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Investigation of Effect of Using Braces in Composite Frames Consisting of Reinforced Concrete Columns and Steel Beams (RCS)

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ABSTRACT

Reinforced concrete column-to-steel beam (RCS) composite connections have been introduced as a structural system since a couple of years ago. Optimally combining metallic and concrete-made structural elements, this system takes advantages of both systems. There are two types of these connections, including through-beam and through-column connections. In the present research, once finished with verifying a finite-element model, a parametric study (considering a cross-braced frame) was performed and the results were compared in terms of strength, cracking, failure stages of the model, and ductility. Results of the present research were indicative of higher strength and force corresponding to the first crack in braced composite frame. Furthermore, the use of bracing resulted in enhanced ductility of the system.

Key words: RCS connection, Through-beam, Through-column, Seismic performance.

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1. INTRODUCTION

Steel systems consisting of concrete column and steel beams have been introduced as a structural system since a couple of years ago. Either of metallic or concrete-based systems comes with advantages and disadvantages. However, optimally combining metallic and concrete-made structural elements, this system takes advantages of both systems. As of now, various beam-to-column connections have been designed and developed for this system. The most important feature of this diaphragm is its ease of construction. Accordingly, these no more need to a concrete-filled core inside the column, while the column is constructed prior to the beam, and then the beam is just connected to the exterior diaphragm. Another new feature of this novel connection is the fact that its details have become simpler and lower volumes of steel and reinforcement is needed for this connection. Most of the research undertaken on steel beam-to-concrete column (RCS) connections has been performed in three countries: United States, Japan, and Taiwan. The first experimental program in United States was held by Sheikh *et al.* at University of Texas in 1987. In this program, 9 RCS connections were constructed at 2/3 scale and then tested under uniform loading. The results indicated that, rotation of the entire connection can be composed of the sum of shear rotation of the connection and solid body rotation of the steel beam inside the connection (1). At the same time when ASCE guidelines were published (1994), a research program was undergoing on RCS connection by Kanno at Cornell University. In this research program, 19 specimens of interior connection were subject to alternate loading. A variety of details were considered for the connection, including compressive column planes, developed compressive column planes, steel columns, strip plates surrounding column zone above and below steel beam, shear connections, and vertical reinforcing bars. The data acquired from the experiments indicated that, details of the used connection impose direct impacts on resistance and ductility of the specimen, while those imposed no influence on total stiffness of the specimens. Furthermore, it was found that, axial forces exerted to column tend to enhance strength, stiffness, and ductility of the specimens (2). In late 1990s, Bugja *et al.* published results of tests on five interior specimens and one exterior specimen of RCS connection with slab under alternate loading along two main directions. Several details of the connection were evaluated in this research, including compressive column planes, steel column, covering plates and strip plates. Based upon this experimental study, it was concluded that, RCS connections with slab may exhibit inelastic and very good energy absorption capacity under reverse-cyclic loads (3). In late 1990s, an extensive analytic and experimental program was held at the University of Michigan by Para and White. All of the specimens showed stable load-displacement responses with some shortening during iterative cycles at the same level of relative lateral displacement. Findings of this research showed that, beam-encompassing strip plates enhance RCS connection performance significantly, because of well confinement and thereby enhanced shear strength, ductility capacity, and energy absorption capacity of the connection. In addition, the strip plates were found to be effective in reducing slippage of the column bars passing through the connection and increasing confinement of the connection (4). The research on RCS connections at Michigan University proceeded with the work performed by Liang *et al.* who conducted tests on two interior and two exterior specimens of RCS connection with slab under reverse-cyclic loading. In these experiments, the specimens were designed based on strong column-weak beam and the connection deformation developed by Para and White (5) for damage control in composite connections. All of the specimens exhibited good seismic performance. Plots of stable hysteresis load-displacement responses of different stories indicated inelastic rotation of the beam as the dominant phenomenon. Further investigated in the present research was the effect of slab on the response of the RCS connection. It was found that, effective width of slab for calculating positive bending capacity of the beam is equal to the column width (6). Izaki *et al.* tested five specimens of interior RCS connections at an approximate scale of ½ under seismic loading. All of the specimens were subjected to lateral displacement of up to 5% and exhibited stable load-displacement response, indicating potentials of RCS frame systems for regions of high seismicity. High levels of ductility and almost no reduction in the strength of the specimens were observed. Based upon the experimental results, it was concluded that, removing the flanges at connection zone due to the reduction in flange support plate area tends to weaken the connection strength (7). Sakaguchi *et al.* examined three specimens of RCS connecting. Objective of this research was to investigate the effect of covering plates within connection zone. For this purpose, one RCS connection without covering plate and two RCS connections with covering plates were tested. Test results showed good load-displacement responses for all of the three specimens and further revealed that, the covering plates tend to significantly enhance connection strength and stiffness (8). Noguchi and Kim undertook a finite-element analysis on interior and knee-type RCS connections to investigate the effect of connection type on shear strength. For this purpose, four specimens previously tested by other researchers were examined a three-dimensional finite-element model. This study concluded that, contributions from effective width of the steel plate of the web into shear strength of exterior and knee-type connections are about 60% and 80% of total width of the connection, respectively (9). In this regard, one may refer to numerous other research works including Nishiyama (10), Kuramoto and Nishiyama (11), Chen *et al.* (12), Liang and Parra-Montesinos (13), Harries *et al.* (14), Bugeja *et al.* (3), and Hu *et al.* (15). Actually performing experiments to investigate behavior of structures is a costly practice. Due to high cost of these experiments and the need for extensive facilities, part of them can be replaced by the powerful finite-element method (FEM). In the present research, the effect of using bracing in composite frames consisting of reinforced concrete column and steel beam is investigated.

2. NUMERICAL MODELING

ABAQUS software was developed in 1978 by ABAQUS Company – a company with activities within the field of finite-element software packages. ABAQUS software is a powerful finite-element software with the ability to simulate various materials such as steel, concrete, soil, etc. This software provides users with the ability to add new subprograms. This package includes three moduli including ABAQUS/Standard, ABAQUS/Explicit, and ABAQUS/CAE; in the present research, ABAQUS/CAE was utilized. In contrast to ANSYS, ABAQUS has no particular element for concrete, and conventional 8-point 3DSTRESS elements are used for this purpose. Numerical integration of this element was performed using the Gaussian method, with the material behavior controlled at these integration points. For other points of the element, stresses and strains are obtained using form functions. In order to consider the elements as concrete, concrete damage plasticity model behavior was assigned to these elements. For linear part of the concrete, the elastic properties available in the preset material library of ABAQUS software was used, wherein Poisson's ratio and modulus of elasticity were used of the materials. For three-dimensional steel elements and welds, similar to the concrete elements, the conventional 8-point 3DSTRESS element was used. In order to consider the steel nature of the corresponding elements, plastic properties were assigned to these elements. Moreover, elastic properties were used for the linear segment of the stress-strain curve. In order to model the behavior of welding materials, it should be noticed that, in areas where complete joint penetration groove weld is applied, the groove weld modeling can be neglected at an acceptable accuracy provided strength of the weld metal exceeds that of base metal. However, in cases where the strength of the weld metal is lower, the groove weld shall be modeled by assigning the behavior of weld material to the modeled zone. In three-dimensional modeling of groove weld and fillet weld, the same procedure as that of steel elements is followed and plastic characteristics are assigned to these elements. Besides, elastic characteristics are used for the linear segment of the stress-strain curve of the materials.

2.1. Verification

For the sake of verification, the experimental model presented by Alizadeh and Attari at the University of Tehran was used. This frame is composed of RCS composite connections of integrated beam type which is analyzed under pushover loading. This specimen includes concrete columns of 1730×400×400 mm in dimensions which are reinforced by 16 pieces of ф18 reinforcement bars longitudinally. ф10 reinforcements were used for column stirrups and connection zone. The steel beam used in the specimen is the one with IPE300 section which is 2800 mm in length. In both of the connections, L-shaped stirrups passed through holes into the web of the beam were used. Within panel zone, 430×260×8 mm plates were welded to the steel beam web to have it reinforced. This specimen includes band plate whose height and thickness is 80 mm and 15 mm, respectively. Furthermore, this specimen has face bearing plate of a width equal to the width of beam web and a length equal to the height of the beam web and a thickness of 15 mm. Figure 1 demonstrates an overall view of the specimen and the finite-element model along with its components.

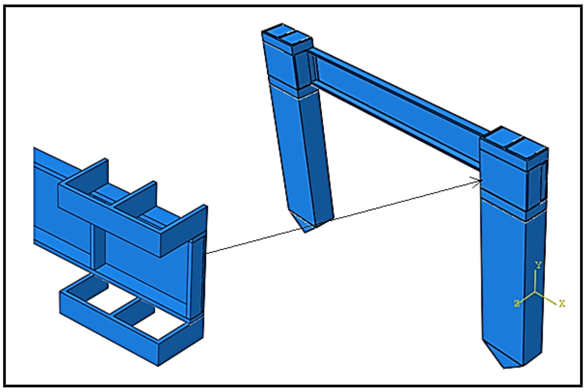


Figure 1. Details of the connection in RCS composite frame

Beam components, double plate, FBP plate, band plate and support of the concrete column were modeled using the three-dimensional element of Solid. Longitudinal reinforcements and stirrups were modeled using two-dimensional truss elements of Wire. Compressive strength, tensile strength, modulus of elasticity, and Poisson's ratio of the concrete were set to 50 MPa, 4 MPa, 33541 MPa, and 0.2, respectively. In order to simulate the behavior of the concrete, concrete damage plasticity model was used, which has the capability for considering tensile and compressive damages in the concrete. In order to model steel behavior of the beam, steel parts and longitudinal and transverse reinforcements, von Misses stress criterion was used, with the steel behavior introduced into the software in terms of a bilinear elasto-plastic curve. In addition, material properties of the specimens demonstrate in Table 1.

Table 1. Material properties of the specimens

F_u = 493.4 MPa	F_Y= 356.6 MPa	Flange	Steel beam
F_u = 496.3 MPa	F_Y= 368.8 MPa	Web	
F_u = 669 MPa	F_Y= 523 MPa	ф18 longitudinal reinforcements	
F_u = 615 MPa	F_Y= 408 MPa	ф10 transverse reinforcements	
F'_c = 50 MPa		Characteristic strength of concrete	

In order to analyze the model, nonlinear static analysis considering geometrical nonlinear effects and nonlinear materials were used. In order to mesh the steel beam, concrete column and steel parts, 8-node three-dimensional solid elements (C3D8R) were used, while longitudinal and transverse reinforcements were meshed using 2-node truss elements of wire (T3D2) (Figure 2).

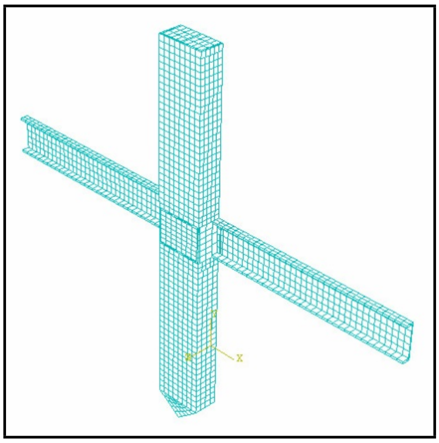


Figure 2. Meshing the finite-element model

Results of verification phase are presented as follows (Figure 3, Figure 4 and Figure 5):

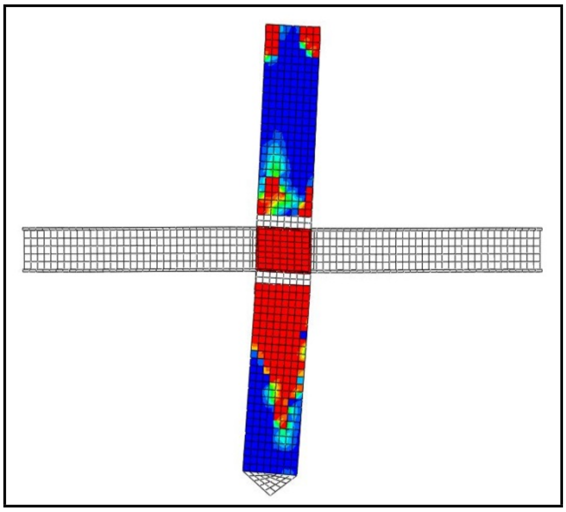


Figure 3. Contours of compressive damage to the concrete

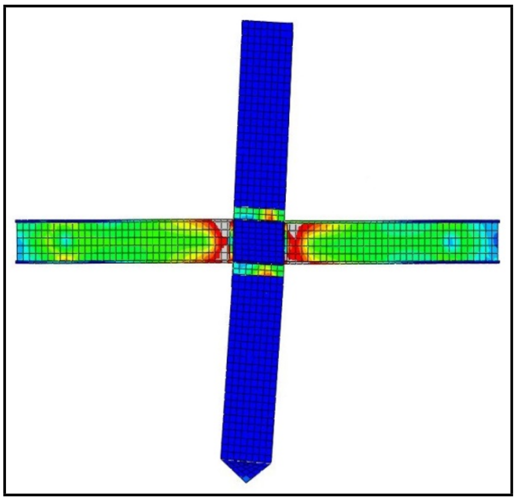


Figure 4. Stress contours in steel beam

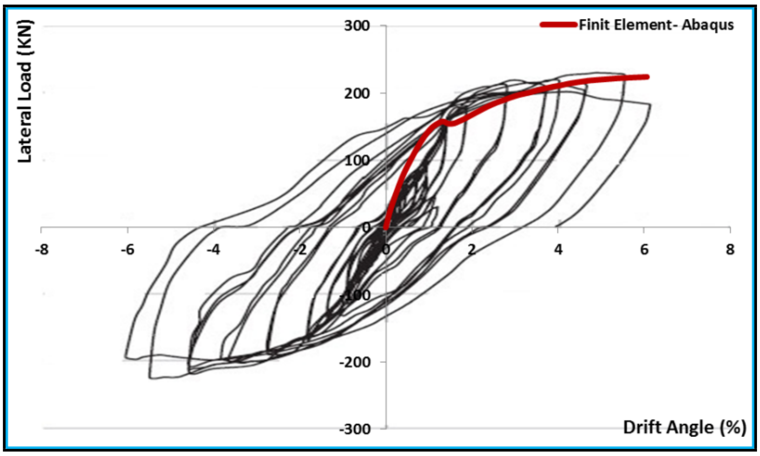


Figure 5. Plot of displacement force – drift for the experimental and numerical analyses

2.2. Parametric study

In order to undertake a parametric study, firstly, a four-story structure was designed, modeled and analyzed in ETABS software once assuming it as fully constructed from concrete, and once assuming it as fully constructed from steel with steel cross bracings. Then, dimensions and characteristics of the columns of the considered frame in the concrete structure and characteristics of steel beam and bracing system of the steel structure were extracted and fed, as initial data, into ABAQUS finite-element software. Characteristics of steel beam and concrete column, reinforcements, and steel bracing are given in Table 2.

Table 2. Sections obtained from the software-based analysis and design

Steel beam	Concrete column	Longitudinal reinforcement	Transverse reinforcement	Cross bracing
IPE270	450×450	$16\phi16$	$\phi10@150$	2UNP 160

Figure 6 gives a general view to details of the specimen, model, and its components.

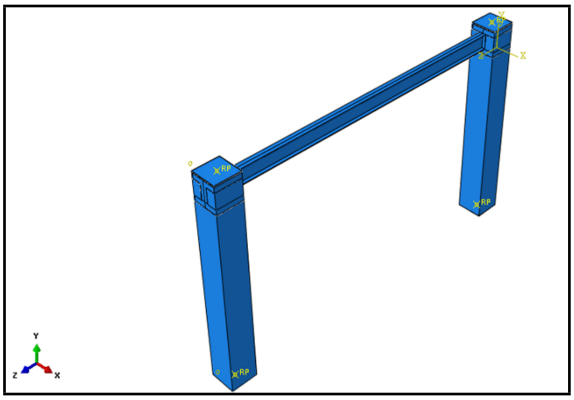


Figure 6. Modeled frame in ABAQUS software

2.3. Modeling and characteristics of RCS composite frame with cross bracing

In addition to all of the characteristics defined in the previous specimen, this specimen has a cross bracing (Figure 7). The frame is 6000 mm in length and 240 mm in height. Dimensions of the connection plate are 450×450×20 mm, with the bracing section being U-shaped (UNP160) with a length of 5280 mm.

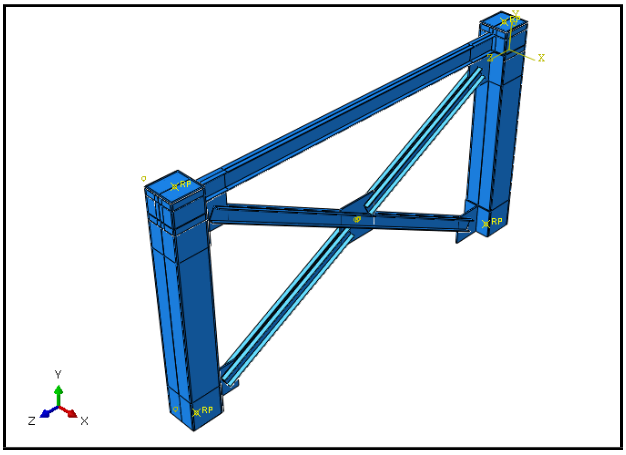
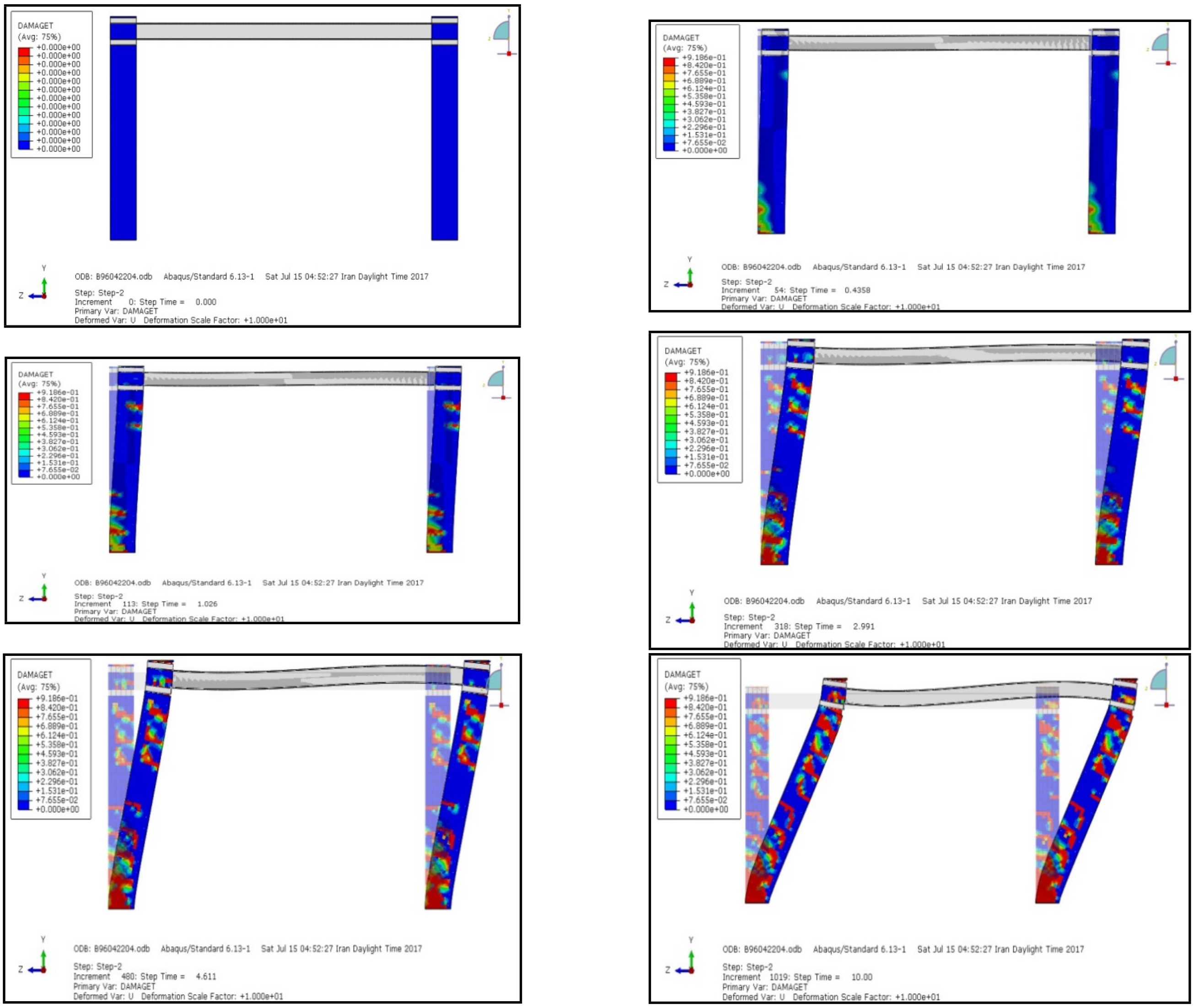


Figure 7. RCS frame model with cross bracings

3. RESULTS AND DISCUSSION

3.1. Cracking and failure stages of the models

In the moment-resisting frame alone, upon the start of loading and increasing the number of loading cycles, cracks are originated from the connection zone and beneath the connection area along the length of the column, and as the number of loading cycles increases, the count and depth of the cracks increase. With increasing the deal of applied force, the cracks extend, as shown in Figure 8, so that it can be stipulated that, in this model, structural failure will occur by formation of a plastic joint within an upper half of the column below the connection.



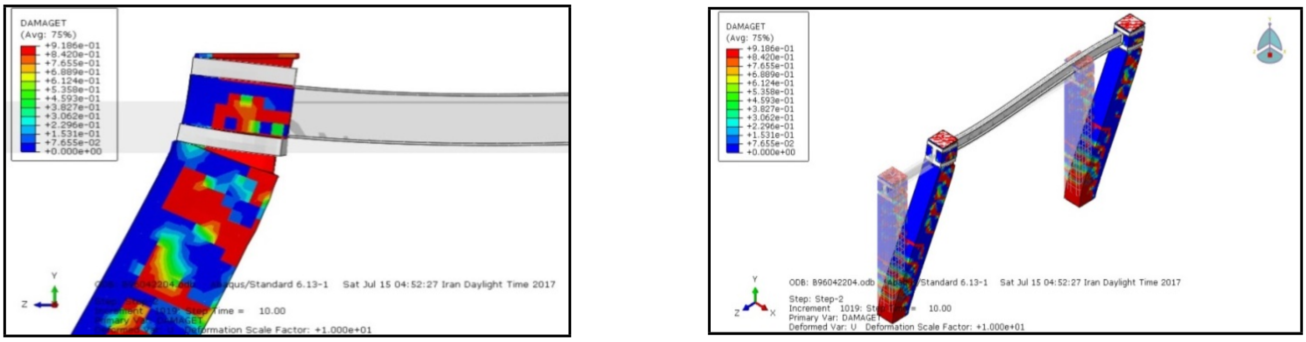


Figure 8. Different stages of compressive and tensile damage to the concrete in moment-resisting frame

The first cracks in the moment-resisting model occurred under 119,723 kN of load and 5.6 mm of displacement. In the model of the frame with bracing (Figure 9), Before the buckling of braces, the cracks slowly expand in number and depth by continuing the steps of loading until the crack propagation accelerates after the braces yield and the force transfers to the frame. Due to the presence of the bracing and stress concentration in the bracing-to-column connection, the first shear cracks are originated from the column base and then form in the fillet below the connection at bracing connection and extend toward the interior connection. The presence of a steel sleeve and more severe cracking of the column compared to the connection cause the cracking to propagate in the longitudinal direction of the column. As a result, the structure collapses by the formation of a plastic joint in the base part of a column. Therefore, the bracing transfers the plastic joint from the upper half of the column to its lower half. Initial cracks (which are of low number and depth) in the composite frame are results of load transmission to the braces. The first cracks in the modeled frame with bracing system occurred under a load of 895 kN at a displacement of 9.2 mm, indicating that the presence of braces enhances the corresponding force to the first crack in the frame.

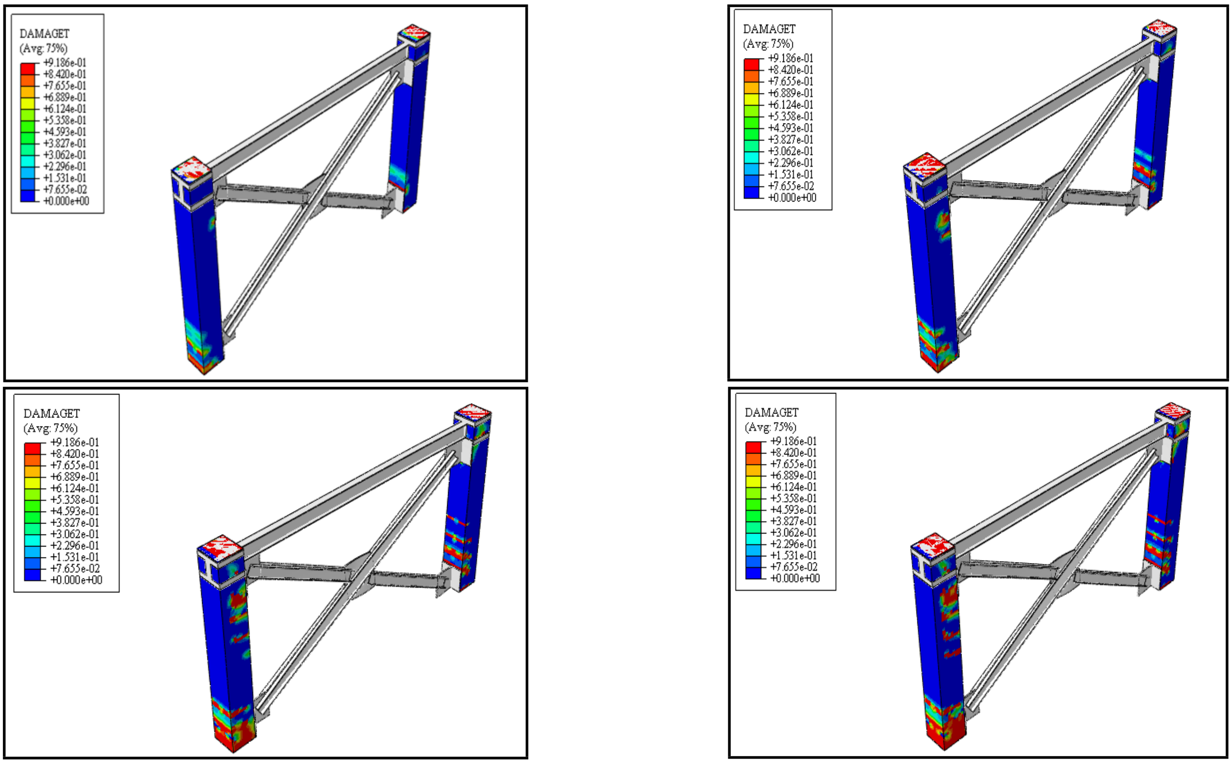


Figure 9. Tensile damage to the concrete in the sample frame with bracing

3.2. Load-bearing strength

Investigating the force-displacement curves of the models, increased load-bearing capacity using the bracing system (bracing connection plates) is well evident (Figure 10). Because the load is carried by the beam, column and connection in RCS structural system and the structure collapses when each of them yields. If bracing is inserted into a moment frame system, it increases the stiffness of the structure. In addition, the braces are members that prevent the horizontal displacement of the structure and since the beginning of loading until the point where the brace is buckled, a major portion of the applied force is bored by the braces. Once the braces yielded, the force is transmitted to the moment-resisting frame which further bears the load. This process increases load-bearing capacity of the braced frames compared to moment-resisting frames with no bracing system. Furthermore, a comparison between load-displacement curves of RCS composite frames with the cross-braced frame shows that load-bearing capacity of the frame has increased significantly to 928 kN, which means 3.5 folds increase compared to the bare frame, which is pretty considerable.

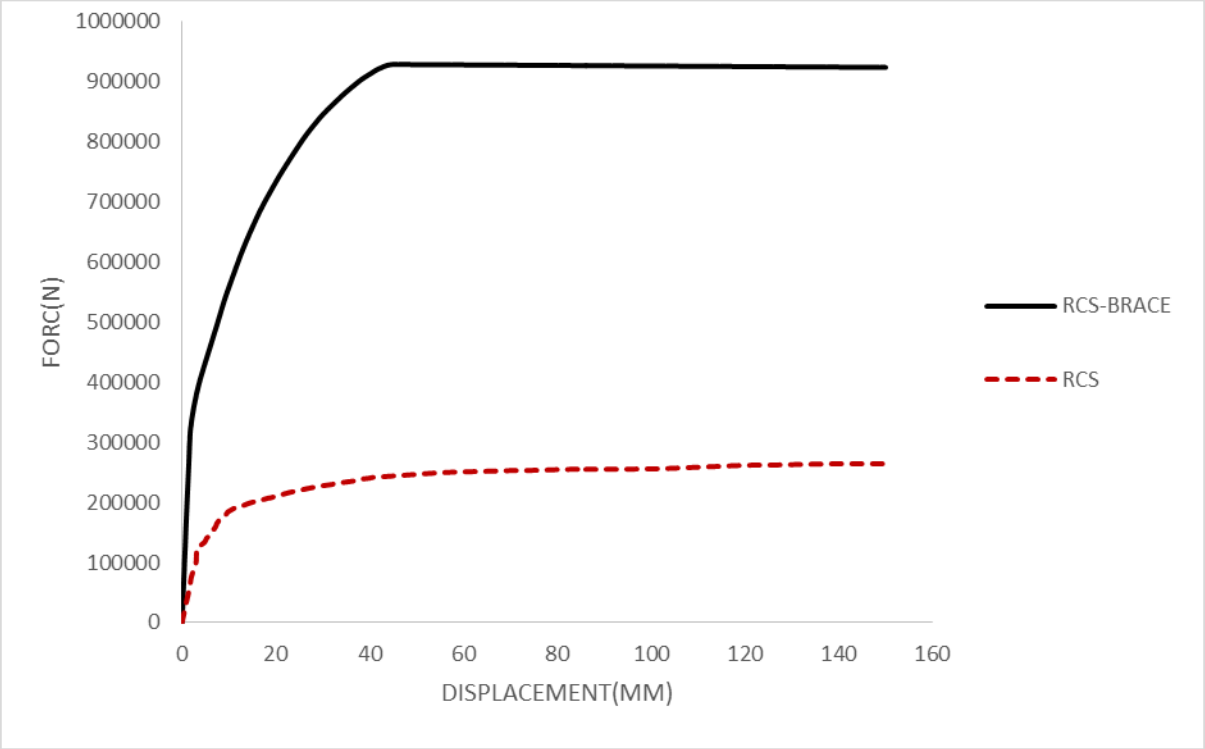
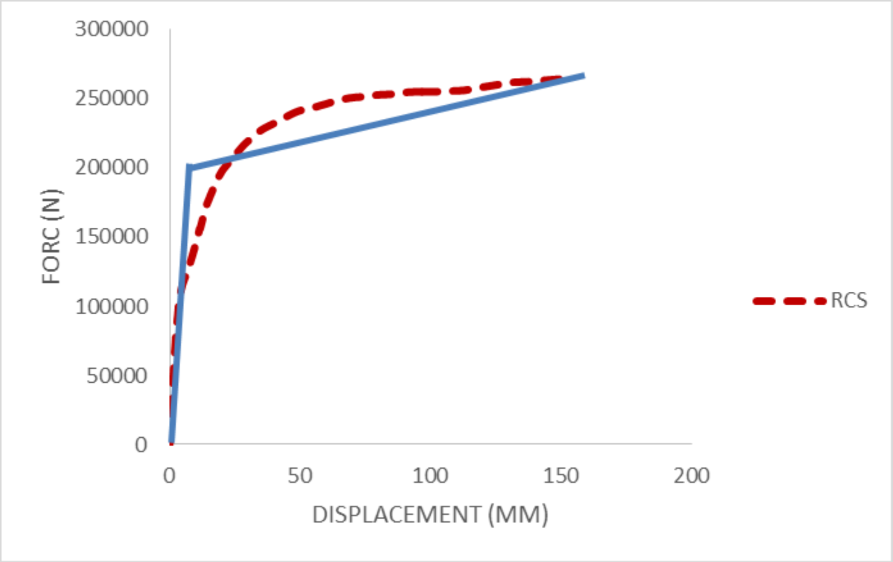


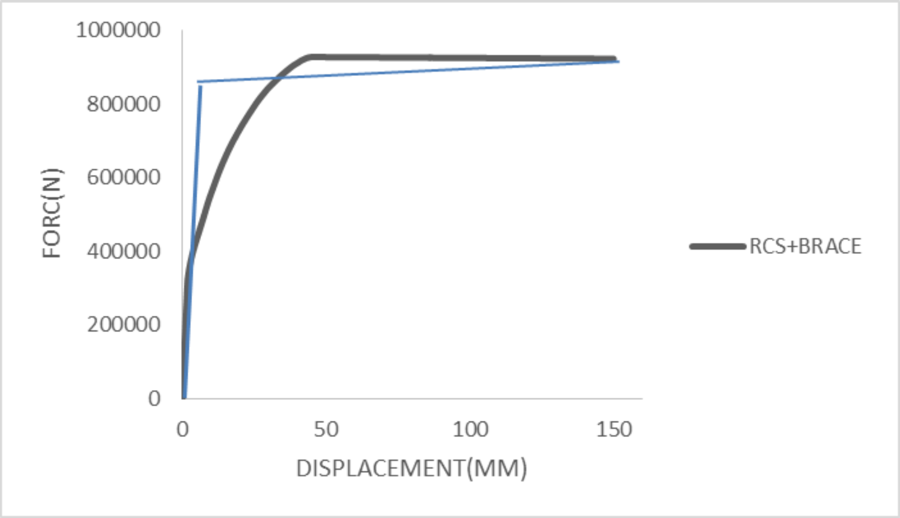
Figure 10. Comparison between load-displacement curves

3.3. Ductility

Ductility was evaluated by applying cyclic displacement to the considered structure and plotting force-displacement curve through numerous iteration of the force-displacement curve. The area under the force-displacement curve indicates the absorbed energy during cyclic behavior. The more complete and fat be this curve, the higher energy will be the amount of energy absorbed by the structure, representing higher ductility of the structure. Figure 11 shows load-displacement curves of the analyzed specimens along with the idealized bilinear curves. Ductility (μ) is equal to the ratio of maximum displacement (Δ_{max}) to displacement at yield (Δ_y) on a real plastic-ideal plastic curve. Table 3 compares ductility of different frames. The ductility has increased about 2.5 times in the model which employs bracing gusset plates and about 2.2 times in the model in which the frame is retrofitted by braces.



(a)



(b)

Figure 11. Load-displacement curve and ideal bilinear curve of the specimens. a) RCS frame, b) RCS frame with cross bracing

Table 3. Values of maximum displacement, displacement at yield, and ductility

Frame	Δ_{max}	Δ_y	μ
Frame	150	11	12.6
Braced Frame	150	5	30
Ductility changes (%)	2.2 times		

4. CONCLUSION

In the present research, the influence of using bracing in composite frame consisting of the reinforced concrete column and steel beam was investigated. Results indicated that, in the braced model, due to the presence of braces and concentration of stress within the brace-to-column connections, initial shear cracks originate from the column base and then at the fillet below the connection at bracing connection and then extends toward connection interior. The presence of bracing increased the force corresponding to the first crack in the frame significantly. Once the brace yields and the applied force is transmitted to the frame, the rate of crack propagation increases. It can be concluded that structural failure will occur by the formation of a plastic joint in column base zone. Moreover, considering force-displacement curves of the models, increased bearing capacity using the braced system was obvious. Compared to the bare frame, the braced system had its load-bearing capacity increased by about 3.5 folds. On the other hand, the ductility of the model reinforced with braces was about 2.2 times as large as the bare model.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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