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INVESTIGATION OF BEHAVIOR OF INTERIOR STEEL CONNECTIONS WITH OPENINGS IN BEAM WEB AND FLANGE UNDER MONOTONIC LOADING

Dan-Dan Yan [1], Bai-Li Zhou [2], Xin Guo [1], Fang Lai [2], Xi Wei [2], Yi-Peng Xu [3, *], Mehdi Esfandi Sarafraz [4] and Maryam Jahanian [5, *]

[1] *School of Energy and Power Engineering, XiHua University, Chengdu, Sichuan, 610039, China*
[2] *School of Civil and Environmental Engineering, Xihua University, Chengdu, Sichuan, 610039, China*
[3] *School of Mathematical Sciences, Tiangong University, Tianjin, 300387, China*
[4] *Department of Civil Engineering, Islamic Azad University, West Tehran Branch, Tehran, Iran*
[5] *MSc graduate of Structural Engineering, University of Tabriz, Tabriz, Iran*
* *(Corresponding author: E-mail: xu.yipeng90@gmail.com; mjahanian454@gmail.com)*

A B S T R A C T

Connections are considered to be one of the most prominent components of steel moment frames and have received studious attention in recent years. The core problem of welded connections is premature brittle fracture of weld in the critical beam-to-column connection region. Within the framework of this issue, various approaches have been proposed to solve the mentioned problem. Intentional weakening of the beam web or flange is in line with the purpose of leading the plastic hinge away from the column face, hence, increasing the ductility. The aim of this research is to investigate the behavior of interior connections subjected to monotonic lateral loading in case of presence of openings in beam web or flange. To do so, an ordinary fully welded rigid connection, reduced beam section, reduced web section, and drilled flange connection models are simulated numerically, utilizing finite element software, ANSYS. The results indicate that scrupulous selection of opening sizes are of great importance to fulfill the desired outcome which is avoiding the brittle failure of connections. Furthermore, the use of drilled flange, reduced beam section, or reduced web section connections satisfy the expected performance and it is proposed to use them according to practicability, architectural and economic considerations as well as site conditions. Shear deformation and local buckling is observed in reduced web section connections while in drilled flange connections, stress concentration around the opening is critical.

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1. Introduction

The premature failure of steel structures due to connection damages, induced by various loadings, has received studious attention leading to the development of beam-to-column connection design processes and revision of different codes in recent years. Consequently, enhancing the structural ductility is the issue that still continues to evoke interest among researchers since the regulations emphasize the urge to design ductile systems. Intentional weakening of beam parts, strengthening the connection or utilizing dissipative elements are among commonly discussed approaches of relocating the plastic hinge away from the column face, hence, increasing the structural ductility, which is consonant with the formation of plastic hinge.

Prequalified steel moment connections described in ACI 358 [1] for SMF and IMF systems are categorized into 10 groups, among which reduced beam section (RBS) connection is a type of connection in which intentional weakening of a part of the beam flange is employed to obtain the desirable performance of beam-to-column connections. Consequently, AISC design codes have imposed some regulations on the design principles of RBS connections. However, the other types of connections are within the group in which strengthening the connection is based on added members including end-plates, steel brackets, plates, etc. Many studies have been published on utilizing RBS connections in steel moment frames [2-9]. Yet, according to [10], one of the major drawbacks to adopting the RBS connections are the limited range of beam and column dimensions in tests. Despite the fact that RBS connections are among the robust connections to be employed in steel moment frames, they experience stiffness degradation as well as loss of moment capacity [5,11-15]. Furthermore, stress concentration due to flange cut fabrication in site is a disadvantage for the seismic performance of RBS connections [16]. Based on some researches, designing RBS connections in conformance to AISC code in case of utilizing IPE sections with large dimensions appears to be insufficient, hence, stiffeners must be provided [17].

In terms of web reduction, limited number of codes including [18-20] have deemed attenuating beam web as a means of improving connection behavior, and there exist limited guidelines on steel frames with perforations in beam web. However, various opening shapes except for rectangular and circular ones are not covered in the afore-mentioned codes. In this regard, other opening shapes including elliptical-shaped, hexagon-shaped, etc. have been investigated by [21-26] and other researches.

DF (drilled flange) connections are not covered in design codes such as [1, 10, 27-29]. Accordingly, neither regulations nor design guidance are suggested on DF connections, hence, utilizing DF connections instead of RBS ones are in their early stages. Despite the fact that fabrication of DF connections is easier than RBS ones, they perform slightly weaker [16] or nearly similar to the RBS connections [30]. However, there is still considerable uncertainty regarding the performance of DF connections. In this regard, some of the researches have approved the desired performance of DF connections in which these connections are capable of satisfying [29] AISC 341-16 requirements for rigid connections [31-34]. Hence, DF connections are deemed a sough-after substitute fo r RBS connections.

Many studies have investigated the behavior of connections [35-39]; also, the behavior of prefabricated beam-to-column connections were studied by many researchers [40-42] among which [40] utilized short post-tensioned prestressed strands to prevent on-site aerial tensions. Furthermore, the connection of H-Shaped steel beam to box columns with flange plate connection was scrutinized by [43]. The behaviour of the TS semi-rigid connections were investigated through utilizing both experiments and numerical simulations by [44-45]; etc. The assessment of performance of joints between steel beam and LSWL-C columns was performed numerically and through experimental tests by [46]; among most recent researches conducted on connections, [47] used folded axillary plates, which are located at the outer side of the beam-end flanges, to improve the behavior of fully welded connection.

Various approaches have been put forward to lead the plastic hinge away from the column face through intentionally attenuating a part of the beam, among which, many attempts have been made with the purpose of improving the connection behavior through cutting of the beam flange [12, 15-16, 48-57]. Plumier [58] was the first to introduce trapezoidal beam flange cuts. Much work on the potential cut profiles of RBS connection was carried out by [11, 59-62], yet the radius cut revealed the appropriate seismic performance in comparison with other cut configurations [11,63]. Furthermore, ameliorating the behavior of RBS connections are the topic of many studies in terms of buckling which leads to an early strength degradation [64-66]. The first investigation on double reduced beam section was carried out by [57], in which two adjacent radius cuts was implemented in beam flange named as DRBS, and concluded that implementing the second cut leads to maximum equivalent plastic strain index reduction as well as delaying the local buckling. Investigating the behavior of RBS connections through numerical or experimental studies in the recent years are conducted by many researchers among which [67-76] can be mentioned. Fanaie et al. [69] pointed to a method in which a mathematical approach in conjunction with principles of structural analysis is employed in order to acquire the drift as well as changes in stiffness of stories in frames with RBS connections. Meng et al. [77] introduced a novel RBS connection with V-shaped reinforcing plate which improved the seismic performance of RBS connections. Moreover, the use of RBS-free and RBS-based systems in moment frames in tall buildings under earthquake excitations were scrutinized by [78]. Sensitivity study on the effect of beam slope angle as well as different design factors, including material or geometry, on the cyclic behavior of RBS connections in terms of initial stiffness, rupture index, plasticity index, moment capacity, yield moment, hysteretic energy dissipation, and strength degradation rate was performed by [79]. Results indicated the significance of the slope angle and beam depth in the response of the RBS connections.

Reduced beam web connections in which an opening is implemented in beam web has been widely investigated by many researchers [22, 24-25, 80-103]. Geol and Itani [104-105] drew the attention of researchers to reducing the beam web as a way of achieving desired performance of moment frames. The possibility of using the connections with reduced beam web was investigated by [88]. In this regard, a more recent evidence reveals that RWS connections are a desirable replacement for RBS connections in terms of story drifts and strength [106]. Furthermore, issues regarding the energy dissipation of RWS connections are addressed by [22, 95]. Detailed examination of influential parameters including opening size, location, etc. was undertaken by many researchers [81, 85-86], leading to the conclusion that scrupulous selection of opening dimension, shape and location is essential in order to obtain the favorable frame behavior. Various shapes of openings in RWS connections is further explored by [21-26]. Also, the capability of RWS models to reach higher story drifts (six percent) was evaluated by [82-83] both in experimental and numerical ways. The behavior of RWS connections via numerical or experimental studies in the recent years are assessed by many researchers among which [107] developed a novel RWS connection with vertical slits; [108] investigated the RWS connection with an elliptic opening in the web; [109] evaluated the cyclic performance of an eight-story welded moment frame with elliptical-shaped RWS and compared it to the conventional RBS connections; Yu and Li [110] evaluated the steel frames with RWS connections and WFP connections using the probabilistic seismic demand analysis and seismic capability analysis; Lin et al. [111] investigated the behavior of RWS in progressive collapse under critical column removal scenario, the results demonstrated the capability of the mentioned connections in terms of rotational capacity; Erfani et al. [112] studied the lateral load carrying behavior of steel moment resisting frames with reduced web beam sections and propounded an algorithm to select appropriate opening size; Bi et al. [113] scrutinized the castellated beam-to-column connections with four regular hexagonal web openings under cyclic loading with and without floor slab, the results indicated the importance of the space between web openings, and depth-to-thickness ratio of the web. Moreover, due to the limitations imposed on beam span-to-depth ratio in different codes which result in the impossibility of the use of short beams in some of the prequalified rigid connections, Hoseinzadeh Asl and Jahanian [114] investigated using web opening located at the mid-span of the deep steel beams in rigid connections in order to lead the plastic hinge away from the column face.

Utilizing drilled flange moment resisting connections is another approach to overcome the problem of weld brittle failure in the beam-to-column connections which is studied by many researchers and is almost in its early stages [17, 31-34, 115-117], among which the optimum algorithm of drilled holes in order to achieve desired performance of structure is proposed by [34, 116-117]; in this regard, initial suggestion of design algorithm for drilled flange connections as well their behavior evaluation under seismic load was performed by [118]. Evaluation of seismic performance of DF connections was reported by [119], leading to the conclusion that DF connections are capable of exhibiting desired behavior. In their 2019 study, [30] used IDA analysis method in order to investigate the seismic performance of special moment resisting frames, the results revealed that DF connections performed similar to RBS connections in case of low-rise buildings, while in high-rise buildings, DF connections demonstrated a more sought-after behavior with 43% higher seismic capacity. Among recent studies, conducted experimentally or numerically, on DF connections, the investigation of rigid connection of drilled beam to CFT columns with external stiffeners is performed by [120]; Vaidian et al. [121] evaluated the effect of different connections on the behavior of steel moment frames including RBS, DF, and DFCV connections, based on the results, DFCV connections (diamond-shaped holes) performed better than the other DF connections; the assessment of the effect of different connections, DF connections included, on the behavior of steel moment frames is performed by [122]; the results obtained in the research performed by [123] showed that clockwise pattern holes drilled in the beam flange are desirable in terms of flexibility, reduction of bending stresses, and transferring the plastic hinge away from the column face. Moreover, the investigation of the arrangement, type, and number of holes in DF connections was assessed by [124] in which it was concluded that the mentioned parameters are of great significance in the ductility, stress concentration, and preventing the brittle failure of the DF connections; [125] investigated different configurations of connections among which CDF c onnection (with combined circular hole and notches) performed better in terms of damage index, and equivalent plastic strain.

It is well-documented that pre-Northridge connections failed to resist the applied loads despite being in conformance with the existing building codes during earthquakes [10]. The afore-mentioned issue piqued interest among researches to utilize two main approaches in order to enhance the structure safety whether through strengthening the connection [96, 126-128] or weakening a part of the beam [48-125]. In terms of reducing a part of the beam, cutting the beam flange or web reduction has been widely evaluated in recent years [22-24, 56, 67-79, 88, 93-99, 127, 129]. Although comparing the behavior of interior connections with voids in beam web or flange has received numerous attention, there exists a significant ambiguity regarding the behavior of frames with web or flange cuts since cutting a part of the beam alters the force transfer from the beam to the column [95, 129] and parameters affecting the strength of the frame such as opening area, shape, use of stiffeners, etc., are of great significance in the behavior, resistance, energy dissipation capacity, and failure mode of the connections[2, 23-25, 114]. Hence, numerous studies have been conducted on steel connections including Reduced Beam Section (RBS)[64-79], Reduced Web Section (RWS) [80-114], Drilled Flange Connection (DFC) [115-125], and many design codes and standards [1, 10, 18-20, 27-29] employed the introduced connections as an engineered connections. Since each connection has advantages and disadvantage, e.g. limited range of beam and column dimensions in tests, stiffness degradation, loss of moment capacity, and stress concentration are among major downsides of RBS connections; limited guidelines and codes, limited shapes of openings, and loss of strength are among drawbacks of RWS connections, while absence of regulations or design guidelines, and in some cases equal or weaker performance of DF connections compared to RBS ones are considered as weaknesses of DF connections, the present study aims to evaluate the effect of different interior connections on the behavior of steel moment frames. It must be noted that connections are classified from different perspectives e.g. from the behavioral, dissipated energy capacity, modes of failure point of view. However, rotational capacity of the connections is among connection features for which there exists no proper way, and accurate estimation of the mentioned features play a significant role in the structural design of different frames and connections. In the present study, an interior connection is utilized to investigate the behavior of the connection in case of presence of openings in beam web or flange, in this regard, models with openings solely implemented in beam web or flange (RBS, RWS, and DF connections) has been investigated under monotonically increasing lateral displacement conditions with varying connection parameters like length and width of openings, and a fully welded rigid connection is simulated as a reference model. Finally, a comparative analysis is made to understand the performance of different connections under imposed monotonic loading in terms of initial stiffness, rotational capacity, resistance, and stress distribution.

2. Modeling

In order to investigate the performance of interior connection subjected to lateral loading, Finite element models are utilized. The numerical models are categorized into four groups, including the interior connections with fully welded rigid connection, RBS connections, interior connections with opening in beam web, and interior connections with voids in beam flange. The beam-to-column connection is deemed as a welded connection due to its vulnerability to brittle failure.

Since the location of plastic hinge formation is an influential parameter in avoiding the brittle failure of column, the spacing between the location of plastic hinge and the column face is proposed to be at least equal to the half of the beam depth [27].

Table 1 presents the properties of A992 steel, used in FE simulation, which is adopted from the coupon tests done by [130]. The weld material is assumed to have the same properties as steel base material. Stress- strain curves of the adopted A992 steel is illustrated in Fig. 1. Material nonlinearities were accounted for using a multilinear kinematic rate independent hardening rule.

This option uses the Besseling model also called the sublayer or overlay model (Zienkiewicz) to characterize the material behavior [131]. In order to predict the yielding of the material, the Von-Mises yield criterion was used in the current paper.

Table 1
Steel properties

Material		Young modulus (GPa)	Yield point		Ultimate point	
			Stress (MPa)	Strain	Stress (MPa)	Strain
A992 Steel	Flange	203	444	0.0042	577	0.1381
	Web	202	409	0.0148	573	0.1555

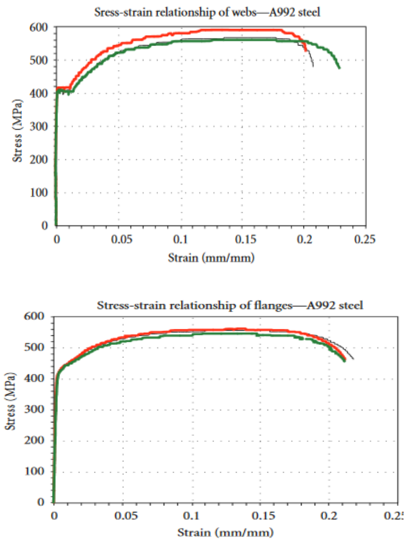


Fig. 1 Stress-strain curves of A992 steel [116]

The software package used to analyze the models was ANSYS; the FE models are comprised of a quadrilateral four-node element with six degrees of freedom per node (three rotations and three translations) which is known as SHELL181 in the ANSYS element library. SHELL181 is suitable for analyzing thin to moderately-thick shell structures [131]. Material plasticity, large deflection, and large strain nonlinearities are of the characteristics of the mentioned element. Furthermore, accurate estimations of displacements and stresses can be provided by shell elements, while according to [132-134], the utilization of the solid elements results in inaccurate prediction of the dissipated energy. Sensitivity mesh analysis was performed in order to optimize the run time, and finer mesh with mesh size 1.5 cm was adopted for critical areas such as connection region and the vicinity of openings while coarser mesh with mesh size 4.5 cm was used for the rest. Geometrical and material nonlinearities were taken into account.

In order to model the interior connection, inflection points are considered at the mid-span as well as mid-height of the column. In this regard, pinned supports is considered at the lower part of the column, besides, roller support condition is applied at the both right and left half-beam ends. The supposed boundary conditions for interior connections are a commonplace assumption which is utilized by many researchers [135-137].

Dimensions of simulated beams and column are deemed constant in all models, in which W36X150 and W14X398 sections are used for beams and column, respectively. The interior joint consists of a 3.65 m column and two beams with half-length of 3.65 m fully welded by fillet-welds to connect the beam and the column, as shown in Fig. 2. The modeled interior connection is extracted from a MRF system which is designed based on the Iranian steel building code and Iranian code "Standard 2800" for seismic resistant design of buildings using the structural analysis software, SAP 2000; in addition; in the afore-mentioned structure, the loading algorithm (the imposed dead load, live load, etc.) is as recommended by design codes (according to Fig. 2). Continuity plates are considered to enhance the column strength as well as transferring the forces from beam to column. Furthermore, doubler plates with thickness of 0.025 m are considered on both sides of panel zone.

In order to investigate the performance of frame, monotonic lateral loading is applied at the tip of the column with steps of 0.002 rad drift ratio. On the other words, the displacement is imposed at the top of the column increasingly until the connection is failed. The loading system is illustrated in Fig. 2. Based on the [29], the capability of the connection to tolerate the inter-story drift ratio of 0.04 rad is required in the seismic-force resisting systems, where the loss of flexural resistance of the connection is not exceeding 0.2 of plastic moment capacity. Consequently, the failure criteria include the weld fracture, local buckling of the beam web, strength loss exceeding 20% of the capacity and plastic strain reaching the ultimate strain of base material.

A parametric study is performed to study the effect of openings on the behavior of interior connections. To do so, an isolated circular opening is considered in RWS models in beam web with 2 influential parameters including the distance of opening from column face and opening diameter. The distance of the opening center from the column face is considered to be 0.87h, 1.3h, and 1.74h. Furthermore, 3 different diameters are considered for opening as well, including 0.5h, 0.65h, and 0.8h in which h is the beam depth. It should be noted that the parameters are taken from the research done by [94]. Similarly, the influential dimensions of DF connections such as L*/D and L/D are considered in accordance with the studies performed by [34, 138], respectively. In the afore-mentioned studies, the parameter L*/D was suggested to be in the range of 3 to 5 and the desired ratio for L/D parameter was taken equal to 2, where L*, L, and D are indicants of the distance between the void and column face, length of opening, and opening diameter, respectively. Accordingly, the L*/D parameter is considered to be 4 in all DF models and L/D is considered to be equal 2 in the HS-40-55-60 model.

Summary and configuration of the studied models are presented in Table 2 and Fig. 3, as well. Also, Fig. 4 indicates the finite element models of different configurations.

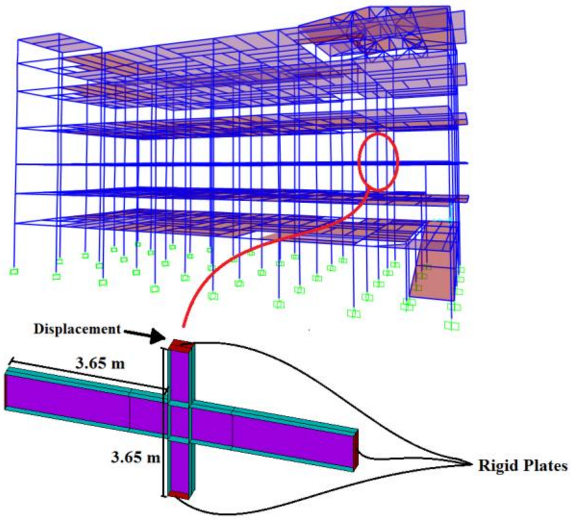


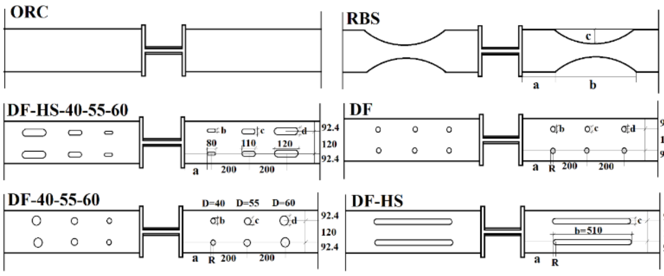
Fig. 2 Location and dimension of studied interior connection

3. Results

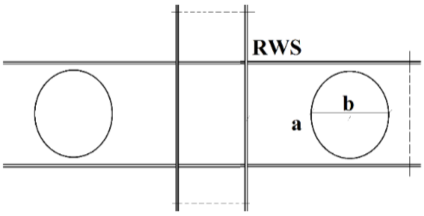
Fig. 5 to 7 present the lateral force-story drift curves of studied models. Also, the Von Mises plastic strain distribution of models in 0.04 story drift is illustrated in Fig. 8.

The brittle failure of the beam-to-column connection in ordinary fully welded rigid connection has occurred at 3.6% story drift. However, introduction of appropriate openings in beam web or flange prevents the premature failure of the connection and brings about the plastic hinge initiation in beam web or flange, away from the critical area. Furthermore, according to the results, utilizing the typical RBS connection prevents connection failure and leads to the increased ductility, which is a desirable behavior. The studied RBS connection, designed in accordance with AISC 358-16, fails at 4.2% story drift, as illustrated in Fig. 7, due to steel rupture.

Although RBS connection is capable of fulfilling the expected performance through leading the failure toward the beam which is considered a ductile behavior, it experiences excessive loss of lateral strength as well as initial stiffness. Compared to RBS connections, drilled flange connections are considered a more practical method in terms of beam flange cut. Based on the results, DF category in which openings are implemented in beam flange, models with different width of singular horizontal slot including DF-HS-40, DF-HS-55, and DF-HS-60 experience an early failure due to more than 20% loss of lateral force at early stages of loading. However, no plastic strain was observed in the vicinity of connection. On the other hand, model with 3 different width of horizontal slots, DF-HS-40-55-60, performs better than the models with similar width of singular horizontal slot, as the story drift of 0.04 rad is reached without connection failure. Based on the Von Mises plastic strain distribution illustrated in Fig. 8, the initiation of plastic hinge has occurred at the opening edge, and the model is perfectly capable of leading the plastic hinge away from the column face.



Top View



Side View

Fig. 3 Configuration of studied models

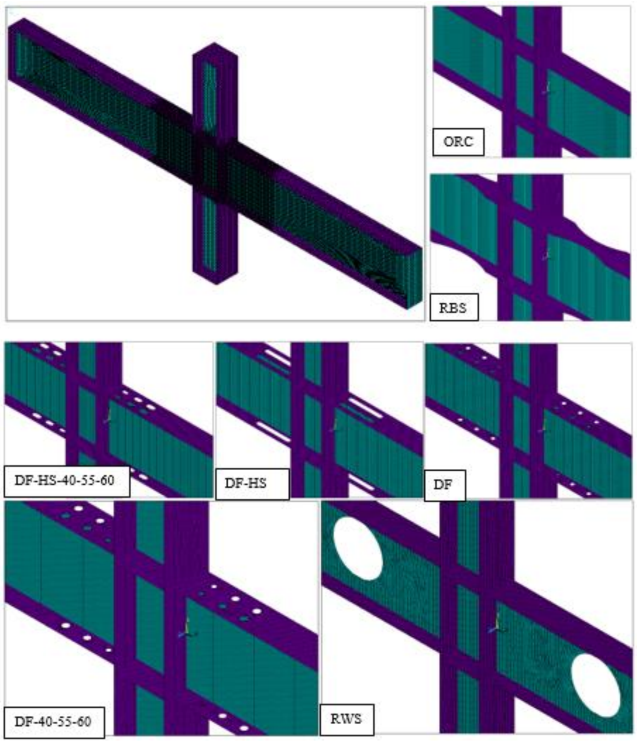


Fig. 4 FE models of different configurations

The initial stiffness of models with 3 circular openings, drilled in 2 rows at beam flange, is higher than the models with singular horizontal opening. The highest initial stiffness and lateral force belongs to the DF-40-40-40 model, in which the connection has experienced weld failure in 0.04 rad story drift. Furthermore, based on the Von Mises plastic strain distribution, the model has failed to move the developed strain away from the connection region. On the other hand, increasing the opening radii leads to the decreased Von-Mises Plastic strain at connection area. However, DF-55-55-55 and DF-60-60-60 models are incapable of reaching 0.04 rad story drift due to steel rupture in opening edges. Use of different opening diameters as indicated in Fig. 5 and Fig. 8 results in a sought-after behavior of interior connection, in which the openings are capable of transmitting the plastic hinge towards the beam length without experiencing beam-to-column connection failure. The lateral force-story drift curve of this model is almost similar to the DF-55-55-55 model with the difference that the DF-40-55-60 model can sustain story drift of 0.044 rad up to its failure. It must be noted that the maximum lateral force of DF-40-55-60 is 7% less than the model DF-40-40-40 which has the highest maximum lateral force amongst the models with opening in beam flange. Yet, DF-40-55-60 has exhibited higher story drift, hence, higher ductility. Furthermore, in terms of initial stiffness, max lateral force, ductility, and the failure drift, interior connections with circular openings consisting of 3 various diameters perform better than the interior connections with 3 horizontal slots having different opening width. Overall, based on the results, model DF-40-55-60 reveals the desired performance amongst the other models, this finding supports previous research into this area by [34].

Also, according to the results, RWS category with singular large opening in beam web is capable of transferring the plastic hinge toward the beam mid-span, provided that the opening radii and the distance between the opening center and column face is selected appropriately. Comparing the developed plastic strain in the beam-to-column critical regions of ORC and RWS models, it is evident that the maximum developed plastic strain as well as highest lateral force has occurred in the model with no opening (ORC). Also, comparing the lateral force-story drift curves of models in terms of the mentioned influential parameters, there was a significant correlation between the ultimate lateral force and the opening radii, indicating that increasing the opening diameter results in the significant decrease of initial stiffness and frame lateral force, as shown in Fig. 6. However, shortening the distance between opening center and the column face causes degradation in lateral force as well as initial stiffness and intensifies the plastic strain in the critical area. Nevertheless, by decreasing the distance of the opening center from the column face, the amount of the lateral force declines slightly. Based on the results, diameters of 0.65h and 0.8h as well as parameter 'a' which is equal to 1.3h and 1.74h can reduce the plastic strain, developed in beam-to-column connection region. Based on the Von Mises plastic strain distribution, appropriate selection of opening size and distance leads to the occurrence of Vierendeel mechanism, hence, increased ductility. The results are in accordance with the [94].

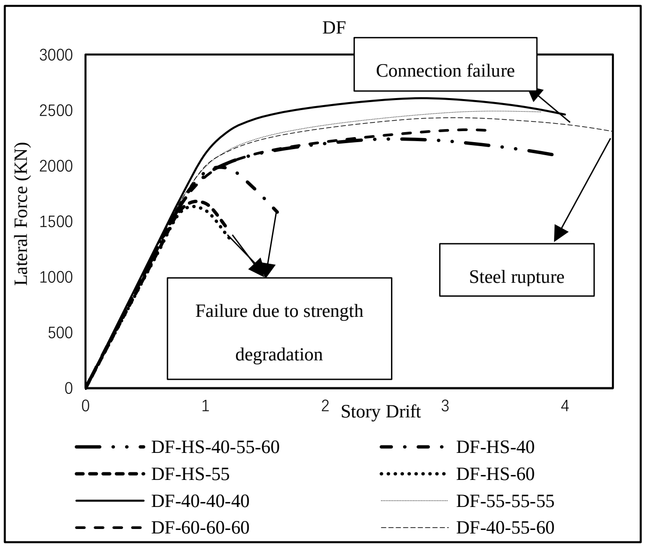


Fig. 5 lateral force-story drift curves of models with opening in beam flange (DF category)

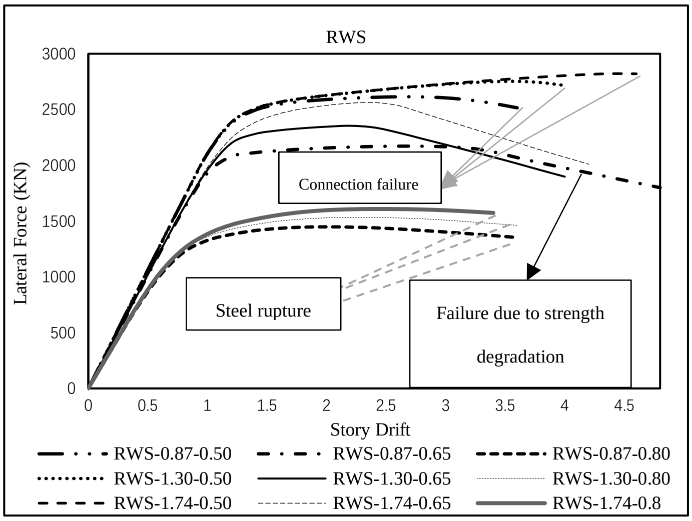


Fig. 6 Lateral forc-story drift curves of models with opening in beam web

4. Discussion

Fig. 7 indicates the lateral force-story drift curves of models in which the story drift of 0.04 rad is reached. Also, the maximum lateral force of interior connections as well as lateral force of frames at 0.04 story drift is presented in Fig. 9 and Fig. 10, respectively. The DF and RWS curves are placed between ORC (reference) and RBS models. Based on the results, the behavior of RWS-1.7-0.5 and RWS-1.3-0.5 models are almost similar to the ORC model, with the difference that RWS-1.7-0.5 and RWS-1.3-0.5 models can withstand story drift up to 4.6% and 4%, respectively. Besides, the degradation of initial stiffness due to introduction of the opening is insignificant in both models and can be neglected. As can be seen in Fig. 8, both models are incapable of transferring the plastic hinge toward the vicinity of the opening, hence, the failure has occurred due to connection fracture. Although initial stiffness of the DF-40-40-40 model is similar to the reference model with a slight difference, the lateral resistance of the model is 12% less than the reference model. This is while, the mentioned model could not satisfy the expected behavior and the failure occurred because of connection fracture. The results show that in case of using DF connections, DF-40-55-60 and DF-HS-40-55-60 models are in accordance with the aim of the connection design in which moving the plastic hinge away from the column face is considered a sough-after behavior. However, DF-40-55-60 performs better than the model with horizontal slots (DF-HS-40-55-60), as the area of the openings in flange is lower than the other model. Furthermore, stress concentration is observed at the edge of openings in flange. Overall, in terms of using DF connections, it is propounded to utilize 2 rows of drilled flange with 3 circular openings in which by shortening the distance of the circular opening from the column face, the diameter of the openings decreases. RWS models including RWS-1.74-0.65, RWS-1.3-0.65, and RWS-0.87-0.65, have experienced local buckling at 2.6, 2.6, and 3.4% drift, consequently, the lateral force-story drift curves of models is projected to decline after occurrence of local buckling. Although shear deformation and Vierendeel mechanism is evident in the mentioned models, according to the Fig. 8, the models are capable of transferring the failure toward the beam, hence, exhibiting desired performance. Furthermore, according to Fig. 9, it is conspicuous that increasing the area of the opening results in decreased lateral load resistance as well as decreased initial stiffness.

As illustrated in Fig. 9, the maximum lateral force of interior connection in RWS-1.74-0.65 is higher than both DF-40-55-60 and DF-HS-40-55-60 models while the maximum area of opening belongs to the mentioned model. In this regard, the lateral force of RWS-1.74-0.65 model at 0.04 story drift is 12% and 0.3% lower than the lateral force of DF-40-55-60 and DF-HS-40-55-60 models at 0.04 story drift. This is because the RWS model has experienced early loss of lateral force which stems from the initiation of local buckling. Accordingly, wise selection of opening sizes in RBS, RWS, and DF connections are of great importance and use of them is dependent on the site condition and implementation considerations as well as design principles.

It must be noted that connections in special moment frames (SMRFs), intermediate moment frames (IMFs), and ordinary moment frames (OMFs) are expected to withstand total rotations of 0.04, 0.03, and 0.02 radian while maintaining 0.03, 0.02, and 0.01 radian plastic rotations, respectively (AISC). The results drawn from the current study is indicant of the fact that RBS, DF-40-55-60, DF-HS-40-55-60, DF-40-40-40, RWS-1.30-0.50, RWS-1.30-0.65, RWS-1.74-0.50, RWS-1.74-0.65, and RWS-0.87-0.65 connections are capable of retaining their strength till story drift angle of 0.04 rad and higher, and are capable of being utilized in the SMRF connections, while ordinary fully welded rigid connections, DF-HS connections, and rest of the studied connections experience early failure due to lateral resistance degradation, steel rupture, or brittle failure at early stages, moreover, from the perspective of initial stiffness, the initial stiffness of DF-HS connections are less than the other studied DF connections, the maximum initial stiffness is for the DF-40-40-40 model, which has the least opening are in flange. Among RWS connections, the highest initial stiffness belongs to the model with minimum opening area.

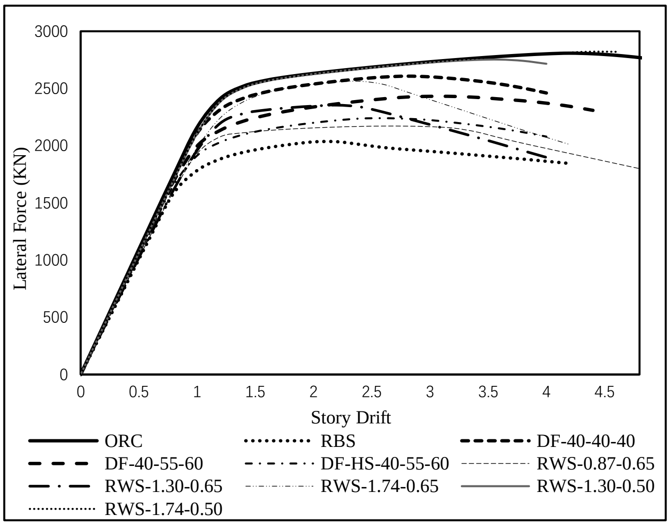


Fig. 7 Comparison of lateral force-story drift curves of DF, RWS, and RBS category with the ORC (reference) model

From the ease of construction point of view, DF connections are considered more practical than RBS ones. the utilization of RWS connections are recommended where there is a need to provide pipelines, or ducts, etc., functionally. However, in case of wise selection of the opening sizes implemented in beam web or flange, DF and RWS connections can be sough-after substitutes for connections in SMRF systems.

Overall, the afore-mentioned connections correspond well with the expected rotational capacity of the SMRFs, OMFs, and IMFs. Nevertheless, few connections are available that have significantly larger rotation capacity as well as capability of leading the plastic hinge away from the column face and are suggested to be used in special moment frames among which DF-40-55-60 connections (DF connection with different opening diameters in flange), RWS connections with diameters of 0.65h and 0.8h, and a parameter of 1.3h, and 1.74 h are suggested to be used in SMRF systems

5. Conclusions

There is a considerable amount of literature on intentionally attenuating a part of the beam whether in beam flange or web to relocate the plastic hinge away from the column face. Thus, this paper questions the behavior of interior connections with openings in beam web or flange subjected to monotonic loading through numerical simulation. The studied models are comprised of an ordinary fully welded rigid connection as a reference model, a model with prevalent RBS cut according to AISC 358-16, models with different configurations of flange cut (DF) as well as the models with singular opening in beam web (RWS). The obtained results are as follows:

The premature failure of the beam-to-column connection in ordinary fully welded rigid connections has led to intentional wakening of the beam as an approach to overcome the mentioned issue. Based on the numerical results, ordinary rigid connection experiences connection failure at 3.6% story drift while the prevalent RBS connection is capable of transferring the plastic hinge toward the beam length, hence, increasing the ductility, which is a sough-after performance. It should be noted that the failure drift of RBS connection due to steel rupture has occurred in 4.2% story drift. In other words, utilizing RBS connections in moment steel frames lead to an increase of 0.6% in story drift, in addition, the location of initiation of plastic hinge instead of column face (in ORC model) is led toward the beam length (reduced are) in RBS connections.

Although RBS connection is capable of fulfilling the expected performance through leading the failure toward the beam which is a ductile behavior, it experiences excessive loss of lateral strength as well as initial stiffness which is calculated to be approximately 27% and 8%, respectively, compared to the ORC model. Compared to RBS connections, drilled flange connections are easier to construct, hence, a more practical method in terms of beam flange cut. Based on the results, utilizing singular horizontal slot with different opening width in beam flange in 2 rows does not lead to the expected outcome and models experience an early failure due to loss of strength and the failure drift is less than 2% story drift due to excessive loss of lateral force which is considered to be 20%. However, model with 3 horizontal slots, having different opening width, results in the desired performance in which the failure from beam-to-column connection region has been transferred towards the beam length, in other words, the model is fully capable of transferring the plastic hinge away from the column face, the failure drift is 4% story drift due to steel rupture around the opening edges.

The initial stiffness and maximum lateral force of circular openings in beam flange is higher than the models with elongated circular opening since the opening area is smaller, e.g. 5% and 32% degradation is observed in stiffness and maximum lateral force of model with elongated circular opening in which the opening diameter is 60 mm compared to the model with circular holes of 60 mm diameter. The same conclusion can be drawn for models with different diameters of openings, since increasing the diameter of drilled holes leads to the decease of both initial stiffness and lateral force in a way that the loss of stiffness and lateral force in the model with opening diameter of 60 mm compared to the model with opening diameter of 40 mm is estimated to be 3% and 6%, approximately. Nevertheless, models with circular openings experience increased Von Mises plastic strain distribution in beam-to-column regions.

However, the use of openings with different diameters brings about an increase in frame ductility as well as transferring the plastic hinge away from the critical region, hence, sough-after substitute for identical opening diameters. In the afore-mentioned model, the failure drift is 4.4% which is the highest experienced drift among models with drilled flange. In addition, the stiffness and lateral force degradation, which is respectively 1.5% and 7%, is negligible compared to the model with 3 drilled holes of 40 mm, yet, the failure in model with 3 different opening diameters is due to steel rupture, while connection fracture is the cause of failure in model with 3 opening having the same diameters.

RWS connections, which consist of circular opening in beam web, fulfill the condition of moving the plastic hinge away from the column face in case of proper selection of opening size and location. Although increasing the opening radii leads to the reduced plastic strain in beam-to-column connection region, it significantly reduces the lateral force and stiffness of the frame. Furthermore, moving the opening away from the column face results in desired performance of the frame in terms of maximum lateral force and initial stiffness, accordingly, it is concluded that the model with opening diameter of 0.8 beam height in which the distance between the column face and opening center is considered to be 0.87 beam height has the lowest values in terms of initial stiffness and lateral force whereas the highest amounts of initial stiffness and lateral force belongs to the model with opening diameter 0.5 times the beam height in which the opening center distance from the column face is considered to be 1.74 times the opening height, the difference of the amount of initial stiffness and lateral force between the mentioned models is respectively considered to be 17% and approximately 50%. Despite the fact that the model with minimum opening radii in conjunction with the maximum opening distance from the column face is expected to have the desired performance in terms of initial stiffness and lateral resistance, the model might be incapable of transferring the plastic hinge away from the column face due to insufficient weakening of beam web. It is concluded that shear deformation and local buckling is observed in RWS connections while in DF connections, stress concentration around the opening is critical.

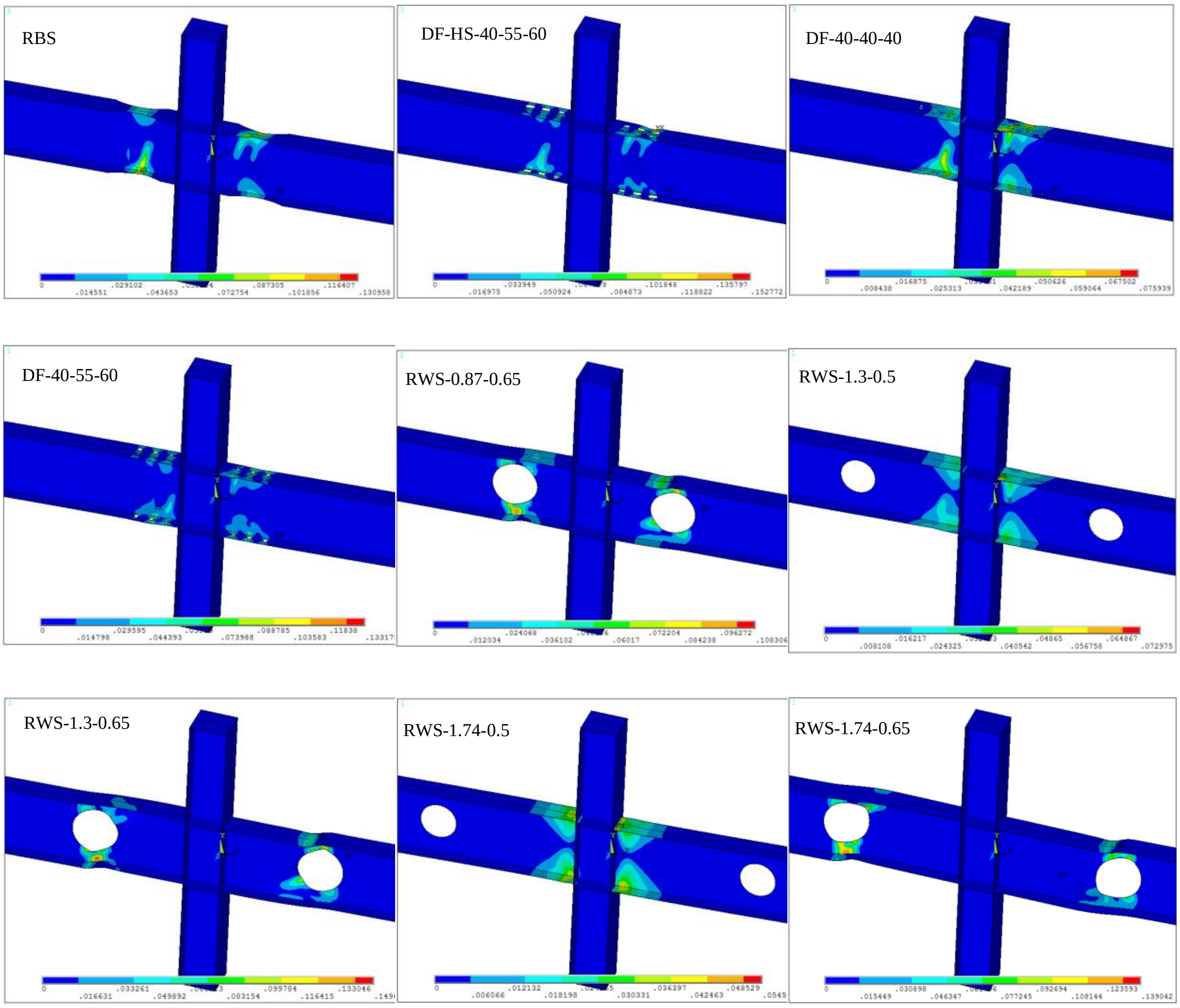


Fig. 8 Von Mises plastic strain distribution of FE models at 0.04 story drift

Table 2
specification of studied models

Category	Model	a (mm)	b (mm)	c (mm)	d (mm)	Description
ORC	ORC	-	-	-	-	Ordinary fully welded rigid connection
RBS	RBS	225	680	75	-	Prevalent reduced beam flange according to AISC 358-16
DF	DF-HS-40-55-60	160	40	55	60	3 horizontal slots with L/D=2 and different opening diameter
	DF-HS-40	160	510	40	-	Single horizontal slot with L=510 mm and D=40 mm
	DF-HS-55	220	510	55	-	Single horizontal slot with L=510 mm and D=55 mm
	DF-HS=60	240	510	60	-	Single horizontal slot with L=510 mm and D=60 mm
	DF-40-40-40	160	40	40	40	3 circular voids with similar diameters of 40 mm
	DF-55-55-55	220	55	55	55	3 circular voids with similar diameters of 55 mm
	DF-60-60-60	240	60	60	60	3 circular voids with similar diameters of 60 mm
	DF-40-55-60	160	40	55	60	3 circular voids with diameters of 40, 55, and 60 mm
RWS	RWS-0.87-0.50	793.	455	-	-	Circular opening at beam web with various a and b parameter
	RWS-0.87-0.65	793.	592	-	-	
	RWS-0.87-0.80	793.	729	-	-	
	RWS-1.30-0.50	1185	455	-	-	
	RWS-1.30-0.65	1185	592	-	-	
	RWS-1.30-0.80	1185	729	-	-	
	RWS-1.74-0.50	1585	455	-	-	
	RWS-1.74-0.65	1585	592	-	-	
	RWS-1.74-0.80	1585	729	-	-	

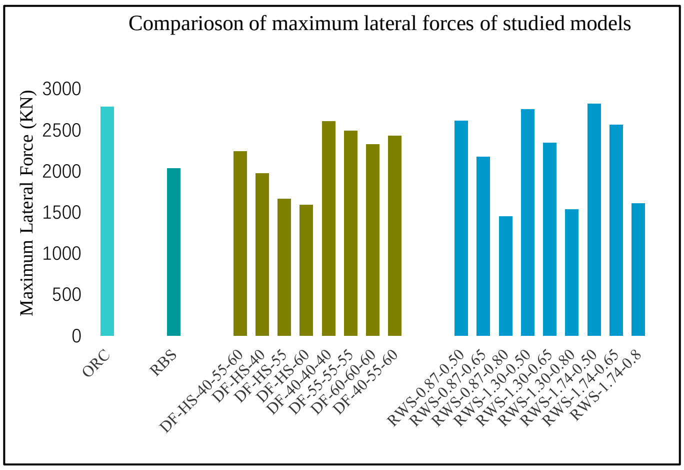


Fig. 9 Comparison of maximum lateral forces of studied models

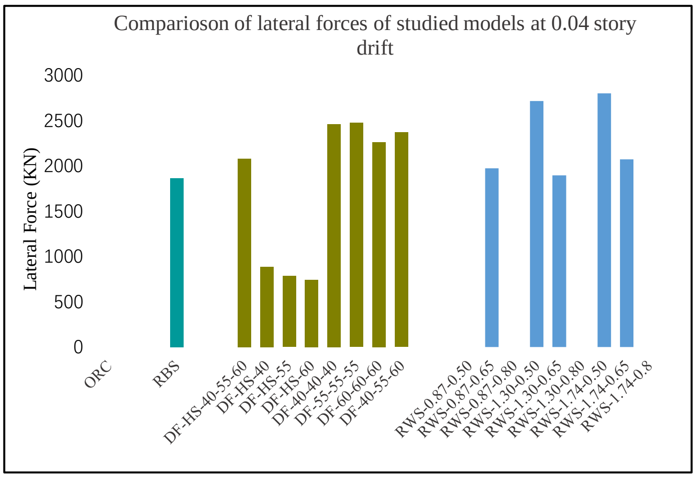


Fig. 10 Comparison of lateral forces of studied models at 0.04 rad story drift

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