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To cite this article: Mehdi Vajdian, S. Mehdi Zahraei, S. Mohammad Mirhosseini & Ehsanollah Zeighami (2020): Investigation of Seismic Performance of (RBS) and Drilled Flange Connection (DFC) Containing rhombus Shaped Hole in Steel Moment Frames, Australian Journal of Civil Engineering, DOI: 10.1080/14488353.2020.1771664

To link to this article: https://doi.org/10.1080/14488353.2020.1771664

Published online: 14 Jun 2020.
Investigation of Seismic Performance of (RBS) and Drilled Flange Connection (DFC) Containing rhombus Shaped Hole in Steel Moment Frames

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ABSTRACT
Objective: Numerous studies have been conducted on steel connections like Reduced Beam Section (RBS) and Drilled Flange Connection (DFC). Each connection has advantages and disadvantages. The present study aimed to evaluate the effect of different connections on the behaviour of steel moment frames.

Design/methodology/approach: In this study, simple connections (No drilled on beam flange), Reduced Beam Section, drilled flange connection, and drilled connection with a variable diameter corresponding to the diamond-shaped hole (DFCV-a proposed model) were evaluated. The connection was modelled using the ABAQUS software, and then the moment-rotation graphs were extracted. Finally, Finite Elements Modelling was utilised to calculate the stiffness of each connection. A frame was modelled in SAP based on the stiffness calculated by Finite Elements Analysis in ABAQUS.

Findings: Based on the results, drilled connections with variable diameter, which are related to diamond-shaped hole, function and behave better than other drilled samples which were considered in this study. In this model, the hinge is formed in the middle of the holes. This model has the most rotational stiffness among all samples. In addition, formed hinges indicated that the connections and plastic hinge in the frames with simple and rigid connections are damaged more. Further, drilled connections caused less damage to the column.

Research limitations/implications: It is recommended to perform an experimental test to have a better understanding of the issue.

Originality/value: In this paper, the effect of beam drilling on moment frame behaviour factor was first evaluated by SAP software and indicated that diamond-shaped drilling has the best beam drilling arrangement results.

1. Introduction

The common damage which is created by earthquake in steel structures is a failure in beam-column connection, which may lead to the collapse of floors and loss of strength in a building. Steel moment frames were considered as a ductile and strong structure among other structure systems until the 1994 Northridge earthquake. The Northridge earthquake in January 1994 caused great damages to steel moment frame structures with a welded beam-column connection due to plastic hinge formation on column face. The 1994 Northridge earthquake was a turning point in designing and constructing Welded Un-reinforced Flange (WUF). Failure of Welded Un-reinforced Flange (WUF) connection in the Northridge earthquake led to the destruction of steel buildings and death of many people (Youssef, Bonowitz, and Gross 1995). Thus, many researchers and engineers have paid attention to the seismic performance of these connections (FEMA 2000). Accordingly, column reinforcement and beam junction weakening were introduced as two strategies after the Northridge earthquake in order to improve the seismic behaviour, flexibility, and performance assurance of connections. In this strategy, the beam section weakens at a specified distance from the column face until moving away the plastic hinge from the column face.

The plastic capacity of the beam section decreases by reducing the flange area, which may lead to the formation of plastic hinge away from the column face which resists against the damage in connection zone. In addition, a reduction in the plastic capacity leads to an increase in in-plane stiffness of the beam, as well as the section lateral torsion strength near that zone, which may result in creating a critical problem for buckling.

The idea of reduced beam section connection, which was first introduced by Plumier (1990) was tested and presented in a time when steel was considered as a major reinforced material. Then, it was discussed and developed by ARBED (1992) in the USA. Further, Chen and Yeh (1994) tested this idea before the Northridge earthquake.
Reduced beam section connections were completely tested during the Northridge earthquake. Constant, conic, and radial sections are considered as three kinds of sections. The constant section was tested by Engelhardt and Plumier (Plumier 1997; Engelhardt et al. 1996). Plumier claimed that RBS with constant section will resist against cracks near the weld. The model tested by Engelhardt was fractured in a reduced beam section flange. RBS connection with the conic section can be modified according to moment changes. Iwankiw, Carter Chen, and Zekioglu reported the rotation of 03.0 and more than 03.0 in most of the 15 tested models, although some were fractured in reduced beam section flanges (Iwankiw and Carter 1996; Zekioglu, Mozaarian, and Uang 1997).

According to Engelhardt and Popov, RBS performed better with the radial section (Popov, Yang, and Chang 1998). The results obtained from testing five models indicated the gradual reduction of strength due to local and lateral buckling, without observing any fracture.

Based on some studies, triaxial stress in full penetration weld of beam flanges leads to a rapid failure of the weld line near the beam flange before any yielding and plastic deformation of the beam (FEMA 2000). In order to modify this connection, reduced connections are developed for reliable and functional solutions to avoid fracture in beam-column welded connections (Engelhardt et al. 2000). Bending connections of Reduced Beam Section establish an intentional weak point in beam flange which produces the proper fuse for reducing the stress of welded connection in the column.

Crisan and Dubina analysed the reciprocal bending-shear effect on short steel connections through reducing section (Crisan and Dubina 2016). Two beams with different lengths were evaluated experimentally and numerically in order to represent the short beams plastic deformation mechanism in steel frames. Based on the results, plastic deformation increased by increasing beam aspect ratio. In experimental and numerical studies of Tahamouli Roudsari et al (Tahamouli Roudsari, Jamshidi, and MohebiZangeneh 2016), the behaviour of reduced section IPE was evaluated by diagonal web stiffeners. Some researchers could delay the web buckling by adding web stiffeners to the reduced area and increased the flexibility of connection. By evaluating several experimental and numerical models, the results indicated that the use of diagonal stiffeners can stabilise the Hysteresis graph and delay the destruction.

Roudsari et al. used box-stiffeners to evaluate the reduced beam section IPE (Tahamouli Roudsari, Jamshidi, and Moradi 2018). The reduction of beam width in RBS can potentially increase the probability of lateral buckling connection. In addition, the box-stiffeners were introduced to overcome this problem. Based on the results, stiffeners largely increased the connection ductility without modifying its resistance. Montouri and Sagarese (Montouri and Sagarese 2018) used steel RBS to increase the ductility of wooden beams. Then, they introduced a set of criteria for assuring the formation of a plastic hinge. Finally, a design chart was designed to be used for the same connections.

Uang and Popov suggested the application of drilled beam flanges for beam section reduction. Using holes in a beam flange could reduce construction costs and helped the construction of RBS connections (Uang, Noel, and Gross 2000). Some indicated that holes with identical diameters cannot correspond to the special bending frame provisions (Qian et al. 2005; Tsai and Chen 1996). Accordingly, some used holes with a variable diameter and special arrangements and indicated that these connections can correspond to bending frames (Sang JuL et al. 2007; Farrokhhi, Danesh, and Eshghi 2009; Vetr, Miri, and Haddad 2012; Saleh et al. 2016a, 2016b).

The present study aimed to compare weakening the beam by reduced beam section (RBS), which is the most commonly used method in this regard, and weakening the beam by drilled flange connection (DFC). The results of this research can be registered in valid and reliable regulations by developing and conducting more research. In this study, four types of models are examined for the numerical study as follows:

1. This type of model is named as a connection with a simple flange and marked with the abbreviation sign of NS. It is worth noting that no hole or reduction is created in the beam flange in these models.
2. In the second type, the models are called connection with reduced flange and specified with the abbreviation of RBS. These models (beam flange) are modelled and evaluated using a common method called RBS in the regulations.
3. In the third type, models are introduced as the connection with a drilled flange and marked with the abbreviation of DFC. In these models, beam flanges are drilled with different arrangements and diameters.
4. In the fourth type, models are called connection with the proposed model, in which the holes are specified with a rhombus pattern on the beam flange (abbreviated to DFCV). This pattern is obtained from the reduced beam section (RBS). The beam pattern with a rhombus-shaped drilled flange is based on RBS and the shape of these holes is perfectly symmetrical. The hole with a small diameter is located at the beginning of the model while the hole with a larger diameter is selected in the middle of the model.

In all of the above models, attempts have been made to evaluate several different models of beams
and columns, as well as arrangement pattern. In this study, four models were studied for the simple beam-
to-column connection model, four models for RBS
connection, 16 models for DFC connection, and 4
models for rhombus-shaped connection. In total,
about 28 different models of connections were evalu-
ated. The final section addresses the application aspect
of the studies.

After extracting Hysteresis graphs, the connection
place was determined, along with calculating connec-
tion stiffness. Then, the specified stiffness was applied
in SAP2000 by using Panel Zone. Thus, an accurate
behaviour of connection was modelled in SAP2000. Finally, the rigid frame (MR-Frame with rigid connec-
tion software default) was modelled in SAP2000 and
compared to a real connection behaviour.

2. Modelling verification

Ismail et al. (Ismail et al. 2016) determined the cor-
rectness of models used in this study. The process and
comparison of the model are as follows:

The model is presented in Figure 1.

In this three dimensional model, plate dimension
and thickness of 20 mm, bolt diameter of 20 mm, and
connection bolt number of 6 are considered. In addi-
tion, the stiffener is used in the end-plate and column.
Table 1 and Figure 2 indicate the beam-column prop-
erties and connection dimensions, respectively.

In the Finite Element Model (FEM), all parts are
modelled by using the continuum three-dimensional
eight nodes solid element with reduced integration
technique (C3D8 R). Table 2 shows the materials
used in the process by assuming the Poisson’s ratio
of 0.3.

The contact is created between model parts to avoid
interlocking. The frictional coefficient of 0.3 is
assumed between two parts and behaviour is defined
as ‘hard’ contact. Tie contacts are used for connecting
bolt to beam-column. Figure 3(a) and B present
boundary conditions of the connection and mesh
structure, respectively.

Considering all of the conditions, static analysis is
selected so that load can be imposed on the beam end
and continued until failure. Figure 4 presents the
results obtained from the moment-rotation graph.

As shown in Figure 4, the fact-checking model is more
accurate than the model in the referred paper. Figure 5
displays the results of comparing applied Von-Mises
stress in the model with a laboratory model.

As shown in Figures 4, 5 and 6 the simulated numerical results are consistent with the results of the laboratory
model. Figure 4 displays a difference of less than 2%
between the Abacus model and the laboratory model,
which is related to some cases in the construction of the

![Figure 1. Model selected for verification (Ismail et al. 2016).](image1)

![Figure 2. Connection details (Ismail et al. 2016).](image2)

| Table 1. The used beam and column (Ismail et al. 2016). |
|---------------------------------|----------------|------------|------------|------------|
| Section depth | Web thickness | Flange width | Flange thickness |
| Beam          | 300            | 8           | 200         | 12          |
| Column        | 300            | 8           | 250         | 12          |

![Figure 4.](image4)
structure in the laboratory. In other words, some conditions such as ideal welding are considered in the software model while these conditions are not completely in accordance with the specifications in the welding and connections laboratory, which can have an error percentage.

<table>
<thead>
<tr>
<th>Material</th>
<th>Measured Yield Stress (MPa)</th>
<th>Measured Tensile Strength (MPa)</th>
<th>Measured Elastic Modulus (MPa)</th>
<th>Measured Bolt average Pretension Force (KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel (t &lt; 16 mm)</td>
<td>391</td>
<td>559</td>
<td>190/707</td>
<td>-</td>
</tr>
<tr>
<td>Steel (t &gt; 16 mm)</td>
<td>363</td>
<td>573</td>
<td>204/228</td>
<td>-</td>
</tr>
<tr>
<td>Bolts (M20)</td>
<td>995</td>
<td>1160</td>
<td>204/228</td>
<td>185</td>
</tr>
<tr>
<td>Bolts (M24)</td>
<td>973</td>
<td>1183</td>
<td>204/228</td>
<td>251</td>
</tr>
</tbody>
</table>

To verify the accuracy of the model as a drilled flange model, the research conducted by Fanaei and Sadeghi Moghadam (2019) was used with the help of Abaqus software, which was named as TSDF samples. Figure 7 demonstrates the results of numerical and laboratory modelling. Figure 8 depicts the equivalent plastic strain.

3. Description of the studied models

The impact of circular holes on the seismic behaviour of steel beam-column connection is evaluated by using Finite Elements Analysis (FEA) in ABAQUS. In addition, hole properties including dimension, diameter, number of rows, and spacing are studied. Finally, RBS connection is analysed and compared.
4. Simple connection (No drilled on beam flange) and RBS models

Table 3 presents the models. ‘Reduced beam section’ is used for naming the samples, where NS is the name of the simple connection in the beam. RBS stands for reduced beam section. IPE beams and box columns are used in models. Dimensions and spacing for shears in flanges are based on millimetre units. Letters and
numbers are used like C25 to show column along with names, where C indicates the column, and 25 presents 250x250x10 box section. The last number and letter are for the beam section. B36 means beam with IPE360.

5. Drilled flange beams

In this section, different drilling methods are evaluated. First, the number and spacing of holes are considered variable but the diameter of holes is identical. In the next part, a drilling shape arrangement is suggested based on Reduced Beam Section (RBS), which is named diamond-shaped because of its similarity with diamond.

5.1. Drilled connections with the identical diameter and various spacing and number of holes

Table 4 shows drilled flange beam-column connection models named Drilled flange connection (DFC) model. All of the presented parameters in Table 4 are based on the millimetre unit. The diameter and number of holes are variable.

Figure 9 presents the hole shape elevation and its position on the beam.

5.2. Drilled connection with a variable diameter (diamond-shaped)- a proposed model

Table 5 shows drilled flange beam-column connection models, named DFCV. Numbers are used to making a distinction between beam and column, and the rest of the names are presented by numbers.

The drilled connection assumed in Table 5 is used for Reduced Beam Section method correspondingly. The shapes of holes are all symmetrical. Small diameter holes are chosen for the bottom of the model, and holes in the middle are the greatest. Finally, the diameter is reduced again. This connection is named diamond-shaped since it is similar to diamond. The connection shown in Table 5 is based on a diamond-shaped pattern as presented in Figure 10.

The connection is modelled using ABAQUS Finite Elements. The connection is tested with a stiffener. Figure 11 presents each beam connection in one figure.

5.3. Modelling process

First, a 6-story frame model is evaluated. Steel no. ST37 is used as the material. Figure 12 presents the applied steel stress-strain graph.
All stories are 3 metres tall. All frames contain 3 spans and each opening is 5 metres wide. Table 6 shows the steel properties. Soil Type III is used for structure placement. Moment frame of intermediate type is used in the process.

Now, dead surface load of 600 kg/m² and live surface load of 200 kg/m² are considered. Then, imposed load amount of 2400 kg/m and live load of 800 kg/m on columns are calculated. In addition, IPE beams and box columns are used in models. Table 7 shows the models with specified sections for each element.

Connection stiffness is modelled and the link element is used by considering calculated connection stiffness. All modelling is done in SAP2000. Nonlinear (pushover) static analysis of the frame is performed. In order to do nonlinear static analysis, the lateral load is applied to the structure based on the first mode and uniformly. Moment hinge type of M3 is used for beams. An interactive compressive hinge and bending moment of PM2 M3 is used for columns.

The loading pattern is imposed on connection based on ATC-24.

Establishing the plastic hinge in reduced beam flange zone and extending the plastic area by using all of the reduced beam sections are considered as the major objectives of connection design, which causes an increment in plastic effective length more than RBS connections with circular shear. In the proposed connection, by considering the uniform extension, plastic strain causes a delay in rotational-lateral strain and resists against instability in the reduced area length than in RBS connection with circular shears. In order to find the proper plastic hinge, the reduced part of the beam flange must be a definite percentage of the plastic moment in the beam, which is calculated by the following formula Vetr, Miri, and Haddad 2012 (Figure 13).

\[
\frac{M_1}{Z_1} = \frac{M_2}{Z_2} = \frac{M_3}{Z_3} = \frac{M_i}{Z_i} \tag{1}
\]

where \(M\) is the reduced moment used to design holes in the section for modifying the beam function for a fuse-like element. Further, \(Z\) is the base for a plastic section of the beam in the reduced area a follows.

\[
M_i = aM_{pr}\left(\frac{L_i}{\frac{L}{2}}\right) \tag{2}
\]

\[
M_{pr} = C_{pr}R_fZ_bF_y \tag{3}
\]

All stories are 3 metres tall. All frames contain 3 spans and each opening is 5 metres wide. Table 6 shows the steel properties. Soil Type III is used for structure placement. Moment frame of intermediate type is used in the process.

Figure 9. Pattern of hole placement on DFC beam wing.

Table 4. DFC connection.

<table>
<thead>
<tr>
<th>Name</th>
<th>Column (mm)</th>
<th>Beam</th>
<th>The first hole distance from the column</th>
<th>Diameter of holes (mm)</th>
<th>Hole distance (mm)</th>
<th>Number of holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFC-C25-B36</td>
<td>250x250x10</td>
<td>IPE360</td>
<td>270</td>
<td>30</td>
<td>75</td>
<td>1</td>
</tr>
<tr>
<td>DFC-C25-B36</td>
<td>250x250x10</td>
<td>IPE360</td>
<td>195</td>
<td>30</td>
<td>75</td>
<td>3</td>
</tr>
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<td>250x250x10</td>
<td>IPE360</td>
<td>195</td>
<td>30</td>
<td>75</td>
<td>4</td>
</tr>
<tr>
<td>DFC-C25-B36</td>
<td>250x250x10</td>
<td>IPE360</td>
<td>270</td>
<td>30</td>
<td>–</td>
<td>1</td>
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<td>30</td>
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<td>1</td>
</tr>
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<td>DFC-C25-B36</td>
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<td>30</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
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<td>250x250x10</td>
<td>IPE360</td>
<td>195</td>
<td>30</td>
<td>75</td>
<td>3</td>
</tr>
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<td>40</td>
<td>75</td>
<td>3</td>
</tr>
<tr>
<td>DFC-C25-B36</td>
<td>250x250x10</td>
<td>IPE360</td>
<td>195</td>
<td>30</td>
<td>75</td>
<td>4</td>
</tr>
</tbody>
</table>
Reduced beam section connection is difficult and costly because of four sections in the flange, especially in current structures. Furthermore, other beam flange reduction connections like DFC are investigated to improve the ductility connection, lessen the costs, and ease construction. Connection ductility differs according to connection type and plastic joint placement, as well as seismic demand which hinges applies to connection. Location, length, shape, and characteristics of plastic hinge affect directly on the connection in steel moment frames in order to to find required ductility, proper energy depreciation, and resistant connection with high stiffness. Beam flange reduction by drilled holes helps to shift the plastic hinge zone from the column face and increases the ductility of connection.

In the present study, a mesh with dimensions of 10 mm was selected as the focus on the created holes. The size of the meshes was 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 mm. It is worth noting that meshes smaller

### Table 5. Connection with drilled sections like a rhombus.

<table>
<thead>
<tr>
<th>Name</th>
<th>Column (mm)</th>
<th>Beam</th>
<th>The first hole distance from the column (mm)</th>
<th>Diameter of the first hole (mm)</th>
<th>Diameter of the second hole (mm)</th>
<th>Diameter of third hole (mm)</th>
<th>Hole distance (mm)</th>
<th>Number of holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFCV-C25-B36</td>
<td>250x250x10</td>
<td>IPE360</td>
<td>195</td>
<td>30</td>
<td>40</td>
<td>30</td>
<td>75</td>
<td>3</td>
</tr>
<tr>
<td>DFCV-C25-B30</td>
<td>250x250x10</td>
<td>IPE300</td>
<td>195</td>
<td>30</td>
<td>40</td>
<td>30</td>
<td>75</td>
<td>3</td>
</tr>
<tr>
<td>DFCV-C22-B27</td>
<td>220x220x10</td>
<td>IPE270</td>
<td>195</td>
<td>30</td>
<td>40</td>
<td>30</td>
<td>75</td>
<td>3</td>
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<td>DFCV-C50-B45</td>
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<td>IPE450</td>
<td>195</td>
<td>30</td>
<td>40</td>
<td>30</td>
<td>75</td>
<td>3</td>
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</tbody>
</table>

Figure 10. A cross-section scheme for provided holes.

Figure 11. An example of the various connections examined in this study.

Figure 12. A steel stress-strain graph.
than 10 mm were studied in 5 models while meshes larger than 10 mm were considered in the other 5 models. Finally, according to the analysis time, the results provided at the location of the holes were selected with a mesh of 10 mm dimension. The larger mesh dimensions caused an inappropriate tension at the holes while the smaller dimensions made the analysis time longer and led to a difference in the results by less than 0.5%. Thus, the 10 mm mesh was used for numerical modelling.

6. Results

Results are not fully presented due to their large amount. Thus, only one sample of each model is shown, and finally all major results are discussed. Table 3 shows the results of NS-C55-B45 and RBS-C50-B45, and Table 4 indicates DFC-C50-B45 to DFV-C50-B45, while DFCV-C50-B45 is shown in Table 5.

7. Simple and RBS connections results

Moment-rotation Hysteresis curves are obtained for each model after modelling, loading, and analysing the models. The surface beneath these curves shows the potential of connection for energy absorption. More surface leads to more energy absorption. The plastic strain equivalent of (PEEQ) is used to analyse the plastic hinge formation zone in which these amounts are calculated on column face on a lateral strip of beam flange. Figure 14 presents the equivalent plastic strains in the rotation of 4% for a simple model.

As shown in Figure 15, plastic strain for model NS-C55-B45 is applied on column face which is not a proper connection function, but the plastic strain is applied on the reduced part in the model RBS-C50-B45. By comparing the behaviour of both beams, the connection function in model RBS-C50-B45 is closer to proper function. Figure 16 presents the moment-rotation connection of model RBS-C50-B45.

As shown in Figure 17, connection stiffness decreases after reducing the beam section. The connection stiffness is more in NS-C55-B45 because the beam section is complete. Thus, its more resistance and moment are more than the RBS-C50-B45 sample. Figure 16 presents the plastic strain of RBS-C25-B30 sample.

As displayed in Figure 18, intermediate samples resist more moment because of greater cross-section, and RBS samples resist less moment due to their decrement of beam section.

8. DFC results

Figure 19 shows the graphic results related to plastic strain in DFC-C50-B45 sample Figure 20 presents the moment-rotation graph for DFC-C50-B45 model. Figure 18 displays the moment-rotation connection for all DFC models.

As shown in Figure 21, load capacity increases by increasing the beam cross-section. In addition, the amount of energy absorption of structure and its load-bearing capacity decreases by increasing the number of holes in the beam flange.

9. DFCV (diamond-shaped) results

Figure 22 presents the plastic strain of DFCV-C50-B45 sample. Figure 23 shows the moment-rotation Hysteresis graph for the DFCV-C50-B45 model. Figure 24 displays the envelope moment-rotation for all DFC models. As shown in Figure 21, the energy absorption is more in the connections in which beam section is stronger, and DFCV model with IPE450 resists the moment almost 50% more than the samples with IPE300 and IPE270. As displayed in Figure 25, the results of rotational stiffness in connection are...
Figure 14. Moment-rotation diagram NS-C55-B45.

Figure 15. The plastic strain in the connection zone

(a) NS-C55-B45

(b) RBS-C50-B45

Figure 16. Moment-rotation diagram of RBS-C50-B45.
Figure 17. Plastic strain on RBS-C25-B30 joint.

Figure 18. The moment-rotation envelopes of NS and RBS samples.

Figure 19. Plastic strain in sample DCF-C50-B45.
Figure 20. Moment-rotation for DFC-C50-B45.

Figure 21. Moment-rotation diagram for the DFC model.

Figure 22. Plastic strain for model DFCV-C50-B45.
calculated for each model. As shown, the rotational stiffness of drilled models is more than the RBS models (Figure 25). Further, the stiffness of drilled models with variable diameters is more than that of other models.

9.1. Connections in the steel moment frame

The frames are named based on Table 8. As shown, the models studied in this paper and the rigid connection model which is available in the software are commonly used by engineers. In this connection model, moment transformation ability, shear, and axial force in the joint are completely considered in software (MR-Frame with rigid connection software default). Therefore, this model is used for comparing the real behaviour with the behaviour presented by the software. Other connections are related to this paper. The results obtained from frame models by SAP2000 are as follows:

As shown in Table 9, the envelope pattern is based on the first mode and has a uniform load. Two compositions of 9.0 dead load for one of them and 1.1 dead loads, along with 1.1 live loads for the other one is considered for dead and live load. In addition, five different connections like rigid connection, RBS, and DFC are used for applying the panel zone in frames and are described by a fame name. In MR-Uni-1 frame, ‘MR’ indicates the first part of the name, i.e. completely rigid connections, ‘Uni’ is enclosed by
applied uniform load, and number 1 means dead load with 90 Association.

In this section, five different frame models are analysed, the connections of which were described above. Further, five frames are established as the frames with rigid connection and frames with connection and stiffness based on the above models including DFC, RBS, DFCV, NS, and MR. Nonlinear static analysis of the frame is applied on the frame based on uniform load imposing and enveloping the first mode based on load pattern. Figure 26(a,b) present formed the hinges on the frame with rigid connection and RBS connection based on the first mode load pattern and 0.9 of dead load.

As shown in Figure 27, the formed hinges on the column are more critical and more in number than RBS and drilled models in a rigid and simple connection. The formed hinge in the column damages more because the rigid connection transforms all moment and shear. Furthermore, energy absorption is not taken in the hinge zone. Drilled connections behave better in forming hinges on beam and column than those in other models.

As displayed in Figure 24, pushover graphs are slightly different from each other in different connection models. By comparing the models, models with rigid connection are yielded sooner than other models, and a delay occurs in the yield point by increasing the amount of connection rigidity. Thus, yield point happens later than other models in RBS connection. In addition, the amount of the energy absorption in the models with rigid connection is more than that of other models due to more ductility. Further, the lowest amount of energy absorption occurs by using RBS models. Table 9 shows the behaviour factor for each frame.

### 10. Conclusion

The present study aimed to evaluate the effect of different connections on the behaviour of steel moment frames. The evaluated connections included simple connections (no holes), RBS, DF connection, and drilled connection with a variable diameter (diamond-shaped). The connection was modelled using ABAQUS Finite Elements. Then, it was modelled in ABAQUS software with all of the related details. Accordingly, the moment-rotation charts were calculated. Finally, Finite Elements Modelling (FEM) was utilised to calculate the stiffness for each connection. In addition, steel moment frame was modelled in SAP, and stiffness was calculated with Finite Elements Analysis of ABAQUS and used for panel zone. The results were as follows:

- The behaviour of the connection indicated that drilled connection and connections containing diamond-shaped holes (two end holes are smaller and the middle hole is bigger) have more
rotational stiffness than those in RBS and simple models (no holes).

- Drilled beam connections could shift plastic hinge better than RBS connection.
- Formed hinges indicated that more damage occurred in the connections and plastic hinge in the frames with simple and rigid connections. In addition, RBS and drilled connections had absorbed energy in the convection zone leading to less damage to the column.
- The stiffness decreased leading to a reduction in the load capacity of the connection by increasing the number of holes with identical diameters.

However, the beams with more holes functioned better than those with a single hole. In the beams with one hole, the hinge was formed in or near the hole, but the hinge was formed between the holes and was far away from the column in the connections with various holes.

- RBS and drilled connection with variable diameter indicated that local buckling happened in the position due to a reduction in beam flange, which is related to the slenderness created in section and a decrement in beam flange stiffness. However, this weak point was not observed in the drilled connection with a variable diameter.

Figure 26. Formed hinges on the frame with rigid connection and RBS connection based on the first mode load pattern and 0.9 of dead load.
Thus, it can be considered as another advantage of drilled section connections.

- The behaviour factor decreased by analysing the frame behaviour factor and their comparison with rigid connection frames.

Disclosure statement

No potential conflict of interest was reported by the authors.

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