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### Numerical Analysis of Beam-to-Column Connection Behavior with Reduced Beam Section and Bolted End Plate

Payam Tarighi

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Assistant Professor, Department of Civil Engineering, Faculty of Technical and Engineering,  
Ahlul Bayt International University, Tehran, Iran.

\* Corresponding author: [p.tarighi@abu.ac.ir](mailto:p.tarighi@abu.ac.ir)

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#### ABSTRACT

Reduced Beam Section (RBS) connections and Bolted Unstiffened End Plate (BUEEP) connections are two types of connections mentioned in the tenth chapter of the National Building Regulations of Iran, under the pre-qualified moment connections section. In this paper, by proposing a connection that combines these two types, an attempt has been made to reduce the amount of welding and the large number of bolts, and to achieve a connection with a high level of safety and suitable performance. To this end, the performance of the proposed connection has been numerically compared with that of the Reduced Beam Section (RBS) connection. The results of these studies showed that the proposed connection with ST52 steel had lower energy absorption, bearing capacity, and stiffness by 24%, 18%, and 35%, respectively, compared to the welded RBS connection, indicating lower performance. However, considering the favorable performance results of the proposed connection, it can be classified within the group of moment connections.

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## **1. Introduction**

Extensive failures in steel moment-resisting frame buildings during the 1994 Northridge earthquake prompted researchers to revise and propose alternative connections to those used before the Northridge earthquake. Researchers proposed two concepts: strengthening the connection region and/or weakening the connection region. Weakening a specific part of the beam to transform it into a reliable energy dissipation zone during an earthquake was an idea first introduced by Andrea in 1980 [1]. Experiments conducted on RBS moment connections significantly influenced their design after the Northridge earthquake [2-4]. In Reduced Beam Section connections, the yielding zone is moved a short distance away from the column face, thus protecting the connection. Different shapes for the cuts (constant, tapered, and radius) have been proposed to reduce the beam section. Extensive experimental and analytical projects have shown that the radius cut provides the highest rotational ductility at the plastic hinge location. Criteria for the design and detailing of RBS connections are provided in FEMA350 [5] and FEMA351 [6]. Numerous studies have been conducted to investigate the effect of the beam section reduction method for American profiles and their connection types [7-9]. Lignos [10] also provided a good description of the behavior of beams with reduced sections based on information from large-scale tests he conducted. Although beam section reduction methods have been extensively studied in the United States, little information is available on them in Iranian and European codes. Recent experimental research using IPB profiles and welded beam-to-column moment connections emphasizes the re-evaluation of geometric parameters for the design of RBS connections with radius cuts [11, 12]. In this paper, the flexural behavior of RBS connections with bolted end plates under cyclic loading on IPB sections and with common steels in Iran is investigated.

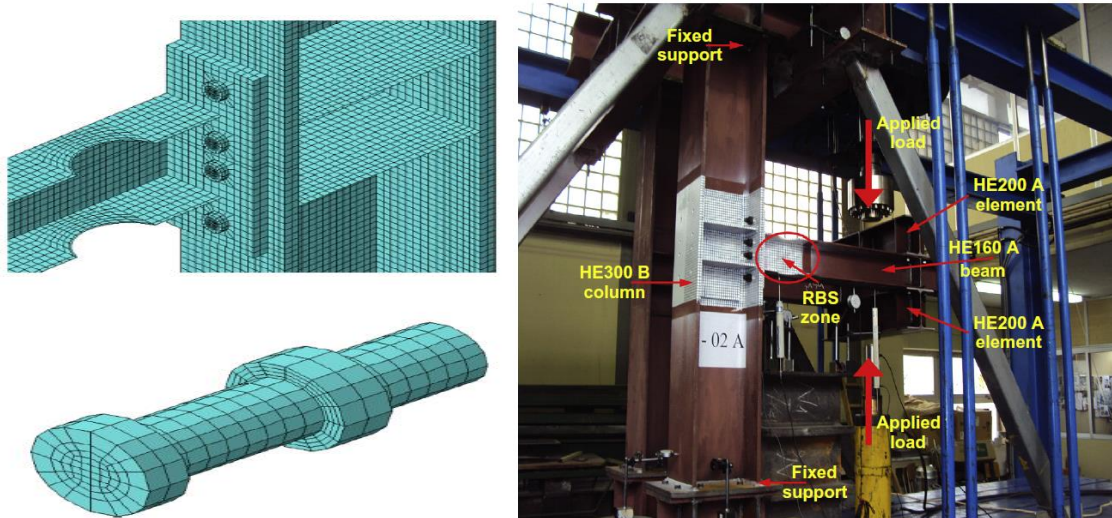
The types of connections proposed in the tenth chapter for beams with reduced sections are classified into two categories. The first category is the connection of the beam flanges and web using complete joint penetration groove welds, which is used for intermediate and special moment frames. The second category is the connection of the beam web to the column flange through a single plate bolted to the beam web, which is proposed for intermediate moment frames.

Considering that RBS connections with beam flange and web connected to the column flange using complete joint penetration groove welds have shown suitable ductile behavior in past studies [11, 12], to avoid welding in the workshop and to ensure higher connection quality, a flange connection can be used. However, due to the large number of bolts in this type of connection, an attempt has been made in this paper to prevent this by proposing the aforementioned connection, and to create a connection with a high level of safety and suitable quality.

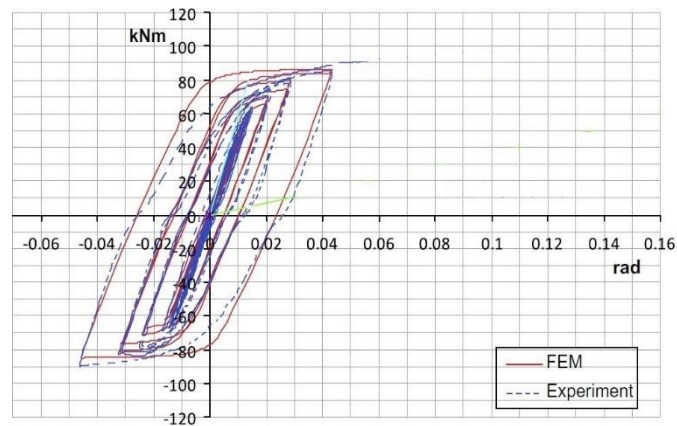
## **2. Validation**

Initially, the numerical modeling is validated against a study conducted experimentally in 2013 by Sofias [13] and colleagues, in which a sample of these connections with two common steel types in Europe was investigated. Figure 1 shows an image of the test setup and the optimal mesh that yielded the closest results to the experimental findings. In this paper, moment-rotation diagrams are presented for distances of 40 and 600 mm from the column face and the center of the

reduced section, under cyclic loading, have been extracted. Figure 2 shows the moment-rotation ( $M-\theta$ ) diagram for the RBSb specimen at a distance of 600 mm from the column face and the diagram obtained from the numerical studies. As observed, the two numerical and experimental models show good agreement.



**Figure 1:** Test setup configuration and optimal mesh dimensions [13]



**Figure 2:** Comparison of laboratory and numerical results

### 3. Specimen Details

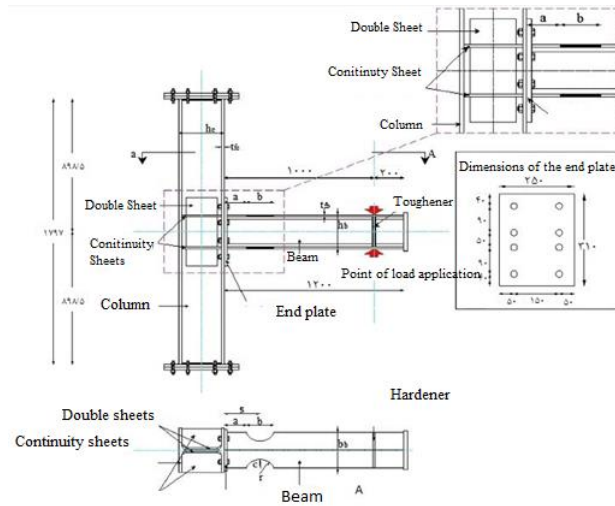
The specifications of the sections used in this study are shown in Table 1, and the parameters of the sections are shown in Table 2. Furthermore, the connection details and specimen configurations are in accordance with Figure 3.

**Table 1:** Beam and Column Specifications

Member	Section Depth	Cross-sectional width	Thicknesses		Abrasion resistance	Cross-sectional area	Weight per unit length	Moment of Inertia	
	d(mm)	b(mm)	$t_w$ (mm)	$t_f$ (mm)	r(mm)	$A$ (cm <sup>2</sup> )	$G$ ( $\frac{Kg}{m}$ )	$I_y$ (mm <sup>4</sup> )	$I_x$ (mm <sup>4</sup> )
IPB160	152	160	6	9	15	388	304	1670	616
IPB 300	300	300	11	19	27	149.1	117	25170	8563

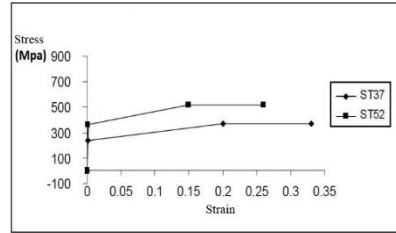
**Table 2:** Parameter Definitions

RBS	Beam with reduced cross-section	$f_y$	Yield Stress
a	The distance from the column to the beginning of the reduced section	$F_u$	Final stress
b	Length of the reduced section	G	Shear Modulus
$b_f$	Wingspan	g	High cutting depth
$d_b$	Beam Depth	s	The distance from the plastic hinge formation location to the column face
E	Elasticity model	v	Poisson's ratio



**Figure 3:** Connection Details and Specimen Dimensions [13]

Also, Figures 2, 3, and 4 show the stress-strain diagrams of the ST37 and ST52 steels used in this study.



**Figure 4:** Stress-Strain Diagrams of ST37 and ST52 Steels

#### 4. Design Procedure for Reduced Beam Section Connections

For the design of RBS connections with a radius cut, sections (1) to (4) of the tenth chapter of the National Building Regulations of Iran have been used [14]:

- (1)  $a = (0.5 - 0.75)b_f$
- (2)  $b = (0.65 - 0.85)d$
- (3)  $c = (0.2 - 0.25)b_f$
- (4)  $b'_f \geq \frac{2}{3} b_f$

where the parameters of relations (1) to (4) are mentioned in Table 3.

**Table 3:** Specifications of Reduced Beam Section Connection

Sample	$b_f$	$d_b$	a		b		c		s	r
	(mm)	(mm)	$\%b_f$ (mm)	(mm)	$\%d_b$ (mm)	(mm)	$\%b_f$ (mm)	(mm)		
1	160	152	60	96	75	114	25	40	153	6061

Also, Table 4 lists the mechanical properties of the materials used in the specimens.

**Table 4:** Mechanical Properties of Materials

Sample	$f_y$ (MPa)	$f_u$ (MPa)	E(MPa)	$\nu$
ST37	240	370	200000	0.3
ST52	360	520	200000	0.3

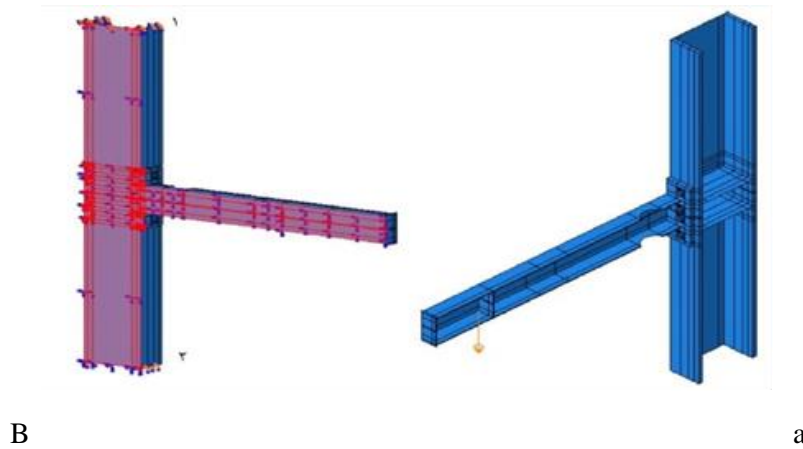
#### 5. Finite Element Modeling

Four models were created in Abaqus software [15]: two specimens with bolted end plates to the column and two other specimens without end plates (welded connection), using ST37 and ST52 steels. This modeling was performed to determine the beam behavior at the center of the RBS

and at a distance of 600 mm from the column face. Table 5 shows the types of elements used in the software. The boundary conditions are shown in Figure 5.

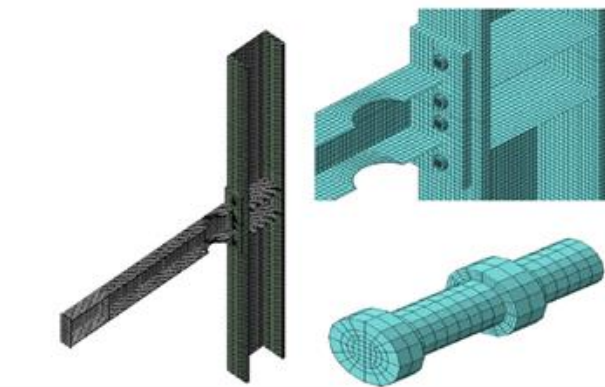
**Table 5:** Element Types Used in Modeling

Element type	Wing Beam	Soul Beam	Wing column	Soul column	End plate	Screw	Beam sheets	Column sheets
C3D8R			*		*	*		*
S4R	*	*		*			*	



**Figure 5:** (a) Boundary conditions on the column supports at points 1 and 2 (b) Loading conditions [13]

Figure 6 also shows the meshing of the elements.



**Figure 6:** Three-dimensional meshing of the bolt and RBS connection [13]

Due to symmetry and to reduce computation time and output data volume, only half of the connection was modeled in the software with the same initial boundary conditions. Loading was applied cyclically to the beam end in the vertical direction based on displacement control. The applied displacement values at the

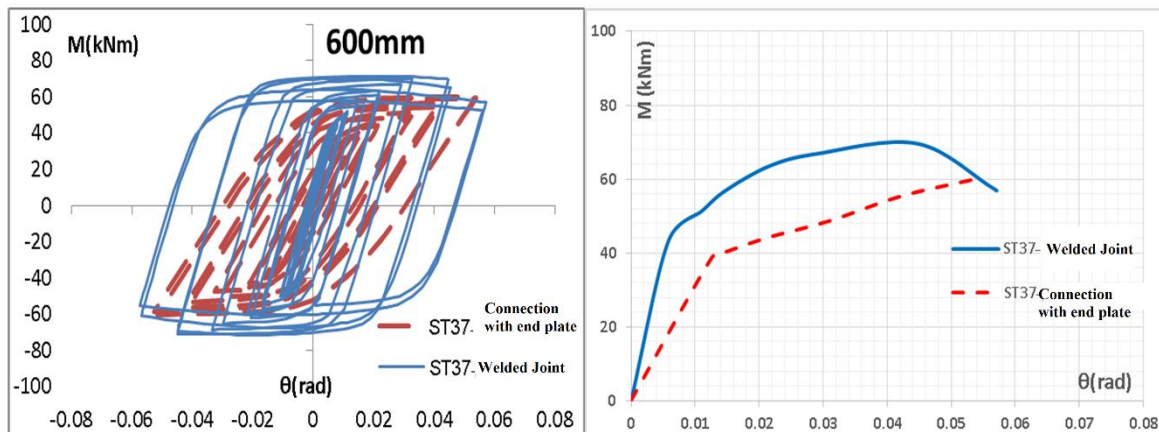
beam end are in accordance with Table 6 and based on the loading protocol of the AISC 2002 code section related to moment frames [16].

**Table 6:** Seismic Loading Protocol Based on AISC 2002 Code for Moment Frames [16]

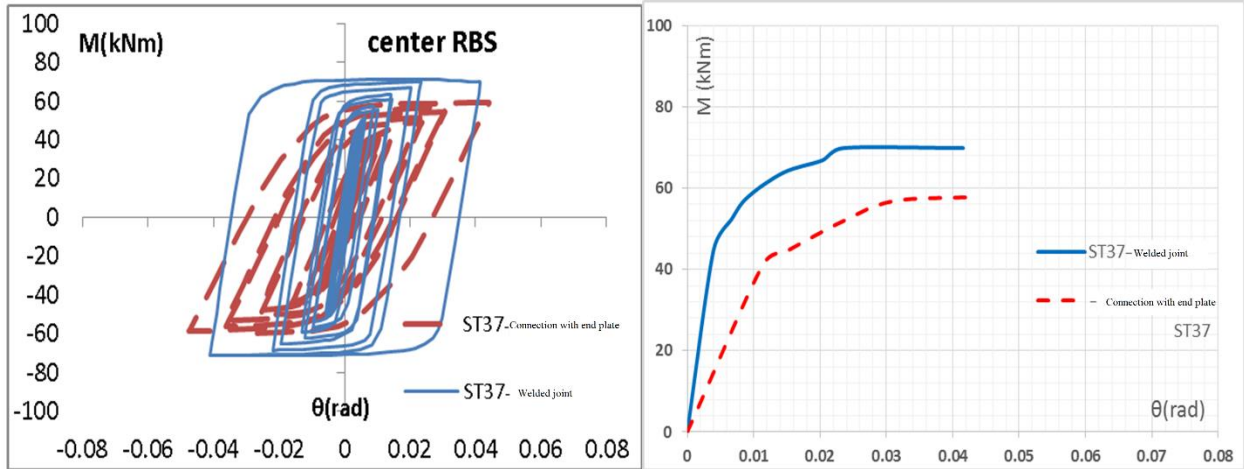
Loading Stage	Maximum displacement, $\delta_y$	Number of load cycles
1	$\pm 0.375$	6
2	$\pm 0.50$	2
3	$\pm 0.75$	2
4	$\pm 1.00$	4
5	$\pm 1.50$	2
6	$\pm 2.00$	2
7	$\pm 3.00$	2
8	$\pm 4.00$	2

## 6. Results and Discussion

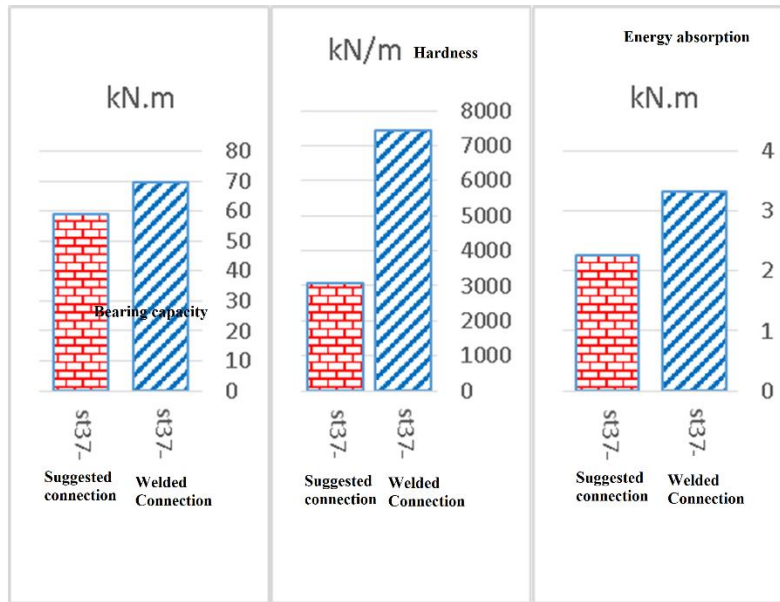
Figures 7 and 8 show the cyclic and pushover moment-rotation diagrams for both the welded connection and the connection with a bolted end plate (proposed connection) with ST37 steel, at two locations: the center of the reduced beam section and at a distance of 600 mm from the column face, to compare their performance. The results obtained from the pushover diagrams, including stiffness, energy absorption, and bearing capacity for the two aforementioned connections, are also shown in Figure 9. These results for ST52 steel are presented in Figures 10 to 12.



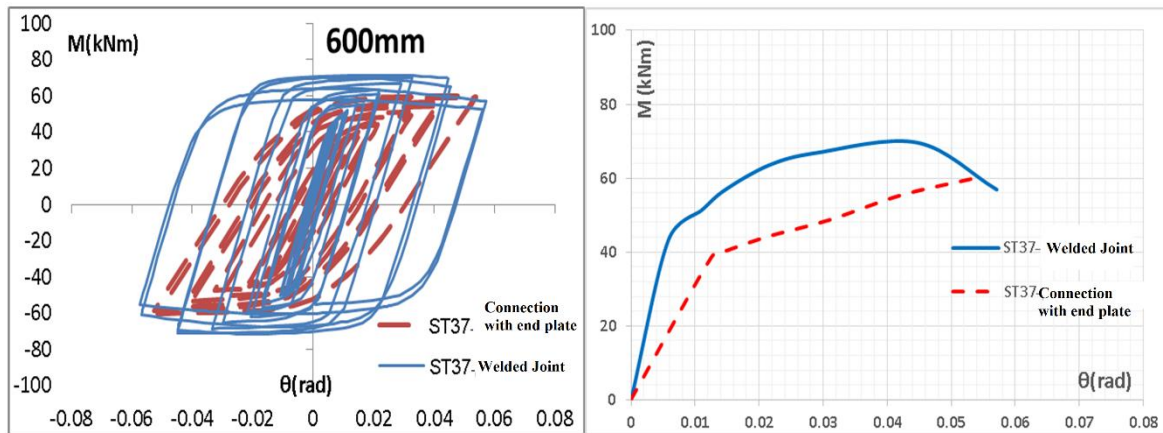
**Figure 7:** Moment-Rotation ( $M-\theta$ ) and Pushover Diagrams at a Distance of 600 mm from the Column Face for Welded Connection and Connection with End Plate Made of ST37 Steel



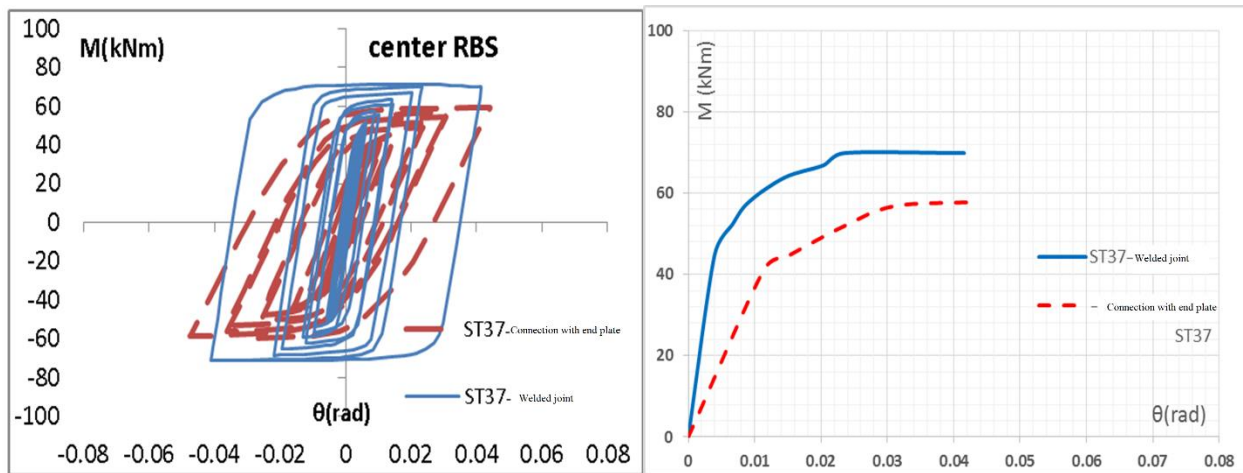
**Figure 8:** Moment-Rotation (M-θ) and Pushover Diagrams at the Center of the RBS for Welded Connection and Connection with End Plate Made of ST37 Steel



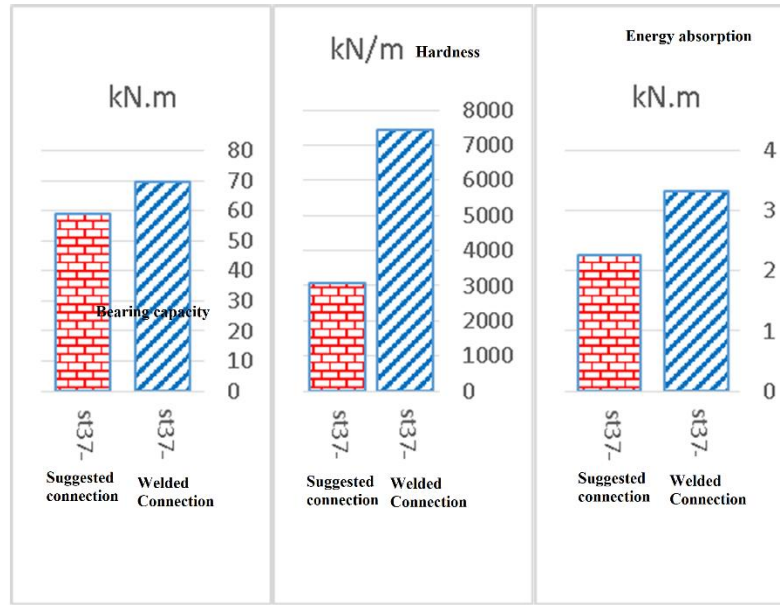
**Figure 9:** Bearing Capacity, Stiffness, and Energy Absorption of Welded Connection and Proposed Connection (ST37)



**Figure 10:** Moment-Rotation ( $M-\theta$ ) and Pushover Diagrams at a Distance of 600 mm from the Column Face for Welded Connection and Connection with End Plate Made of ST52 Steel



**Figure 11:** Moment-Rotation ( $M-\theta$ ) Diagram at the Center of the RBS for Welded Connection and Connection with End Plate Made of ST52 Steel

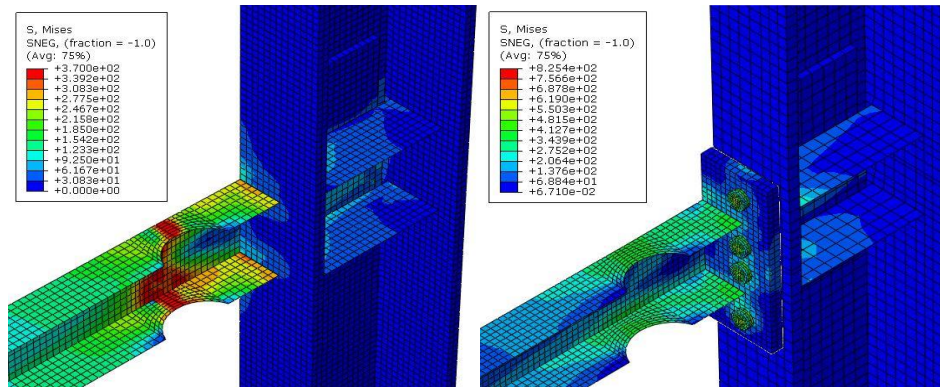


**Figure 12 :** Bearing Capacity, Stiffness, and Energy Absorption of Welded Connection and Proposed Connection (ST52)

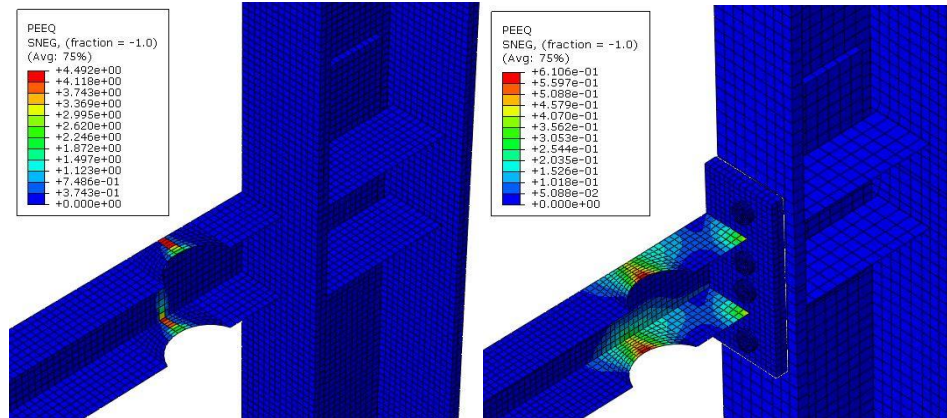
As can be seen in Figures 7 to 9, the conventional welded RBS connection with ST37 steel has 32%, 15%, and 58% higher energy absorption, bearing capacity, and stiffness, respectively, compared to the proposed connection. This comparison for the two connections with ST52 steel shows that the welded RBS connection has 24%, 18%, and 35% higher energy absorption, bearing capacity, and stiffness, respectively, compared to the proposed connection. The results indicate that the proposed connection has a lower performance level than the welded RBS connection. Using higher strength steel results in this reduction having less impact on the connection's performance. Consequently, it is recommended to use ST52 steel in the design of this connection.

Figures 13 and 14 show the Von Mises stress and equivalent plastic strain distribution for the proposed connection and the welded beam-to-column connection for ST37 steel.

As shown in Figure 14, the plastic strain in the reduced section region is higher in both connections compared to other points. However, in the proposed connection, there is some plastic strain in the beam-to-end-plate connection region, whereas no strain is observed in the connection region of the welded connection.

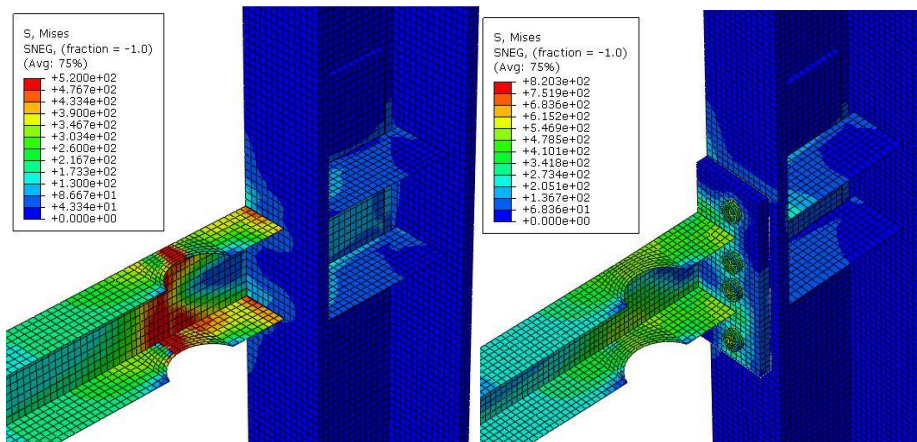


**Figure 13:** Von Mises Stress Distribution (a) Welded Connection (b) Proposed Connection for ST37 Steel

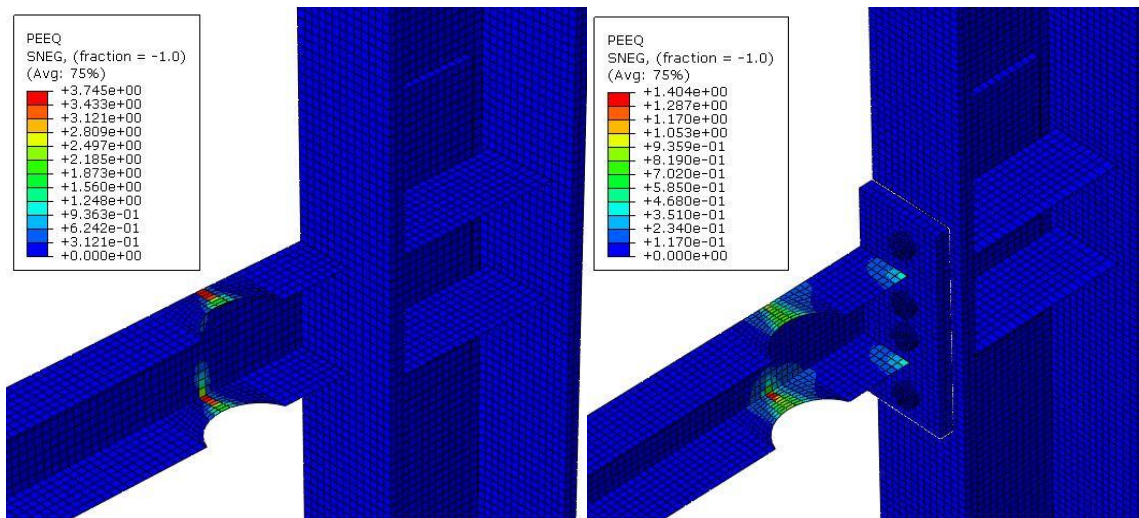


**Figure 14:** Equivalent Plastic Strain Distribution (a) Welded Connection (b) Proposed Connection for ST37 Steel

Figures 15 and 16 also show the Von Mises stress and plastic strain distribution for the proposed connection and the welded beam-to-column connection for ST52 steel. As observed, in both connections, the maximum stress occurs in the reduced section region, causing the formation of a plastic hinge in this area. Also, the equivalent plastic strain for both connections shows that the amount of equivalent plastic strain in the welded beam-to-column connection is greater than that in the proposed connection. This can also be observed in the moment-rotation ( $M-\theta$ ) diagrams plotted for the connections.



**Figure 15:** Von Mises Stress Distribution (a) Welded Connection (b) Proposed Connection for ST52 Steel



**Figure 16:** Equivalent Plastic Strain Distribution (a) Welded Connection (b) Proposed Connection for ST52 Steel

## 7. Conclusion

In this paper, an attempt has been made to minimize welding in the workshop environment by using a connection with an end plate bolted to the column, and to achieve a connection with a high level of safety and suitable quality. A comparison was also made between this connection and a welded beam-to-column connection. The results of the studies showed that both connections exhibited acceptable rotation capacity, and the plastic hinge formed precisely in the reduced section region. Furthermore, the results indicated that the conventional welded RBS connection with ST37 steel had 32%, 15%, and 58% higher energy absorption, bearing capacity, and stiffness, respectively, compared to the proposed connection. This comparison for the two connections with ST52 steel showed that the welded RBS connection had 24%, 18%, and 35% higher energy absorption, bearing capacity, and stiffness, respectively, compared to the proposed connection.

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