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The Effects of Internal and External Stiffeners on Hysteretic Behavior of Steel Beam to CFT Column Connections

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ABSTRACT

This study focuses on the performance of H-shaped steel beams to CFT column rigid connections. To this end, the effects of internal and external stiffeners on hysteretic behavior of connections were studied. Comparative numerical analyses were carried out on eight different connections. To this end,finite element models were prepared using ANSYS and nonlinear cyclic analyses were carried out. Results of this study revealed that external stiffeners are key elements to increase the ductility and strength of steel beam to CFT column connections. The connections with internal stiffeners, without any external stiffeners did not exhibit observable hysteretic behavior. On the other hands T-shaped stiffened connections exhibited stable hysteresis loops. Furthermore the capacities of T-stiffened connections were about 1.75 times greater than that of models with horizontal or vertical stiffeners.

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NOMENCLATURE

S	Failure surface	**Greek Symbols**	
f'_c	Axial strength of concrete	σ_{zp}	Principal stress (MPa)
L_s	Length of vertical element of T-shaped stiffeners (mm)	Δ	Vertical displacement at the end of the beam (mm)
H_s	Height of vertical element of T-shaped stiffeners (mm)	Δ_y	Vertical displacement of the end of the beam at yield point (mm)

1. INTRODUCTION

Concrete filled tube (CFT) composite columns are widely used in different types of structures especially high rise buildings. It is a common knowledge that CFT columns combine advantages of both concrete and steel material [1]. For this reason, CFT column possesses many advantages compared to conventional RC and/or steel structural members. Steel tube confines concrete core and may cause increasing in compression strength of concrete [2]. Meanwhile the concrete core may restrain the steel tube against local buckling [3]. During the construction, steel tube can act as a cast for fresh concrete and provide rapid erecting. Moreover, concrete is one of the most economical materials for bearing compression. Hence CFT columns would be economically acceptable [4]. Based on the abovementioned specifications of CFT columns, there is a worldwide interest in investigation of performance of CFT columns. During the last decades, several experimental and numerical studies on behavior of CFT columns have been presented in the literature. Some of these studies can be found elsewhere [5, 6]. The behavior of beam to CFT rigid connections is very important especially in earthquake prone areas. Several researches have been conducted in order to investigate the behavior of beam to CFT column connections. Gupta et al. [1] presented the influence of the grade of concrete and diameter to thickness ratio of steel tube on

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behavior of beam to CFT columns. Shin et al. [7] conducted experimental and numerical investigations on beam to CFT column connections with external stiffeners. Han and Li [8], experimentally investigated the seismic behavior of steel beam to CFT column connections. Several researches conducted in order to investigate the effects of fire on steel beam to CFT column connections [9-11]. Several other valuable studies are presented in the literature [12-17]. In rigid connections, bending moment causes tension in beam flange. Transmitted tension to steel wall may cause separation in concrete and steel interface. Following the separation of concrete core and steel wall, wrinkling or rupture of steel wall may occur. Internal stiffeners and shear connections could be useful tools for decreasing separation of concrete core and steel tube, whilst external stiffeners may be used to limit damage to steel wall. The focus of this study is on the effects of internal shear connections and external stiffeners on cyclic performance of H-beam to concrete filled rectangular tube columns. Herein, different arrangements of internal and external stiffeners are numerically modeled and monotonic and seismic behavior of connections is studied.

2. FINITE ELEMENT MODELING

Finite element (FE) analysis was carried out in order to study the behavior of beam to column connections. To this end, ANSYS multipurpose finite element software was used [18]. Material and geometric nonlinearity have been taken into account in finite element analysis.

2. 1. Elements Used for FE Analyses

Three dimensional solid elements (Solid 45) were used for modeling steel tube, T-stiffeners, H-beam and shear connections. Solid 45 elements are eight node quadratic elements having three degrees of freedom at each node. Eight node Solid 65 models were used for modeling concrete core. These elements have three degrees of freedom at each node. They are capable of modeling concrete cracking in tension and crushing in pressure. Geometry of solid elements is presented in Figure 1a.

Special attention should be paid for modeling interface between steel tube and concrete core. In this study, node-to-node contact elements were used to model the contact between steel tube along with its shear connections and concrete core. The contact elements were connected adjacent nodes of steel and concrete. These elements have three translational degrees of freedom at each node. They are capable of modeling compression of concrete core into steel tube. They are also capable of modeling separation and sliding of concrete to steel. In other words, only compression can be transferred in normal direction to the surface. Meanwhile sliding can be modeled by Coulomb friction in tangential direction to the surface. Figure 1b indicates node-to-node contact elements. Material nonlinearity of steel was accounted for the analyses based on Von Mises yield criterion. Kinematic hardening rule was used to define the material property in these elements. As indicated in Figure 2, multi-linear stress-strain model was considered for steel elements of connection. The concrete failure criterion can be expressed as follows:

$$\frac{F}{f'_c} - S \geq 0 \qquad (1)$$

where S is the failure surface which is expressed by five input parameters: ultimate uniaxial compressive and tensile strength, ultimate biaxial compressive strength, ultimate compressive strength for a state of biaxial compression superimposed on hydrostatic stress state and ultimate compressive strength for a state of uniaxial compression superimposed on hydrostatic stress state. The stress-strain relationship for concrete core and failure surface in principal stress space σ_{zp} close to zero is indicated in Figure 3.

2. 2. Sample Models

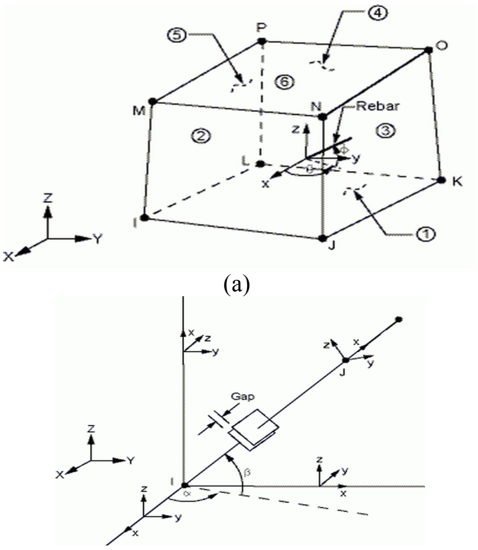
In this study, the influence of internal and external stiffeners on cyclic behavior of H-beam to CFT column connection was studied. To this end, beam to column connections with different arrangements of internal and external stiffeners were considered. Herein three categories of connections were modeled as follows:

- Direct connection of beam to column with internal stiffeners without external stiffeners (Class I)
- Direct connection of beam to column with both internal and external stiffeners (Class II)
- Direct connection of beam to column with external stiffeners without internal stiffeners (Class III)

The internal stiffeners have been suggested by some researchers [2]. The production process of these elements is shown in Figure 4. It is worth mentioning that material properties and geometric specifications of beam and column in every model were the same and arrangements of stiffeners were the only difference between different specimens. Geometric specifications of beam and columns are presented in Table 1. In this section every category of specimens is presented.

2. 2. 1. Class I

In this category, single internal stiffeners were used in each face of tubular column. In this study, the internal stiffeners were steel plates of 88 mm in width and 12 mm in thickness. Two different types of connections were considered. In model C1-S, the H-beam was simply connected to tubular columns whereas in model C1-D jacket plates were used to strengthen the column in panel zone. No external stiffener was considered for this class of connections. The finite element models of C1-S and C1-D samples are presented in Figure 5.



(a)

(b)

Figure1. Geometry of elements: (a) solid elements and (b) gap elements [18]

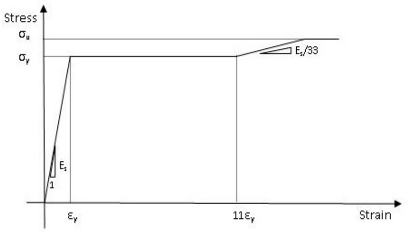
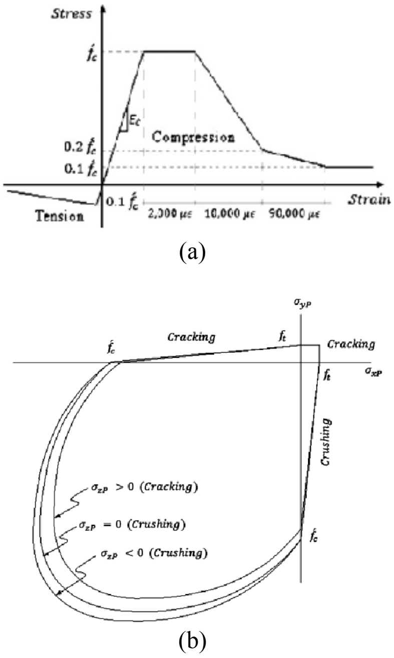


Figure2. Stress-strain model of steel in FE model



(a)

(b)

Figure 3. Material model for concrete core: (a) stress-strain relationship and (b) failure surface in principal stress space close to zero

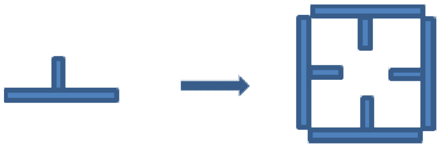


Figure 4. Production process of the internal stiffeners

2. 2. 2. Class II This class contains three arrangements of external stiffeners. In model C2-H, horizontal stiffeners were used. This model is illustrated in Figure 6a. Figure6b illustrates model C2-V in which vertical external stiffeners were used. Model C2-T contains T-stiffeners (see Figure 6c). This model can be considered as combination of models C2-H and C2-V. The internal stiffeners in connections of class I and II were completely the same. Model C2-TV contained both external T-stiffeners and additional vertical stiffeners (see Figure 6d). Another model of this class is C2-T2 which is approximately same as C2-V. The only difference of these connections is that model C2-T2 has two internal stiffeners on each face of the column. This model is shown in Figure 6e.

2. 2. 3. Class III In this category of connections external T-shaped stiffeners same as C2-T models were used. The difference of this model (C3-S) with C2-T specimen is that C3-S doesn't have internal stiffeners. Figure 7 shows the finite element model of C3-S. It is worth mentioning that the geometric and material properties of the models are presented in Table 2 and Table 3, respectively.

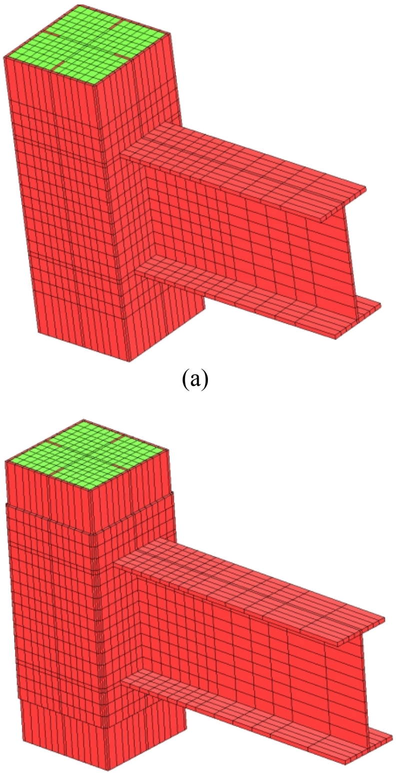
3. FE ANALYSES AND RESULTS

Nonlinear cyclic analyses were performed on above mentioned models. Constant axial load of P=775kN were applied to composite column. Coincidently cyclic vertical displacements were applied to the free end of H-shaped beam (See Figure 8). Beam flanges were constrained against out of plane movements. In other words, the beams were restrained against lateral torsional buckling. Hysteresis loops for different models are presented in Figure 9. As indicated in this figure, none of the connections of "class I" have observable hysteresis loops.

Hysteresis loops of C2-H and C2-V are extremely thin. Meanwhile other models in "Class II" and "Class III"have stable broad hysteresis loops. Distribution of Von-Mises stress, fvm, in Figure 10showsconsiderable stress concentration in conjunction of beam flange and column face. The Von-Mises stress contour in model C2-H shows that the failure mode of this model would be damage to horizontal stiffener-column face junction due to noticeable stress concentration. Finite element model predicts failure of vertical stiffener in C2-V model. Meanwhile no considerable stress concentration occurred in T-stiffened connections (i.e. C2-T, C2-TV, C2-T2 and C3-S).

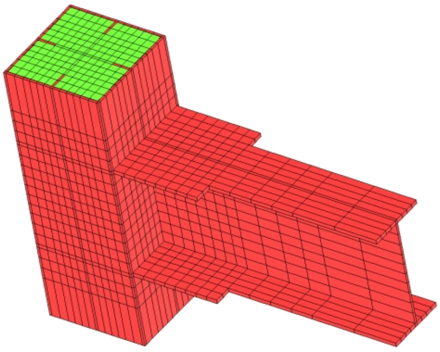
TABLE 1. Geometric specification of beams and columns

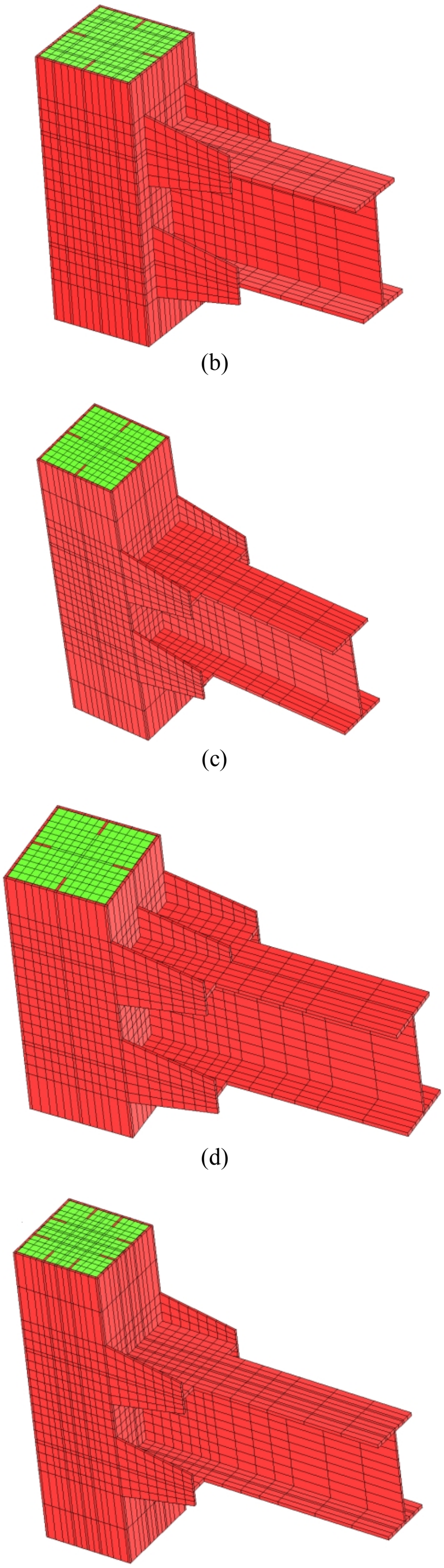
Member	Shape	Web thickness (mm)	Flange thickness (mm)	External height (mm)	Flange width (mm)
Column	Box	12	12	500	500
Beam	H	12	20	588	300


(a)

(b)

Figure 5. Finite element model of class I connections: (a) model C1-S and(b) model C1-D


(a)


(b)

(c)

(d)

(f)

Figure 6. Finite element models of class II connections: (a) model C2-H, (b) model C2-V, (c) model C2-T, (d) model C2-TV and (e) model C2-T2

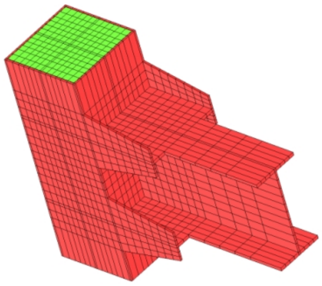


Figure 7. Finite element model of C3-S

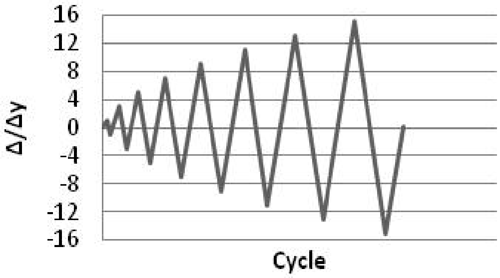


Figure 8. Displacement control loading scheme [7]

4. MODEL VERIFICATION

In order to verify the accuracy of the finite element models, the numerical results obtained from cyclic and analyses were compared to experimental data. The experimental data were conducted on T-stiffened connections by Shin et al. [7]. The geometric and material specifications of test sample are presented in Tables 2 and 3, respectively. Figure 11, illustrates the numerical and experimental moment-rotation response of the connection under cyclic loadings. A close comparison of experimental and numerical results reveals that numerical hysteresis loops are slightly sharper than experimental ones. But as can be seen in Figure 11, the behavior of connection predicted by FEM was close to actual behavior of the connection exhibited by the experiment. In other words, finite element model were reliable enough to conduct comparative investigations on nonlinear behavior of beam to CFT column connections. Moreover, numerical results showed a reasonably good correlation with failure modes in experimental model [7]. As indicated in Figure 11, both numerical and experimental models have shown damage to beam web and flange near panel zone. Hence the numerical model has acceptable ability in prediction of failure mode of the connection.

5. DISCUSSION

5. 1. Influence of External Stiffeners

As indicated in Figure 8,models C1-S and C1-D didn't show observable hysteretic behavior. The maximum rotation of C1-S model was 0.00175 radians where the maximum rotation of C1-D was 0.004 radians. In other words connections of "Class I" did not exhibit nonlinear energy absorption. The main reason for such behavior is considerable stress concentration in column near beam flanges (Figure 10). The stress concentration causes excessive cracking and or crushing in concrete core, whereas no noticeable failure occurs in steel. Distribution of cracks in concrete core at the end of the last stage of loading ($\Delta \leq \Delta y$) is shown in Figure 13. According to this figure,FE model predictsconsiderable damage to concrete near conjunction of column and beam flange. The only difference of crack pattern in model C1-S and C1-D is that the concentration of cracks near beam flanges in C1-D is slightly less than that of C1-S. It is worth mentioning that such cracking doesn't occur in "Class II" and "Class III" connections even after $\Delta = 3\Delta y$. In other words, in connections without external stiffeners, extensive damage to concrete core happens prior to damage to steel tube and/or beam. Meanwhile in connections with external stiffeners considerable cracking doesn't occur in concrete core before yielding of steel material in tubular column or beam.

TABLE 2. Geometric specifications of test specimen

H beam flange	H beam web	Tubular column	L_s (mm)	H_s (mm)
PL 300x20	PL 548x12	Box 500x500x12	440	360

Ls and Hs are length and height of vertical element of T-shapedstiffeners, respectively.

TABLE 3. Material properties of TS-3

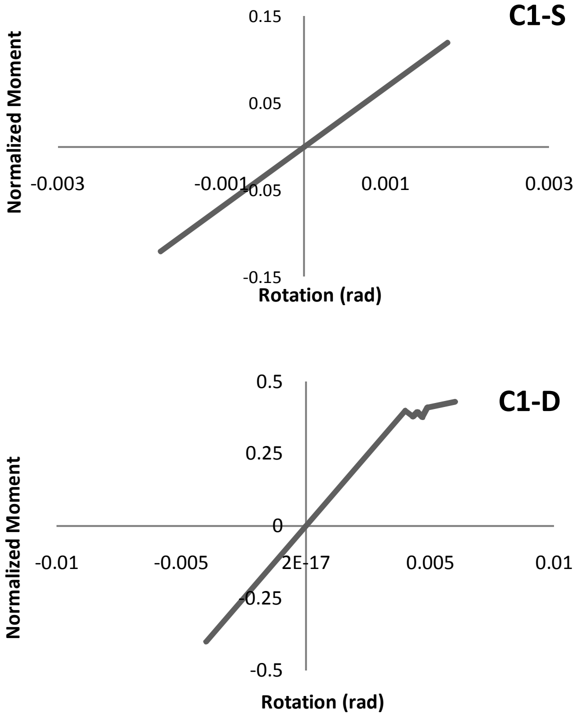
Member	Compressive strength (MPa)	Yield stress (MPa)	Ultimate stress (MPa)	Elongation (%)
Beam flange	-	306	445	24
Beam web	-	319	440	28
Tubular column	-	271	458	26
Concrete core	26.46	-	-	-

5. 2. Influence of the Shape of External Stiffeners

In order to investigate the effect of the shape and arrangement of external stiffeners on behavior of connections, maximum moment and rotation of connections in "Class II" were compared. To this end, maximum moment and rotation of each connection was normalized to the plastic moment and rotation of C1-S respectively. Results of this comparative analysis are illustrated in Figure 13. As indicated in this figure, the capacities of T-stiffened connections are about 1.75 times greater than that of models with horizontal or vertical stiffeners. Moreover, the maximum rotations of T-stiffened connections are 4.58 times of maximum rotation of connections with horizontal or vertical connections. In other words, T-shaped stiffeners may remarkably increase the ductility of steel beam to CFT column connections. The main reason for such influence on ductility is well distribution of stress in column and beam and considerable reduction in stress concentration in column. Figure 14 also indicates that there is not meaningful difference between performances of neither C2-V and C2-H nor C2-T and C2-TV.

5. 3. Influence of the Internal Stiffeners

In order to investigate the effect of internal stiffeners on cyclic performance of beam to CFT column connections, performance of C2-V, C2-T2 and C3-S samples were compared. To this end, the envelop curve of the moment rotation hysteresis loops of these connections were used. As shown in Figure 15, the envelop curves of C2-T2 and C2-V are almost the same.



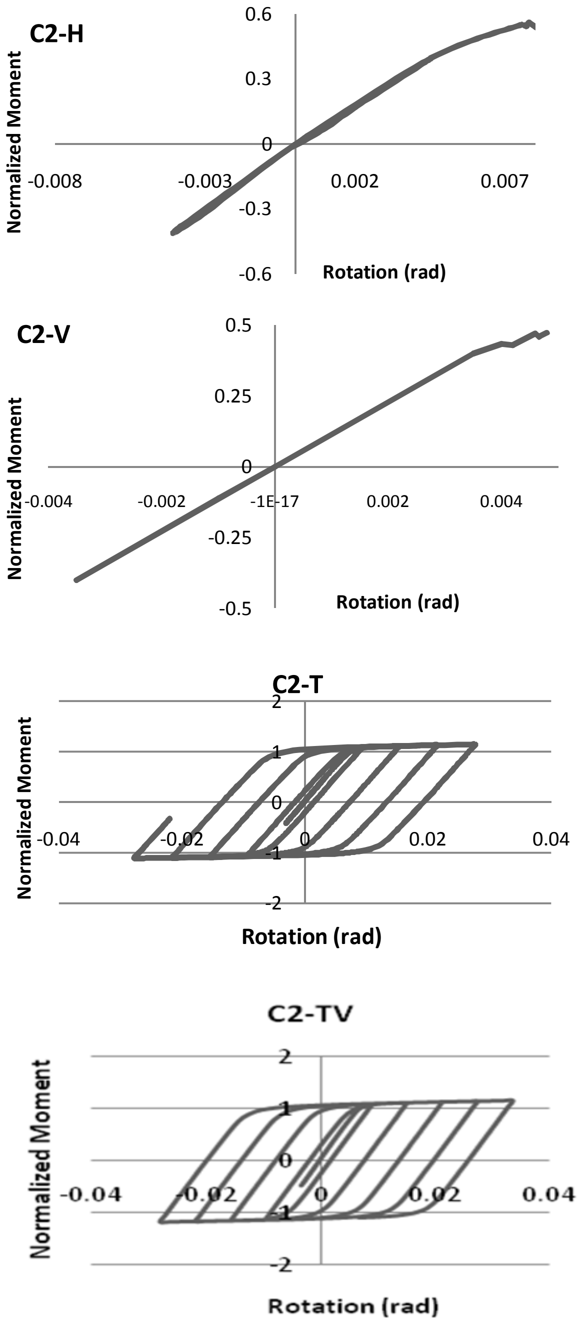
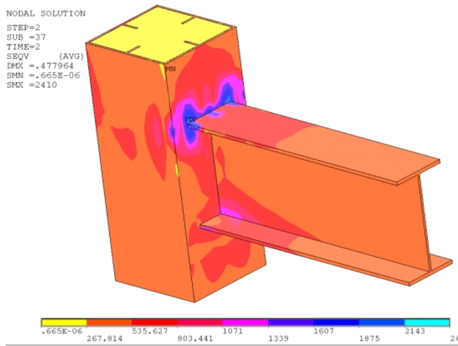
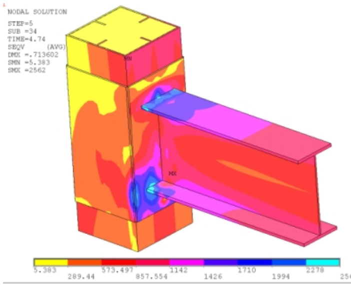


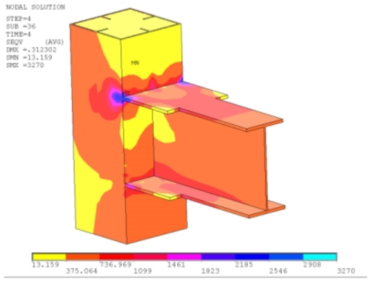
Figure 9. Hysteresis loops of different types of connections



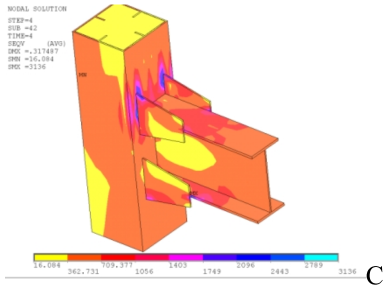
C1-S



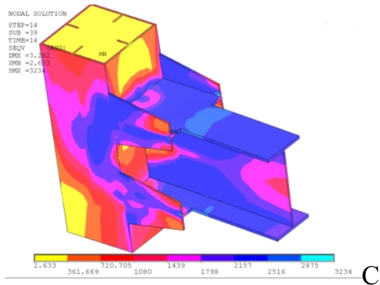
C1-D



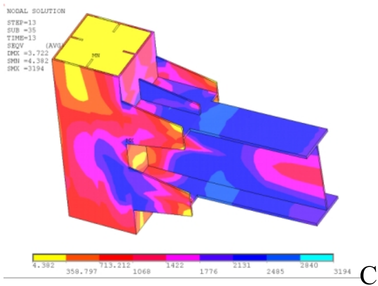
C2-H



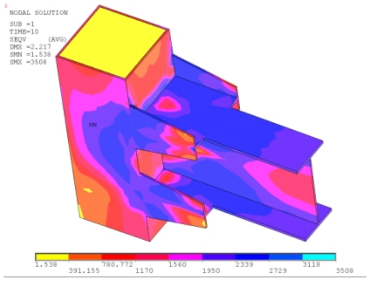
C2-V



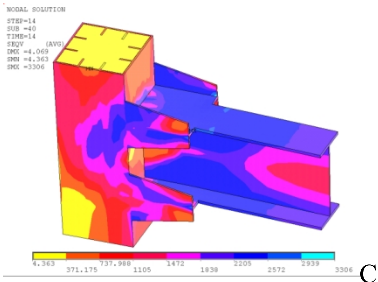
C2-T



C2-TV



C3-S



C2-T2

Figure 10. The Von-Mises stress contour in different models

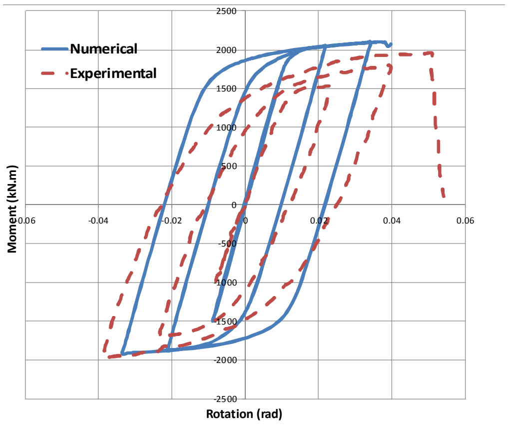


Figure 11. Comparison of experimental and numerical hysteresis loops

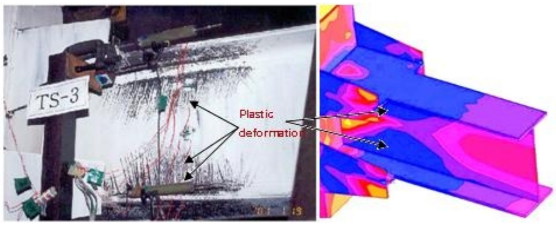
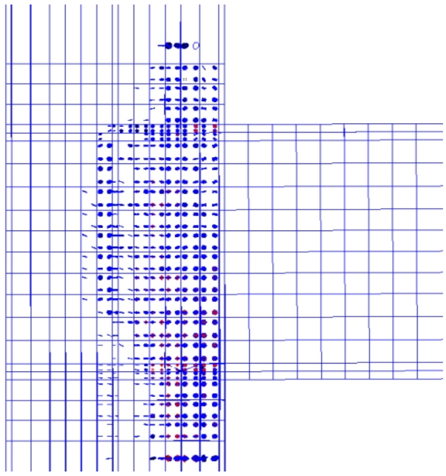


Figure 12. Location of plastic hinge in experimental sample and FEM model



C1-S

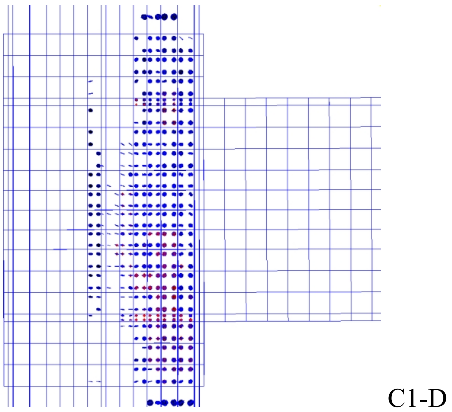


Figure 13. Crack pattern in concrete core of C1-D and C1-S

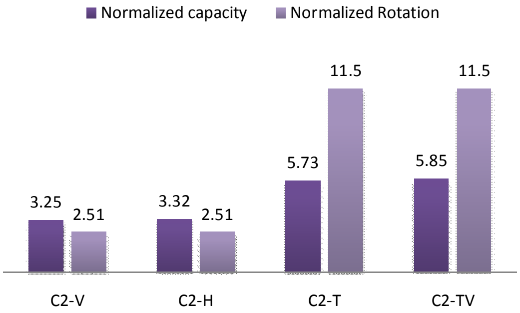


Figure 14. Comparison of the capacity and rotation of connections with external stiffeners

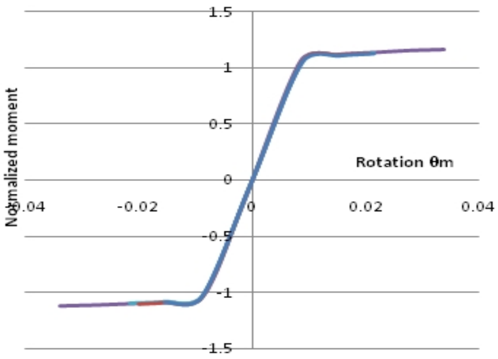


Figure15. Envelop curve of the hysteresis loops of C2-V, C2-T2 and C3-S

6. CONCLUSION

This study aimed to investigate the cyclic behavior of beam to CFT column rigid connection. Comparative nonlinear FE analyses were conducted to study the effects of internal and external stiffeners on cyclic performance of steel beam to CFT column connections. Herein hysteretic behaviors of different types of steel beam to CFT column connections as well as the capacity and of the connections were investigated. Results of this study revealed that among the considered arrangements of the connections, only T-stiffened connections exhibited the observable and stable hysteresis loops.Moreover, the maximum rotations of T-stiffened connections were considerably higher than that of other types of connections.It was also shown that in those connections which didn’t have external stiffeners, the stress concentration may cause damage to concrete core. In connections with horizontal or vertical stiffeners, stress concentration in junction of stiffener and column face may cause damage to stiffener and/or column face. The best stress distributions were happened in T-stiffened connections in which the maximum Von-Mises occurred in H-shaped beam. The most important components of the connection were the external stiffeners. Removing internal stiffeners didn’t make noticeable change in hysteretic behavior of T-stiffened connections.

7. ACKNOWLEDGEMENTS

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The Effects of Internal and External Stiffeners on Hysteretic Behavior of Steel Beam to CFT Column Connections

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چکیده

این پژوهش بر عملکرد اتصال صلب تیرهای H شکل به ستون های فولادی پر شده با بتن متمرکز است. برای این منظور اثر سخت کننده های داخلی و خارجی بر رفتار چرخه ای اتصالات بررسی شده است. مطالعات عددی مقایسه ای بر روی هشت اتصال مختلف به انجام رسید. برای این منظور روش اجزای محدود با استفاده از نرم افزار ANSYS به خدمت گرفته شد و تحلیل های غیر خطی تناوبی به انجام رسید. نتایج این تحلیل ها نشان داد که سخت کننده های بیرونی اجزایی کلیدی در افزایش شکل پذیری و مقاومت اتصالات تیر به ستون های فولادی پر شده با بتن هستند. اتصالاتی که تنها دارای سخت کننده های داخلی هستند رفتار چرخه ای قابل مشاهده ای از خود نشان نمی دهند. از سوی دیگر اتصالات با سخت کننده های T شکل رفتار هیسترزیس پایداری را نشان می دهند. علاوه بر این ظرفیت اتصالات دارای سخت کننده های T شکل تقریبا ۱/۷۵ برابر ظرفیت اتصالات با سخت کننده های افقی یا عمودی هستند.

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