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Numerical investigation of the effect of materials on intensified shear and moment in IPE steel beams with reduced beam section

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ABSTRACT

Looking at the structures damaged by the force of the earthquake in the past years around the world, it has been observed that the most failed part of the structures is the panel zone or beam-to-column connection. Therefore, strengthening the panel zone is very important. One of the connections that can be used in steel structures is the beam connection with a reduced section or (RBS connection). In the RBS connection, by weakening the flange near the connection, excessive force and moment to the connection are prevented, and the plastic hinge is formed outside the connection. In this research, numerical tests were performed on three IPE beam and column samples with different sections that were connected in the panel zone. The analysis was nonlinear static. For each model, intensified shear based on the results of ABAQUS was compared with the moment, and intensified moment and shear was compared to the code of design and implementation of steel buildings (10th topic of the National Building Regulations). After comparing the moment and shear parameters It was observed that the regulation parameters were always higher compared to the analytical parameters, and in all the models, the highest stress occurred in the reduced area of the beam, and as we moved away from the place of the plastic hinge of the beam, the stresses decreased to a minimum, and the resistance of the panel zone was increased by increasing the size of the beam and columns.

1. Introduction

Considering the occurrence of various earthquakes and their destructive effects and the existence of buildings whose design does not consider the structure under the influence of earthquake conditions, it is necessary to repair and strengthen the structures, especially the connections. Connections are one of the most important members of the structure. The task of hinges in steel buildings is to connect the beam to the column and also to divide the forces between the beam and the column. The study and examination of connections can improve the overall behavior of the structure and to some extent improve the behavior of the structure against earthquakes. So that by creating a plastic hinge in the beam, the final damages of the column are reduced and the structure maintains its stability at the final moment. One of the common connections in steel structures is rigid connections. This connection's behavior is such that the beam and column rotate simultaneously and no angular change occurs between them. In rigid connection, the panel zone greatly influences the process of energy consumption in the structure and the behavior of the structure in severe earthquakes. So, if the panel zone is weak, even if the connection is completely rigid with a connection strength greater than the tension, which makes the failure not in the connection area, there will still be a large deformation, and as a result, it will cause the brittle failure of the connection. Extensive researches during the last few decades indicate that if the height of the steel bending the frame structure is changed, and the panel zone has different effects on the response of these structures. For example, in short, in steel bending frame structures, the panel zone will not have much effect on the seismic response of the structure, while the panel zone has significant effects on the seismic response of medium and long steel bending frame structures. The main reason for these different effects of the panel zone in the seismic response of steel bending frames is the change in the height of the structure and the change in the stiffness of the connections in structures with different heights.

Regarding the connection of steel structures. The research was done on rigid steel hinges that had a hardener near the hinge area, and they concluded that with the increase in the dimensions of the sheet, there was no noticeable and significant change in the hinge behavior [1].

Experimental and numerical research on connections with RBS beams concluded that the best state of connection will be when the plastic hinge occurs in the weakened place of the connection [2-3].

One of the studies in this field was conducted analytical and laboratory research on rigid steel hinges with weakened beams, for this purpose, examined these sections by using holes embedded in the wing of the beam and placing three types of stiffeners. The researchers concluded that the use of stiffeners improves plasticity and reduces the energy absorption of the connection [4].

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Conducted numerical studies on the cross-section of the beam to investigate the rigid connection behavior of the steel beam to the CFT column with external stiffeners. For this purpose, the section of the beam was reduced using the method of drilled or reduced beam wing to reduce stress concentration and increase ductility. According to the obtained results, the piercing of the wing of the beam led to a reduction of the stress concentration at the connection point of the stiffener to the beam and column [5].

Many other researchers have also researched RBS connections and have shown that these connections perform well under seismic loading. Considering that no special research has been focused on the effect of steel materials on the behavior of the panel zone in RBS connections, the purpose of this research is to investigate the effect of materials on intensified shear and moment in the panel zone in IPE steel beams with reduced wings. And the comparison of the maximum moment and shear in the panel zone obtained from the ABAQUS software with the intensified moment and shear in the panel zone obtained from the relationships of the design and implementation regulations of steel buildings. For this purpose, the criteria contained in the tenth topic of the National Building Regulations regarding the reduction of the beam cross-section and the design of the panel zone were used as the basis of the work. In this research, numerical studies were conducted on three samples of IPE beams and columns with different cross-sections that were connected in the panel zone. The models are modeled and analyzed in ABAQUS finite element software, and things such as stress and damage in the panel zone and intensified moment and shear values will be evaluated.

2. Modeling and accuracy

2.1. RBS connection design process

To design the beam connection with a reduced cross-section (RBS) with radial cut, FEMA's proposed relations were used (relations 1, 2, 3, and 4) [6].

$$0.5b_{bf} \le a \le 0.75b_{bf} \quad (1)$$

$$0.65d \le b \le 0.85d \quad (2)$$

$$0.1b_{bf} \le c \le 0.25b_{bf} \quad (3)$$

$$R = \frac{4c^2+b^2}{8c} \quad (4)$$

Where R is the cut radius, 'c' is the maximum cut rate, 'b' is the cut length, and 'a' is the distance from the beginning of the cut area to the column. (Figure. 1) In addition, b_{bf} is the width of the beam wing and d is the height of the beam section.

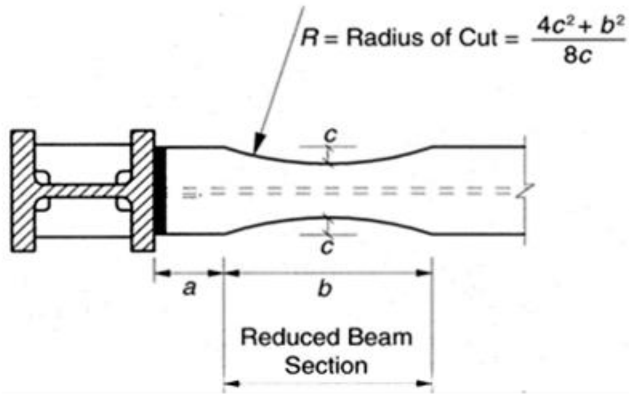

Fig 1. Connection design schematic with the radial cut.

Table 1. Specifications of sections in RBS connection.

Beam	a	b	c	R
IPE160	5cm	12cm	1.4cm	13.2cm
IPE180	5.6cm	13.5cm	1.5cm	15.1cm
IPE200	6.2cm	15cm	1.7cm	16.9cm

2.2. Connection modeling in ABAQUS

ABAQUS finite element software has been used to analyze and model the desired connections because this software has better capabilities than other similar software in modeling the behavior of steel. The SHELL element was used in the modeling. This element had 6 degrees of freedom in each node and the ability to consider material nonlinearity and large deformations. In this research, the models were defined in three dimensions, and the design of the models was based on the controls of the 10th topic of the National Building Regulations, 2012 edition [7]. In general, 3 IPE beam models were verified in ABAQUS finite element software, in each model, columns were considered 2 sizes larger than the beam, and for each model, we performed the analysis 4 times with different σ_y, because this was the goal. To investigate the effect of materials on intensified shear and moment in rigid connections of reduced wing IPE beams. The elements were considered Shell type. According to the control instructions of the design and implementation of steel buildings and the control of the strong column-weak beam criteria in RBS connections, members with the following specifications were used: IPE steel column 2 meters long and IPE steel beam with a length of 1.5 meters. In the desired connection, to strengthen the panel zone, a double sheet was used in the place of the panel zone, whose thickness was considered equal to the total thickness of the beam and column. Also, four connection sheets were used in the modeling, and the thickness of the connection sheets was considered equal to the thickness of the beam wing. Table 2 shows the modeled samples in this research.

Table 2. Introducing and naming models.

Model	Beam section	Column section	σ_{yield}(Pa)
M1	IPE160	IPE200	200×10^6
M2	IPE160	IPE200	220×10^6
M3	IPE160	IPE200	240×10^6
M4	IPE160	IPE200	260×10^6
M5	IPE180	IPE220	200×10^6
M6	IPE180	IPE220	220×10^6
M7	IPE180	IPE220	240×10^6
M8	IPE180	IPE220	260×10^6
M9	IPE200	IPE240	200×10^6
M10	IPE200	IPE240	220×10^6
M11	IPE200	IPE240	240×10^6
M12	IPE200	IPE240	260×10^6

In all models, Poisson's ratio equal to 0.3, Young's modulus equal to $2\times10^{11}\,N/m^2$ and density equal to $7850\,kg/m^2$ were considered, and the (combination) model was used for the hardening of materials because it was in better agreement with cyclic behavior modeling. Displacement at the end of the beam was applied according to the AISC protocol and quasi-static analysis was performed considering the geometric nonlinearity. The connection modeled in ABAQUS software is shown in Figure 2.

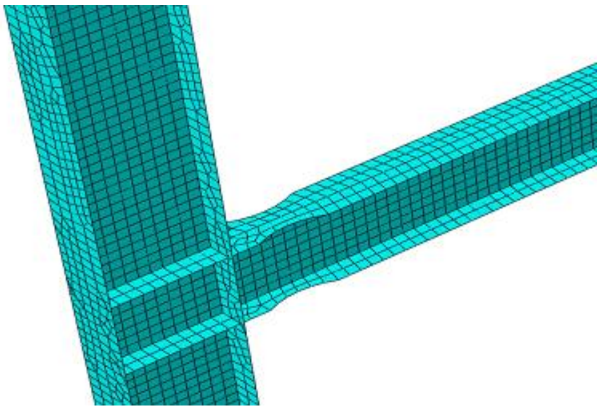

Fig 2. Connection modeled in ABAQUS.

After analyzing the designed sample, the plastic hinge was formed in the reduced area. Von Mises stress changes in the connection after loading can be seen in Figure 3.

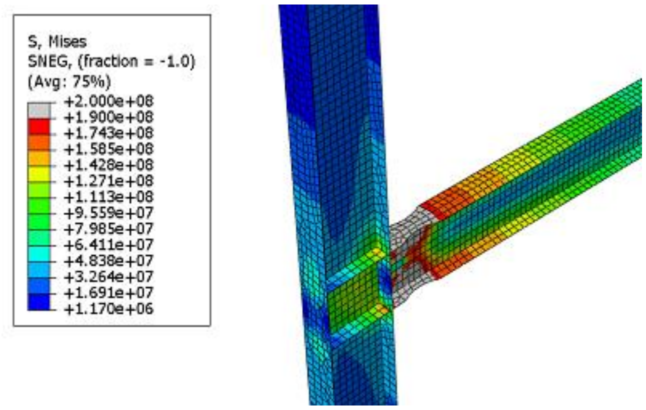

Fig 3. Von Mises stress contour of the connection, after loading.

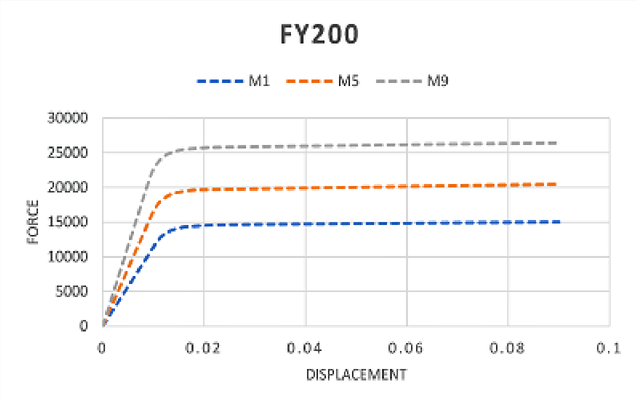

Fig 5. Force-displacement related to M1, M5, M9 models.

2.3. Connection support conditions

In this research, the support conditions of the column were defined as fully braced, and on the right side of the beam, at the free end, we applied the displacement downwards, perpendicular to the plane, by 6% of the length of the beam in the form of a ramp.

2.4. Regulations

According to the requirements of the 10th chapter of the National Building Regulations, the seismic effects caused by bending and cutting are determined according to Equations 5 and 6, respectively.

$$M_{pr} = C_{pr} R_y Z_{RBS} F_y \tag{5}$$

$$V_{pr} = \frac{M_{pr}}{1.5 - S_h} \tag{6}$$

In the above relations, R_y is the ratio of the expected yield stress to the minimum yield stress of the beam material, which is equal to 1.20 for the rolled sections of Figure I. C_{pr} was considered equal to 1.1 because the yield stress of beam steel (F_y) and ultimate tensile stress of beam steel (F_u) were equal in this research [7]. Finally, the intensified shear and moment were calculated according to the regulations based on relations 7 and 8, respectively.

$$V_c = V_{pr} \tag{7}$$

$$M_c = M_{pr} + V_{pr}(S_h + \frac{d'}{2}) \tag{8}$$

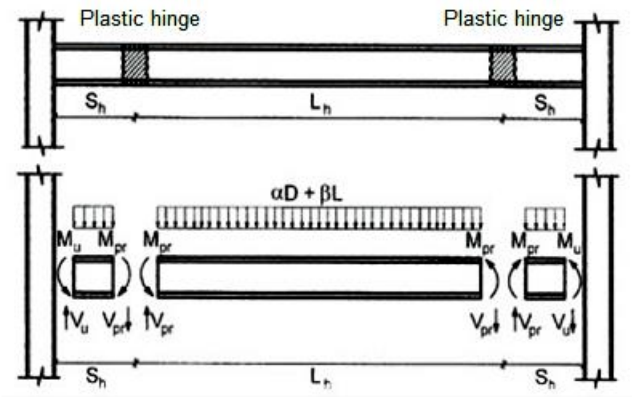

Fig 4. The location of plastic hinges in the side-bearing beam.

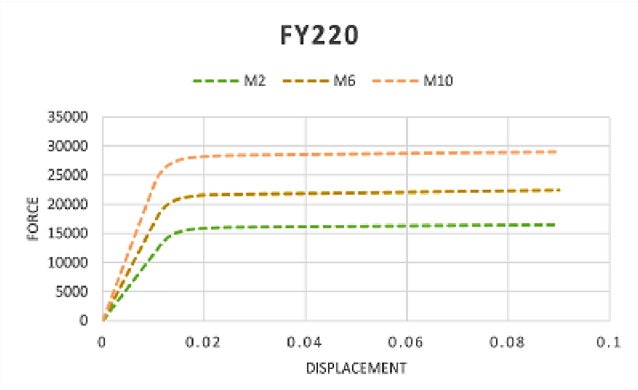

Fig 6. Force-displacement related to M2, M6, M10 models.

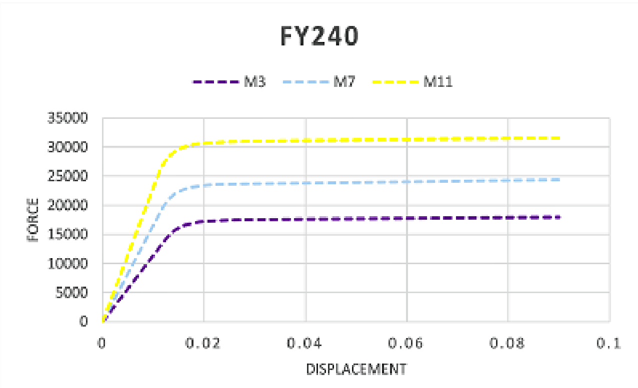

Fig 7. Force-displacement related to M3, M7, M11 models.

3. Results

The force-displacement diagrams obtained from the numerical analyzes for all models can be seen in Figures 5, 6, 7, and 8.

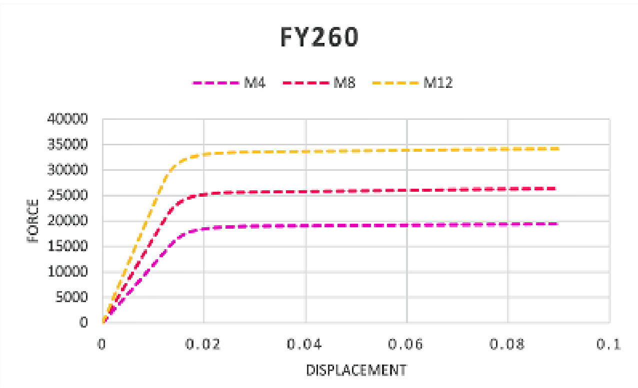

Fig 8. Force-displacement related to M4, M8, M12 models.

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This force was drawn for all the end points of the beam and the displacement of one point in ABAQUS finite element software. On the other hand, to compare the values of intensified shear and moment based on ABAQUS analysis with intensified shear and moment based on the regulations of steel buildings. The maximum moment of the panel zone or intensified moment was obtained based on ABAQUS software according to equation 9.

$$M_{max} = F_{max}(1.5 + \frac{d'}{2}) \quad (9)$$

And the intensified shear equal to the maximum force value was calculated in each model.

$$V_{max} = F_{max} \quad (10)$$

Therefore, the shear and moment parameters were extracted according to ABAQUS software and regulations. In Tables 3 and 4, these parameters are significant.

Table 3. Comparison of the results maximum shear of the regulation and analysis of all models.

Model	Max analytical shear (N)	Max regulation shear (N)
M1	15011	16576
M2	16480	18233
M3	17949	19891
M4	19413	21549
M5	20436	22611
M6	22422	24873
M7	24396	27134
M8	26309	29395
M9	26396	29819
M10	28983	32801
M11	31568	35783
M12	34151	38765

Table 4. Comparison of the results maximum moment of the regulation and analysis of all models.

Model	Max analytical moment (N.m)	Max regulation moment (N.m)
M1	24018	26521
M2	26369	29173
M3	28718	31825
M4	31061	34479
M5	32901	36404
M6	36100	40045
M7	39278	43685
M8	42358	47326
M9	42762	48307
M10	46952	53138
M11	51140	57969
M12	55325	62799

After calculating the moment and shear based on the relations of the regulations and ABAQUS, these parameters were compared and it can be seen that in all models the analytical moment and shear is always less than the moment and shear obtained according to the relations of the regulations. In the following, these parameters were compared in Figures 9 and 10.

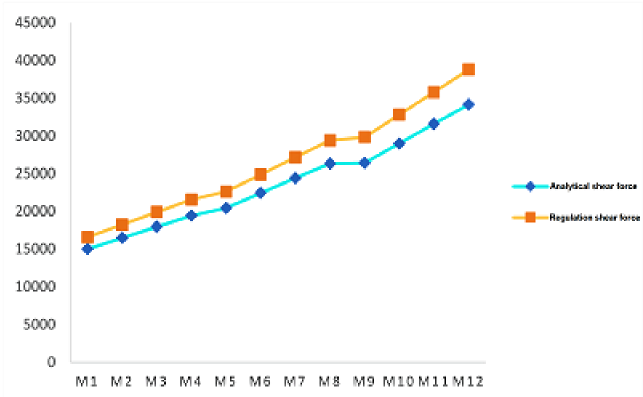

Fig 9. Comparison of analytical and regulation shear force.

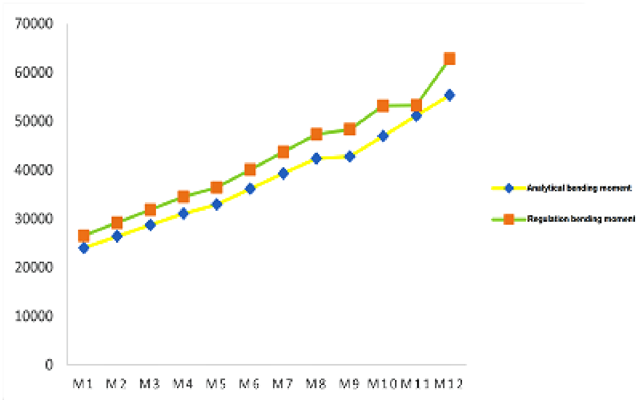

Fig 10. Comparison of analytical and regulation bending moment.

As can be seen in the above figures, in all models, the bending moment and analytical shear force are always lower than the bending moment and shear force obtained according to the regulations. By obtaining the ratio of the regulation shear force to the analytical shear force Also, the ratio of the bending moment of the regulation to the analytical bending moment in MODEL1 and MODEL2 results that V_C/V_M and M_C/M_M are between 10 and 11% higher. This value has increased between 12 and 13 percent in MODEL3. These values are fully listed in Table 5.

Table 5. The ratio of the bending moment of the regulation to the analytical bending moment and the regulation shear force to the analytical shear force.

		V_c/V_M	M_c/M_M
MODEL1	M1	1.104257	1.104214
	M2	1.106371	1.106337
	M3	1.108195	1.10819
	M4	1.110029	1.110042
MODEL2	M5	1.10643	1.106471
	M6	1.109312	1.10928
	M7	1.112232	1.1122
	M8	1.117298	1.117286
MODEL3	M9	1.129679	1.129671
	M10	1.131732	1.131752
	M11	1.133521	1.133535
	M12	1.135106	1.135093

4. Findings

In this research, the effect of materials on intensified shear and moment in the panel zone in IPE steel beams with reduced wings has been investigated in ABAQUS finite element software and compared with intensified shear and moment based on the relationships of the regulations. For this purpose, three IPE beam and column models were designed. The beams were of RBS type and the rules of the 10th topic of the National Building Regulations have been controlled for them. RBS connection is a connection that prevents the transfer of force and moment to the connection by weakening the wing near the connection and causing the plastic hinge to form outside the connection. In practice, in RBS connections, due to the formation of a plastic hinge near the connect, the moment that enters the place is slightly more than the anchor at the place of the plastic hinge, to which the anchor is intensified, and the shear that is transferred to the panel zone of the connection may be greater than the plastic shear of the beam. Even more, we call it intensified cutting. The regulation has proposed relations for calculating the anchor and the intensified shear that is transferred to the RBS connection to the column. In this research, our goal was to see how effective the steel material can be on the anchor and the intensified shear. For this purpose, the steel yield stress (F_y) was changed between 200 and 220 and 240 and 260(Pa) in each model. Pushover analysis was taken up to 6% drift, and as a result, the maximum anchor of the panel zone or intensified anchor based on the outputs obtained from ABAQUS software was equal to the product of the maximum force applied to the connection in the beam arm. The maximum shear of the panel zone or intensified shear was considered equal to the maximum force that was applied to the connection. Finally, the anchor and shear obtained from the analytical results were compared with the anchor and shear of the regulations. The obtained results can be summarized as follows:

• With the increase in the size of the beam and column, the values of anchorage and intensified shear increased.

• In all models, the highest stress occurred in the reduced area of the beam, and as we moved away from the plastic hinge of the beam, the stress decreased.

• Serious damage to the column was prevented due to the presence of connection sheets in front of the beam wing in the column and double sheet in the column core.

• In all models, the anchor and analytical shear were always less than the anchor and shear obtained from the regulations.

• By obtaining the ratio of the regulation shear to the analytical shear and also the ratio of the regulation anchor to the analytical anchor in MODEL1 and MODEL2, it was concluded that VC/VM and MC/MM are between 10 and 11% higher. This value has increased between 12 and 13 percent in MODEL3.

Conflict of interest

There is not conflict of interest.

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