Numerical study of slotted web drilled flange moment frame connection

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Abstract:

Beam connections with reduced drilled section and slotted web have been presented after the Northridge earthquake (1994). Their new geometrical shapes have been resulted in weakening of beams and subsequently the bette rperformance of connections in the earthquakes. In this research, the advantages of both connections, mentioned above, have been studied in the Slotted Web Drilled Flange (SWDF) composite connections. Accordingly, the effects of different parameters of slot such as length, width and end hole dimension have been assessed as well. Based on the results obtained in this research,energy dissipation is reduced due to the increase of length of slot web in the SWDF connection, exceeded the values recommended in the codes. Besides, the stability of hysteresis curve decreases because of increasing in the width and end hole diameter of web slot.

1. Introduction

Since 1994 Northridge earthquake, two solutions have been suggested for improving the ductility of beam to column connections. In the first method, the strengths of connections have increased by using stiffeners and proper welds, preventing their early damage. In the second solution it has been suggested to use the beams with reduced sections in a distance from column face. In this way, the plastic hinge is formed far from the column and critical region of beam to column connection. Reduced Beam Section (RBS) and Slotted Beam Web (SBW) connections have been presented according to the second suggested method [1]. RBS connection is based on the omitting a part of beam flange in a distance from beam to column connection in such a way to reduce a part of upper and lower flanges [2]. The reducing of section in a part of beam causes the reduction of flexural capacity and consequently formation of plastic hinge in the cut off region of beam there [3].

The shape of web slot in Slotted Beam Web (SBW) connection allows buckling of flanges and web of beam independently. This status will annul the lateral torsional buckling which occurs in the slotless beam. The torsional moment and shearing stress, formed in the beam flanges and column flange welds are omitted due to the mentioned buckling. In SBW connection, the flange and web of beam are separated from each other and consequently tri-axial stress and strain is converted to bi-axial ones in the connection region causing the increase of beam fatigue age. The details of such connections are presented in Figure 1 [4].

Seismic structural design association has published the detailed design of beam with slot in its web after numerous studies. SBW connection can well rescue the connections designed before Northridge earthquake (1994) from damage. Therefore, it can be applied in the seismic rehabilitation of existing structures The purposes of design of SBW are to achieve maximum flexural capacity of beam and also transfer the plastic hinge from column face to beam. The ductility increases by omitting lateral torsional buckling from the beam with slotted web as well as reducing the residual stresses of weld [5]. Focusing on a special kind of RBS connections maybe ended in ignoring the connections with economical and executive effects.

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Reduced Beam Section appears to be one of the more promising connection concepts for designing ductile steel moment frames regarding severe seismic applications. The radius cut dogbone connection appears to be able to provide a high level of performance with reliable cost [6]. RBS can be viewed as a ductile fuse that forces yielding to occur within the reduced section of the beam, an area that can sustain large inelastic strains. While at the same time the stress is limited in the less ductile region near the face of the column [7]. Drilled Beam Sections (DBS) and SBW connection have their own special advantages in the earthquake. Different connection types of RBS is shown in Figure 2 [8].

SWDF connection, the composition of DBS and SBW connections, is presented for the first time in this research. The proposed connection is the drilled type of Slotted Web Reduced Flange (SWRF) connection, proposed by Maleki et al. [10]. Utilizing the advantages of the two mentioned kinds of connection can significantly affect the seismic performance of different structural systems. Concerning the applied changes in this connection, it is expected to meet the advantages of DBS and SBW connections by drilling the beam section. These advantages are reducing tri-axial stress, omitting lateral torsional buckling mode of the beam from slot connection in the beam web and increasing the ductility as well as the period of building. The plastic hinge, formed in the beam-slotted web connection is located in the connection joint, exactly in front of the shear plate and shown in Figures 3 and 4. In the connections of beam with reduced section and with side plates, the plastic hinge is approximately formed in the distance of beam depth from column face [4].

In this research an innovative hybrid connection is studied concerning the advantages of DBS and SBW connections. In this connection both beam flanges are reduced in section (like DBS) and the beam web is cut with two slots (like SBW).
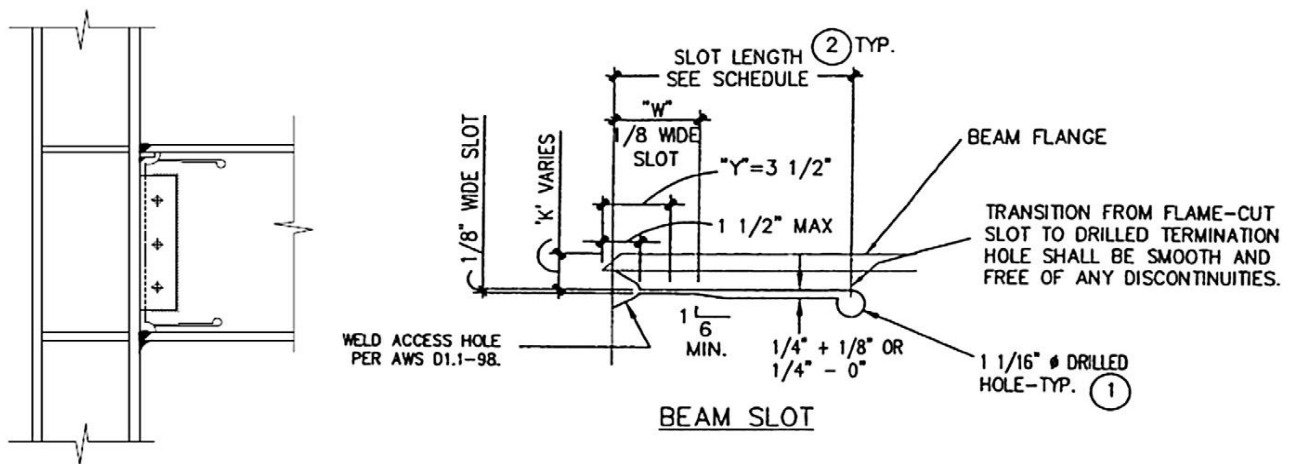

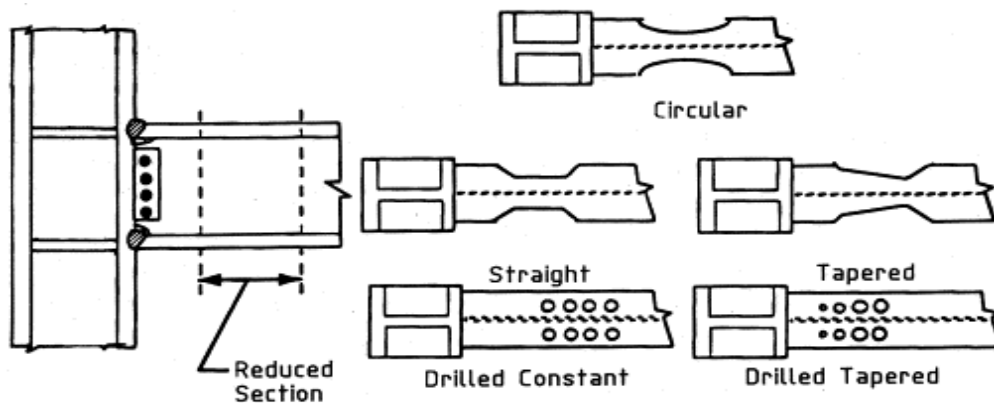**Fig.1:** The details of SBW connection [5]
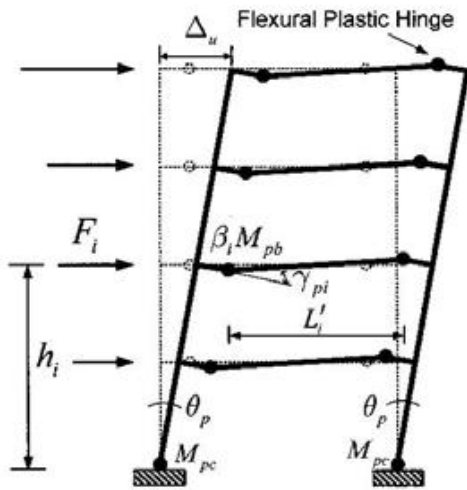

Fig.2: Different connection types of RBS [9]
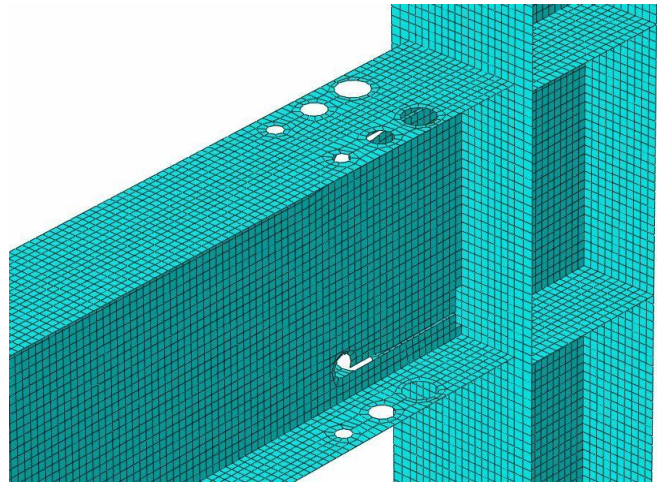
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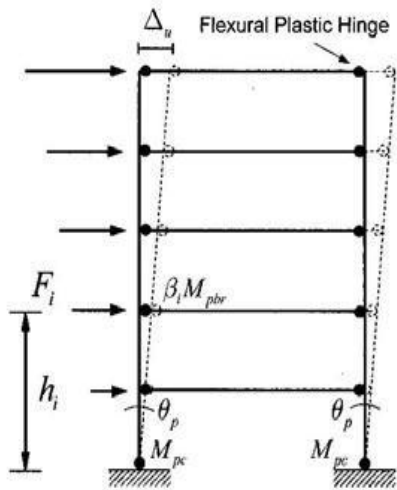**Fig.3:** SMRF with Slotted Web Connections [4]

Fig.4: SMRF with RBS Connections under lateral loadings [4]

2. Analytical Studying of SWDF Moment Connection

BDD3-200-150-100 model shows more appropriate performance comparing to other different kinds of connections. It has been used and composed with the slotted web concerning the results obtained from the performances of DBS types [8]. At the end, 9 samples have been considered with SWDF connections. 3 of the samples have been constructed for studying the effect of slot length, 3 for the slot width and 3 for the size of end hole slot. A sample of the constructed models has been depicted in Figure 5.

2.1. Slot Length Variation

According to the international code council, the standard slot length is 180 mm. In order to study the slot length, the minimum and maximum lengths of shear plate have been considered as 110 mm and 360 mm, respectively. The three constructed models have been subjected to the cyclic

Fig.5: Three dimensional finite element model of SWDF

loading. Then, the seismic performance of different lengths of slot have been studied in the beam web of new connection, concerning the hysteresis curves as well as the location of maximum Von Mises stress.

2.2. Slot Width Variation

In this section, the slot length and the end hole diameter of slot have been considered as 180 mm and 21 mm, respectively. Then, the three models have been analyzed with the slot widths of 3.2, 6.4 and 9.6 mm.

2.3. Variation in End Hole Dimension of Beam Web Slot

In this section the length and width of slot are considered as 180 mm and 6.4 mm, respectively. Two models with the diameters of 1.6 mm and 2.6 mm and another one with 2.1 mm [11] have been constructed to study the effect of dimensions of end hole of beam web slot. The models have been subjected to the cyclic loading to study the seismic performance of the connection.

3. Finite Element Analysis

In this section firstly, the specifications, listed in Tables 1 and 2, are entered in the part module in the form of shell extrude. In this model the span length of the mentioned beam has been considered as 2.5m and the column height as 3m.

Table.1: The specifications of beam section [10]

BEAM	Width(mm)	Thickness(mm)	Yield Stress(N/mm²)
Flange	150	10.7	335
Web	300	7.1	335

Table.2: The specifications of column section [10]

Column	Width(mm)	Thickness(mm)	Yield Stress(N/mm²)
Flange	200	15	335
Web	200	9	335

3.1. Elements and Meshing

The subassemblies are modeled using a quadrilateral four-node shell element (element SHELL extrude in ABAQUS). This element has plasticity, large deflection, and large strain modeling capability. It has six degrees of freedom per node: translations in x, y and z directions; and rotations about x, y and z axes. The finite element meshing, used in this study, is presented in Figure 5. According to this figure, a more refined mesh is employed in the regions near drilled beam section and web slots.

3.2. Material Modeling

Nonlinear material with kinematic hardening is used in all steels applied in the metallic connections. The plasticity of model is based on Von Mises yielding criterion and its relevant flow rules. Stress–strain diagram of ASTM A572 steel is shown in Figure 6.

The properties of steel are completed by assigning the specifications of the steel used in the experiments and devoting the material to the considered sections. The stress-strain curve, introduced to the software, has been shown in Figure 6. In this process Young's modulus and Poisson's ratio have considered as 0.21×10^6 and 0.3, respectively [10].
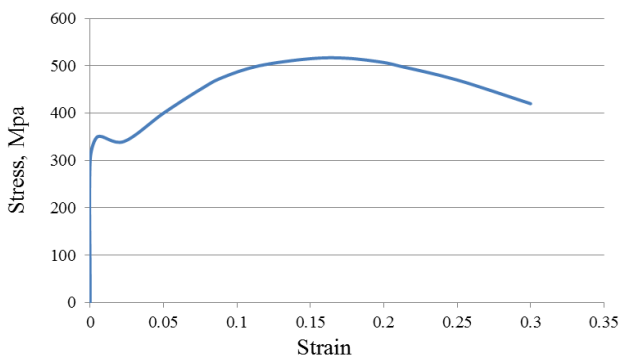

Fig.6: Stress–strain diagram of steel [10]

3.3. Loading Protocol

For loading the above mentioned connection, the considered rotation is properly entered by defining the boundary condition at the end of the beam and applying displacement/rotation in that region. AISC seismic provisions loading protocol has been introduced to the software and presented in Figure 7 [12].
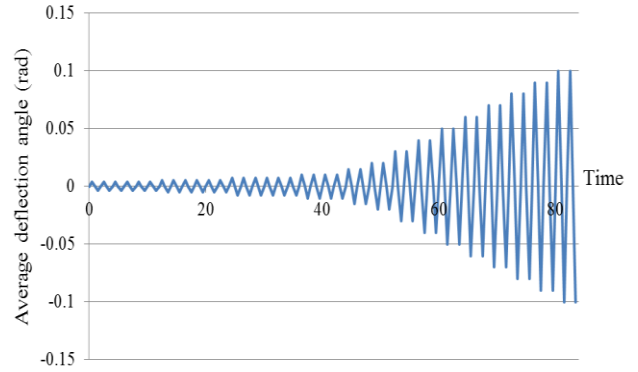

Fig.7: The applied loading protocol [12]

Regarding the displacement control, each subassembly is loaded at the free end of the beam in such a way that its drift angle satisfies AISC seismic provisions loading protocol. All specimens are loaded up to 0.04 rad of drift angle. Before loading the beam, the buckling mode shapes of the model have been computed in a separate buckling analysis by software. In order to consider the local and lateral buckling effects, the deformed buckled shape is then analyzed under cyclic loading [10].

4. Results and Discussion

Studying the connections under cyclic loading is the best way to assess the seismic performance of structures. What is very important in this procedure is the response of the system, presented as the hysteresis moment-rotation or force-displacement curve. In this research 9 samples have been subjected to cyclic loading for parametric studying of SWDF beam to column connection. This loading is conducted based on the loading protocol of moment connections presented in the American seismic code [12].

4.1. Slot Length Effect

According to Figure 8, if the length of slot web increases much more than the codes recommended value, then the performance of considered connection will meet problems and the area under its hysteresis curve is reduced. This fact is seen in the improper distribution of Von Mises stress in the connection with the slot length of 360 mm.

Von Mises stress distribution in the beam web has been presented in Figure 9. If the length of slot, formed in the

beam, exceeds the code recommended value, the stress is concentrated in the beam flange and subsequently the fracture is created in the weld region. This fact reduces loading capacity of connection. Figure 10 shows Von Mises stress distribution in the beam flange. According to this figure, the plastic hinge is extended in different regions of the connection. The distribution of yielding points in large parts of section and the failure of connection zone are resulted in the decrease of energy dissipation.

If the length of slot, formed in the beam, is lower than the code recommended value, the plastic hinge range will decrease. Therefore, the connection practically goes toward those before Northridge earthquake ending in brittleness, early failure and consequently loading capacity reduction. According to Figure 10, the stress distribution of beam dosen't satisfy the expectation of international code council.
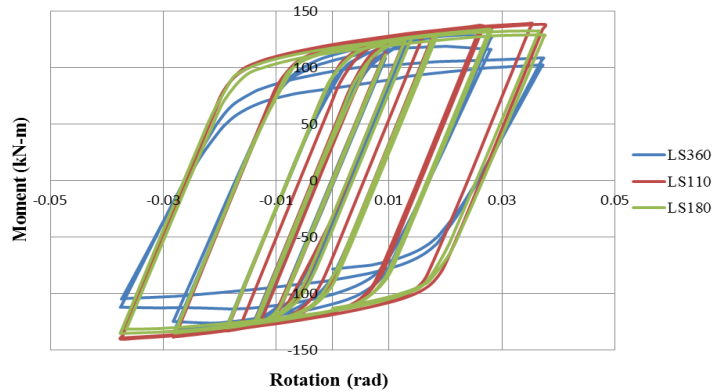

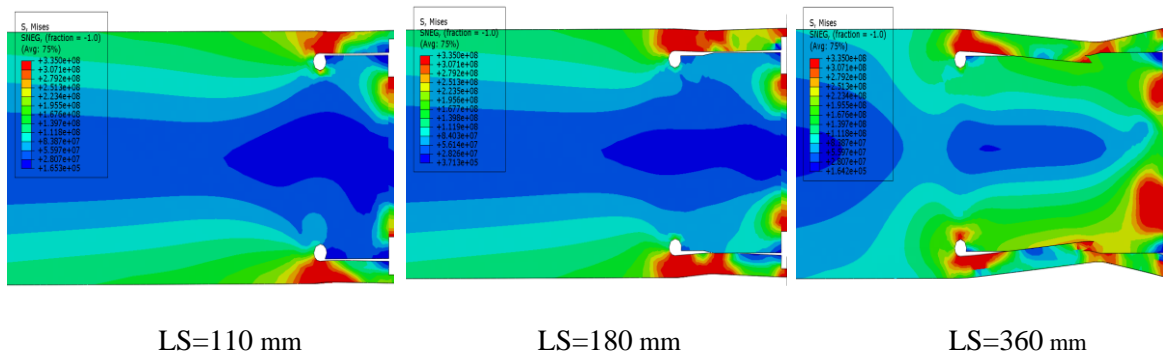**Fig.8:** The hysteretic response of connection with different slot lengths

LS=110 mm   LS=180 mm   LS=360 mm

Fig.9: The Von Mises stress distribution in the beam web of SWDF connection

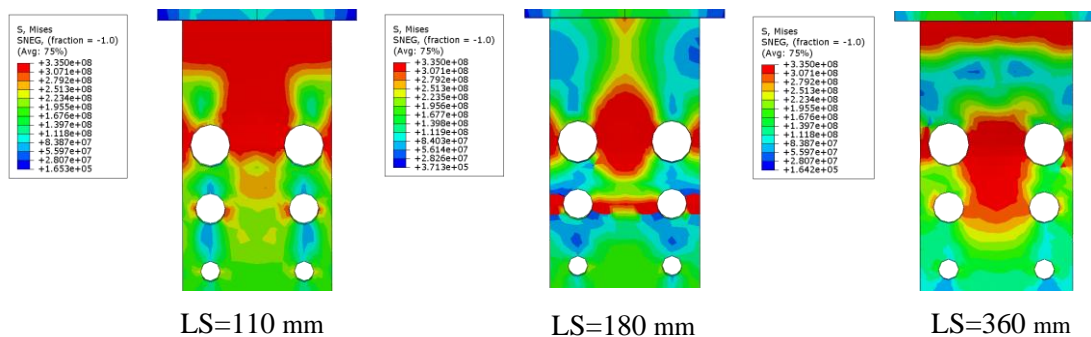LS=110 mm   LS=180 mm   LS=360 mm

Fig.10: The Von Mises stress distribution in the beam flange of SWDF connection

4.2. Slot Width Effect

Figure 11 shows the hysteresis curves of the connection with the slot widths of 3.2, 6.4 and 9.6 mm. The seismic response of beam connection with the slot width of 9.6 mm, considered over the code ranges, shows unstable hysteresis behavior. The instability of seismic behavior is happened in this connection while its Von Mises stress distribution is close to that of the connections with slot widths of 3.2 and 6.4 mm. Von Mises stress distributions of beam flange and beam web are presented in Figures 12 and 13 respectively.

4.3. The Effect of End Hole Dimension of Beam Web Slot

According to Figure 14, high increasing in the end hole diameter of slotted web will cause the instability in the seismic performance of connection.

In such cases the seismic performance of system will meet problems. Therefore, increasing the diameter of end hole has improper effect on the connections. Figure 15 shows the distribution of Von Mises stress in the connection. The mentioned improper effect is referred to the web cross section reduction due to the increasing in the dimension of end hole. Consequently, the web is dramatically weakened. Regarding the conducted analyses, decreasing in the dimensions of end hole in the slotted beam web (SBW) will cause the early rupturing of connection in the beam web region. This fact is not seen in the introduced composite connection and presented clearly in Figure 16.
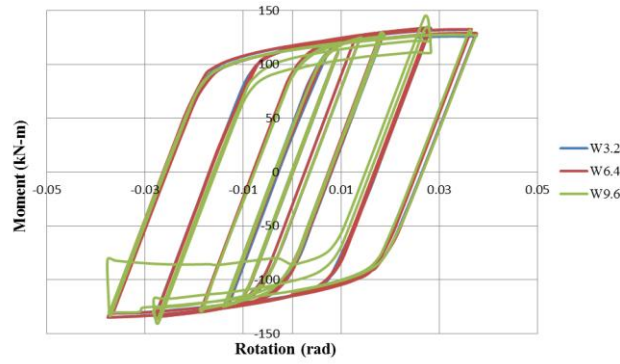

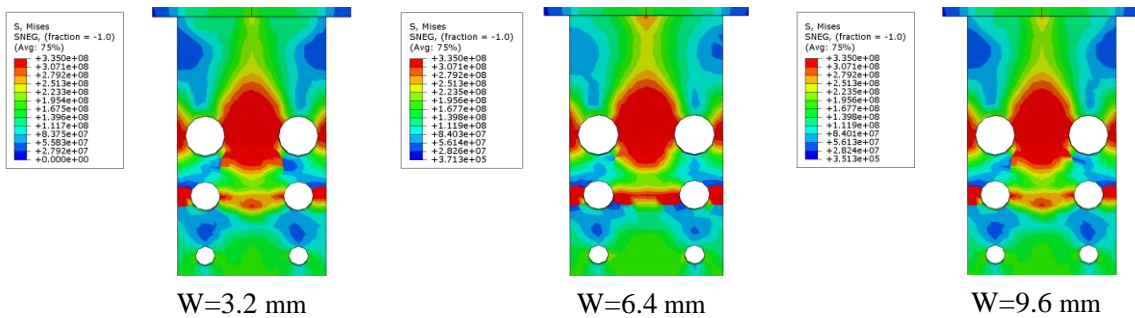**Fig.11:** Hysteretic response of SWDF connection with different slot widths

W=3.2 mm   W=6.4 mm   W=9.6 mm

Fig.12: Von Mises stress distribution in the beam flange of SWDF connection
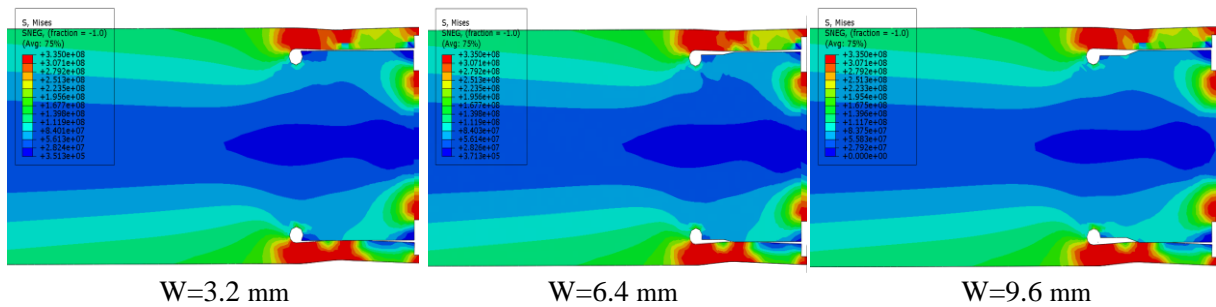

W=3.2 mm   W=6.4 mm   W=9.6 mm

Fig.13: Von Mises stress distribution in the beam web of SWDF connection
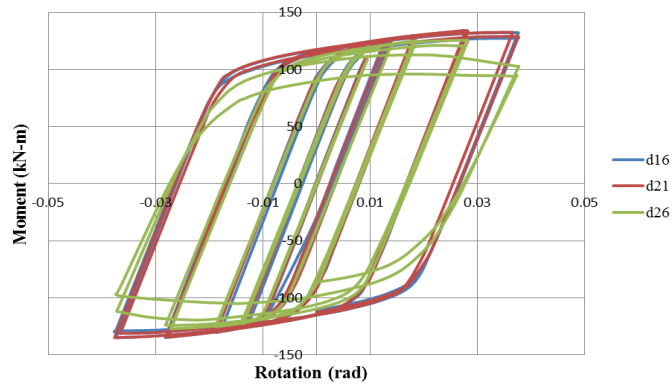
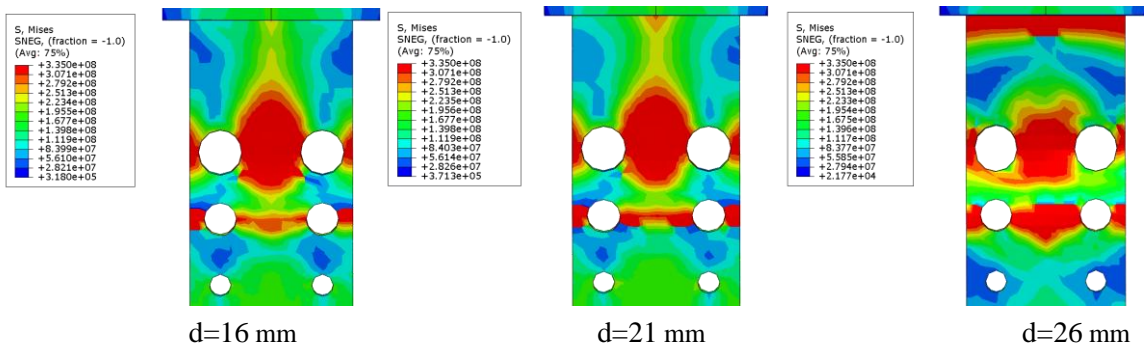**Fig.14:** Hysteresis curve of the connection with slotted web of different dimensions of slot end hole

d=16 mm	d=21 mm	d=26 mm

Fig.15: The distribution of Von Mises stress in the beam flange of SWDF connection

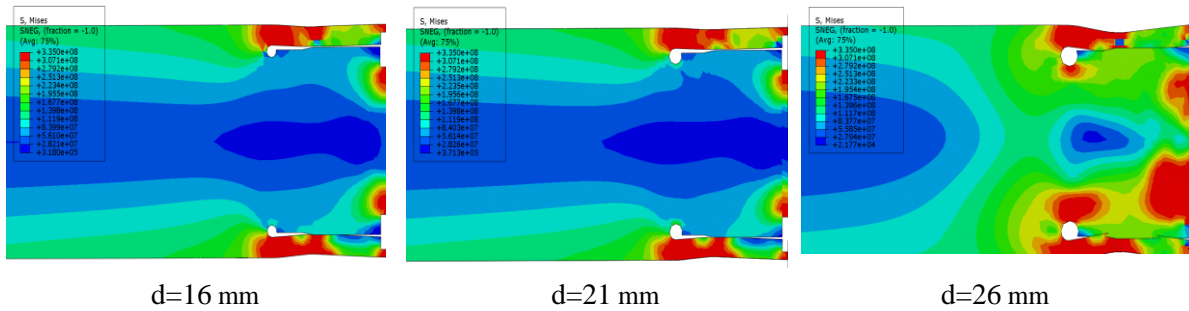|		
d=16 mm	d=21 mm	d=26 mm

Fig.16: The distribution of Von Mises stress in the beam web of SWDF connection

5. Conclusion

This analytical research has indicated many advantages in using DBS and SBW moment connections in steel structures subjected to earthquake loading. This paper investigated the possibility of having both connection details and their advantages in one new connection called Slotted Web Drilled Flange (SWDF) connection. A nonlinear finite element model has been used to examine and analyze the hysteretic behavior of the new connection.

The effects of slot length, slot width and end hole dimension of beam web slot are also investigated. The following general conclusions can be drawn:

1) Disorderly increase of length of slot web in the SWDF connection, exceeding the values recommended in the codes, is resulted in reducing the energy dissipation. Decreasing in the slot length will extend the plastic hinge to the connection region. The seismic performance of the connection

is generally improved by following the code ranges.

2) The new connection has presented appropriate seismic performance and stable hysteresis curve like Slotted Web Reduced Flange (SWRF) connection. Therefore, it has particular importance due to its executive capability in the constructed and under construction buildings.

3) Increasing the width of web slot in SWDF connection is ended in decreasing of the stability of hysteresis curve. If this width does not exceed the code maximum value, then selecting different widths will not affect the seismic performance of connection.

4) Increasing the diameter of end hole of web slot in the SWDF connection causes the decrease of stability of hysteresis curve. If this diameter does not exceed the code maximum value, then selecting different diameters will not affect the seismic performance of connection.

These results are all based on the numerical studies and computer simulations. To ascertain, experimental testing on SWDF connections is definitely needed.

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