary with increasing of the drift in the positive loading direction and remains more or less constant, while in the opposite loading direction this specimen exhibits a relatively better stiffness performance. Specimen S2, by and large, possesses a stable stiffness performance; however, its stiffness performance is found to be higher in the negative loading direction. Specimen S3, on the other hand, is found to have the highest stiffness in the positive loading direction. Lastly, it is shown that specimen S4 has the highest initial stiffness in all cases; nonetheless, the rate of decay of stiffness of this specimen is found to be relatively high.

The performance of the test specimens is also evaluated by considering the *toughness* criterion which is a measure of the energy absorption capacity of a structure or structural component. The toughnesses of the specimens under unrepeated and repeated cycles, estimated using the area under the load-drift curves, are shown in Figure 15. Specimens 2, 3, and 4 exhibit higher energy absorption capacity under unrepeated cycles, while the toughness value is slightly higher in case of repeated cycles for specimen S1. It is also found that specimens S3 and S1 by and large have the highest and the lowest energy absorption capacities, respectively. Moreover, from the figure it is evident that specimen S2 has a slightly better toughness performance compared to specimen S4; however, the discrepancy is not that significant.

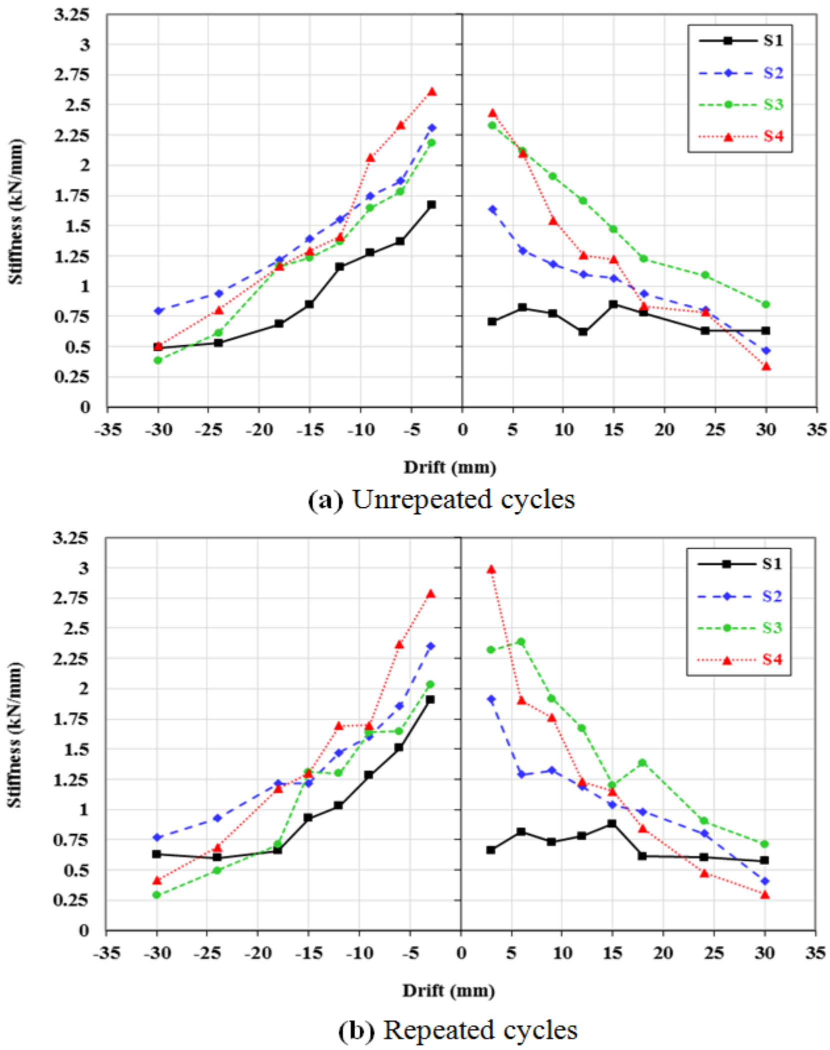


Figure 14. Stiffness performance of the specimens

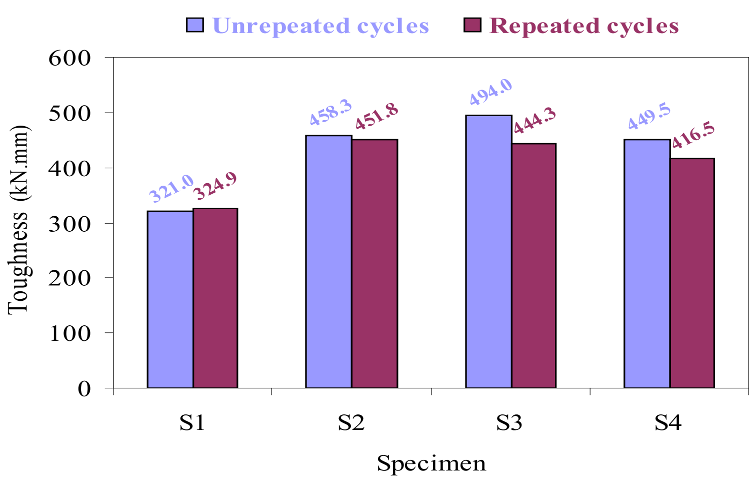


Figure 15. Toughness of the specimens

In conclusion, evaluation of the strength, stiffness, and toughness performances of the four specimens demonstrates that specimen S3 with two crossing intermediate joint stiffeners has the highest structural performance among the test specimens. Specimen S1, on the other hand, with the thickest joint cover plates (0.8 mm) possesses the weakest structural performance. Moreover, it seems that specimen S2 with 0.6-mm-thick joint cover plates has a slightly better structural performance relative to specimen S4 with 0.5-mm-thick joint cover plates. Overall, proper detailing of a through-column-type beam-to-column joint, i.e. herein addition of two crossing intermediate stiffeners in specimen S3, can effectively enhance the strength, stiffness, and energy absorption capability of such an important structural component, while design of overly rigid and/or flexible joints may adversely affect the performance of the structure.

4. Numerical Simulation and Results

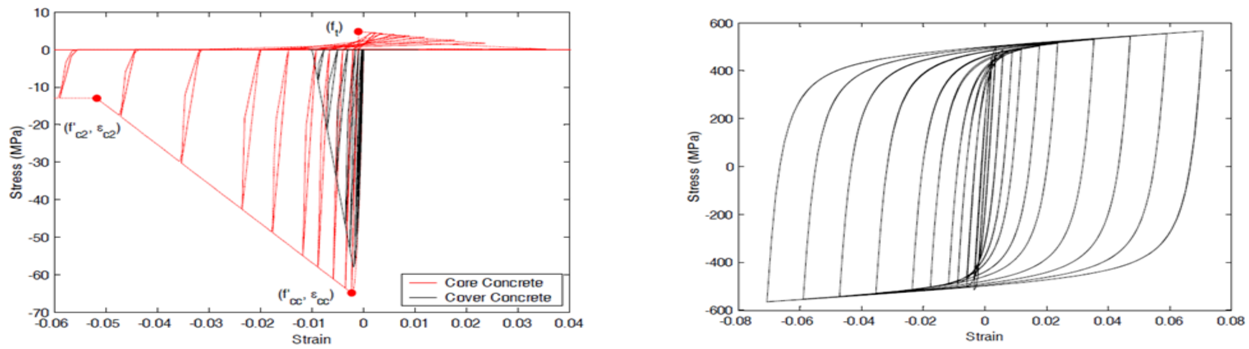
OpenSees [12] program was applied to simulate the force-displacement behaviors of the test specimens. OpenSees [12] is a powerful academic and open-source program which can be used to simulate the structural behavior and seismic performance of structural systems.

The Fiber Section in OpenSees [12] was used to model the reinforced concrete column. To this end, fiber section was divided into three parts including the concrete cover, the concrete core, and the reinforcing steel rebar. In fact, use of fiber sections enables accurate simulation of the reinforce concrete column and the interaction between the concrete and the rebars in OpenSees [12].

Concrete02 and Steel02 models were used in OpenSees [12] to model the concrete and steel materials, respectively. Concrete02 material model was selected to model the core and cover concrete. In addition, Steel02 material model was used in modeling of bars, cover plates, stiffeners, and steel beams. The hysteretic responses of the selected concrete and steel material models are shown in Figure 16(a) and Figure 16(b), respectively.

The two-dimensional beam-column-joint element, Joint2D, was used to model the composite joint panel in OpenSees [12]. As shown in Figure 17, the two-dimensional beam-column joint is idealized as a parallelogram shaped shear panel with adjacent elements connected to its mid-points which are referred to as external nodes. These nodes connect the joint element to the surrounding structure. The joint region behavior is simulated through assignment of a rotational spring to the panel zone. This rotational spring is capable of representing the two main joint failure mechanisms, i.e. the panel shear and the vertical bearing distortions [7].

The experimental results as well as numerical predictions for load-drift responses of the test specimens under unrepeated and repeated cycles are shown in Figure 18 and Figure 19, respectively. In spite of some scatter in the depicted results especially the strength degradation developed during the testing of some specimens under the two different loading conditions, it can be concluded that the OpenSees [12] models have been able to fairly accurately predict the stiffness and strength performances of the test specimens. This is indeed indicative of capability of OpenSees [12] program in simulating the structural response of RCS frames with through-column-type beam-to-column joints.



(a) Concrete02 material (b) Steel02 material

Figure 16. Hysteretic responses of the selected material models in OpenSees [12]

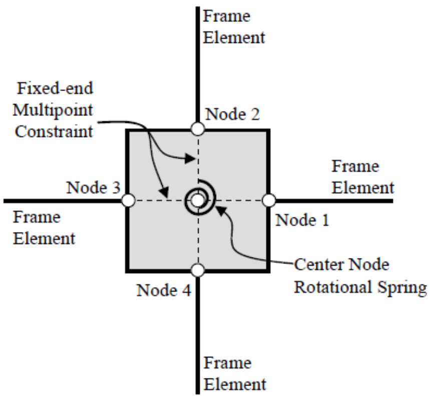


Figure 17. Schematic representation of OpenSees joint element used in this study

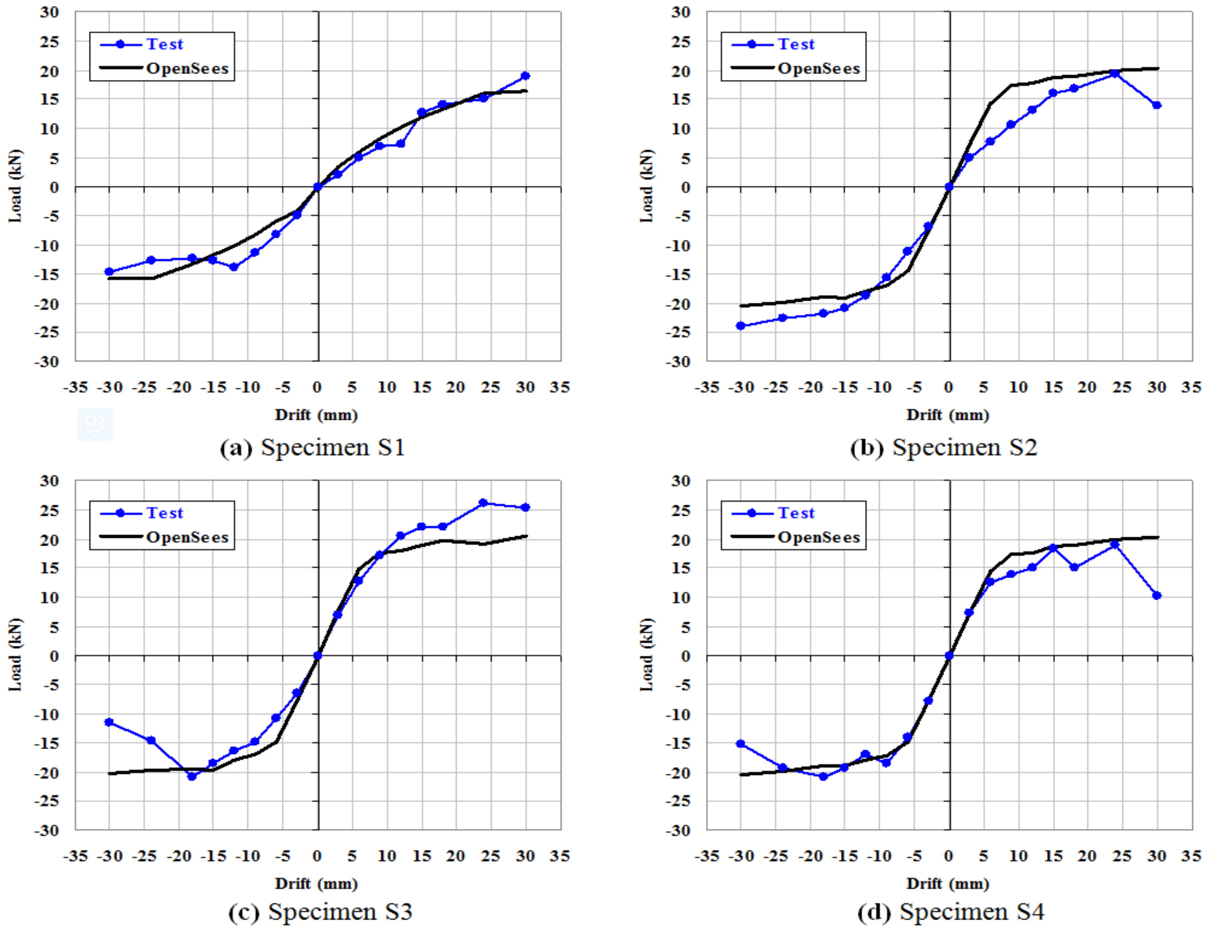


Figure 18. Comparison of test and numerical simulation results (unrepeated cycles)

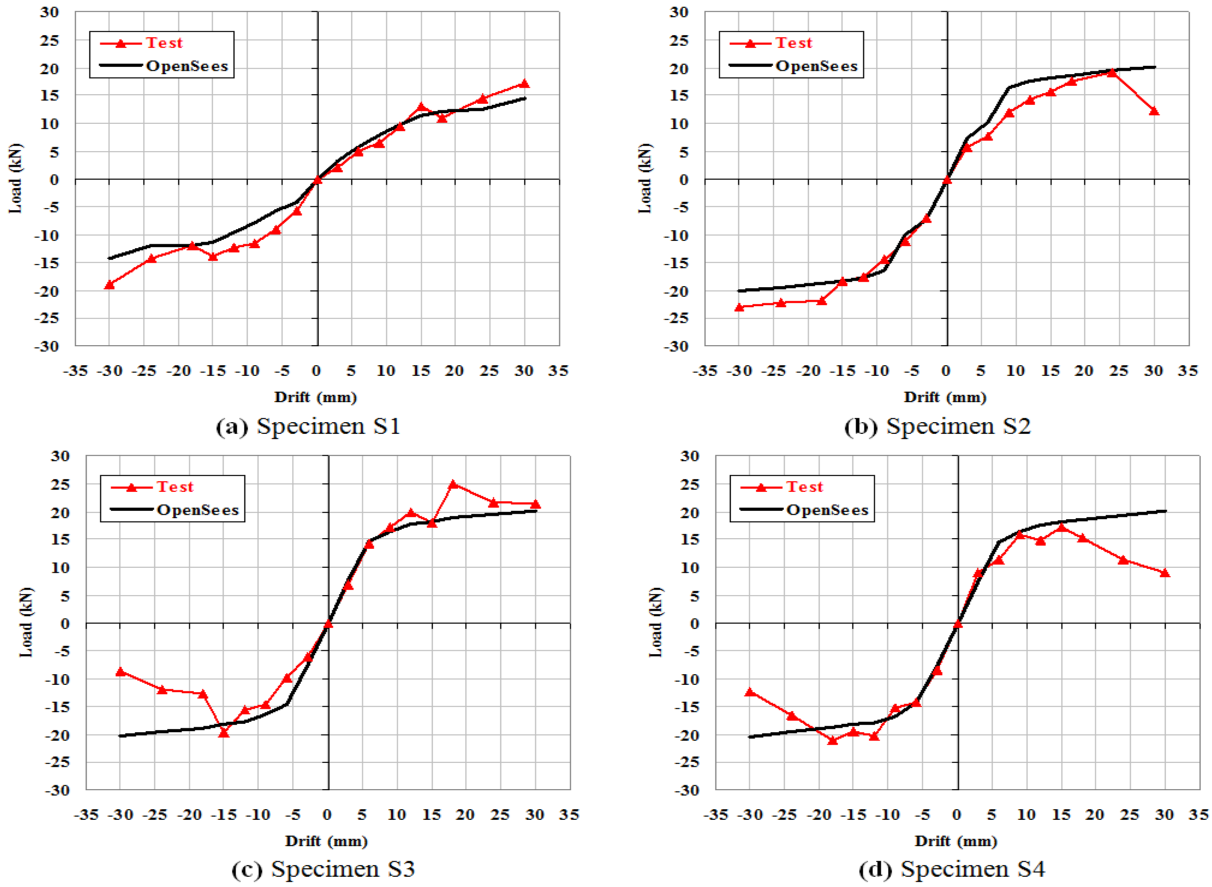


Figure 19. Comparison of test and numerical simulation results (repeated cycles)

5. Effect of Repetition of Load Cycles

It is important to know how the repetition of load cycles influences the strength performance of the through-column-type beam-to-column joints, since this issue can have a major impact on the structural behavior and seismic performance of structures. Similar studies have been performed on bridges and it has been verified that repetition of live load cycles during a bridge's life time can result in diminution of the maximum load attained at the steel to concrete connection [13].

In this study, the experimental and numerical results were analyzed in order to quantify the loss of load capacity of the joints due to the repetition of the load cycles. Table 3 summarizes the average $P_{repeated}$-to-$P_{unrepeated}$ ratios as well as the percentage strength reduction for the four joints under investigation. It is noted that $P_{repeated}$ and $P_{unrepeated}$ are the load capacities of the joints under repeated and unrepeated load cycles, respectively.

From Table 3, it is quite evident that the load capacity of the joints has been reduced due to repetition of the load cycles, except for the result obtained from the testing of specimen S1. Such nonuniformity in experimental results may be attributed to the testing conditions. From the numerical results, specimen S1 with the most unfavorable structural behavior has the highest strength reduction. Overall, in spite of the scatter in the tabulated results, it can be concluded that repetition of load cycles has adversely affected the strength performance by lowering the load capacity of the joints.

Table 3. Results on the loss of load capacity due to repetition of load cycles

Measuring parameter	Experimental				Numerical			
	S1	S2	S3	S4	S1	S2	S3	S4
Average $\left(\frac{P_{repeated}}{P_{unrepeated}}\right)$	1.03	1.00	0.92	0.97	0.92	0.94	0.98	0.98
Average reduction in strength (%)	-2.9	0.2	7.8	3.3	7.9	5.8	2.3	1.6

6. Conclusion

In this study, the structural behavior and performance of through-column-type beam-to-column joints with cover plates of different thicknesses and stiffened with one and two transverse stiffeners were investigated primarily on the basis of experimental observations and findings. Moreover, the force-displacement behaviors of the test specimens were simulated through numerical modeling, and subsequently the numerical results were used to evaluate the effects of the load-cycles repetition on the load capacity of the joints.

Based on the experimental observations of this research endeavor, three different damage patterns, i.e. cracking of the reinforced concrete column, warping of the cover plates, and formation of beam-end plastic hinges, were identified for the specimens with through-column-type beam-to-column joints. It was demonstrated that proper design and detailing of a through-column-type beam-to-column joint, e.g. addition of two crossing intermediate stiffeners and employment of cover plates with optimal thickness, can prevent the occurrence of unfavorable damage patterns and enhance the strength, stiffness, and toughness performances of such a structural component.

The good agreement between the experimental and numerical results of this study was indicative of capability of the OpenSees program in simulating the structural response of RCS frames with through-column-type beam-to-column joints. Furthermore, the numerical predictions along with the test results showed that the load capacity of the through-column-type beam-to-column joints can be reduced due to repetition of the load cycles.

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