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Numerical Investigation of the Beam Web Weakening Pattern Impact On the Seismic Behavior of the Steel Beam-Column Connection

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ABSTRACT

Due to the damage that occurred in the unreinforced welded flange (WUF) connections during the 1994 Northridge earthquake, the use of reduced beam section (RBS) connections and subsequently the reduced web section (RWS) connections became common to prevent premature brittle failure in the welded connections. The RWS connections are created to provide a controlled weak point for the formation of a plastic hinge, which can prevent stress concentrations in the groove welds of the connection. This method, where the transfer of the plastic hinge is achieved by weakening the beam web and without the need to remove the concrete slab, is proposed as a suitable solution for the rehabilitation of connections. In this paper, the effect of different beam web weakening patterns on the seismic performance of the connection is investigated analytically and numerically. Seven beam web weakening designs were studied and compared with the uniform web slotting pattern, and the seismic behavior of the mentioned connections was simulated using the Abaqus software, and the effect of using each of them on the distribution of equivalent plastic strains and the moment-rotation curve was examined. The results showed that the appropriate beam web weakening pattern plays an effective role in reducing the plastic strain in the penetration weld of the direct beam-to-column connection and preventing their premature tearing and failure, so that one of the perforation designs studied can reduce the maximum equivalent plastic strain in the upper penetration weld of the direct beam-to-column connection by an average of 48% compared to the uniform web slotting pattern as the reference connection.

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1. Introduction

The Northridge earthquake that occurred on January 17, 1994, in California, led to brittle and premature failures and lack of ductility in the welded unreinforced flange (WUF) beam-to-column connections, as shown in Figure 1. The most common damage originated from fractures in the complete joint penetration (CJP) weld of the beam flange to the column or in the vicinity of the connection. Consequently, after the Northridge earthquake, research progressed towards increasing the ductility of rigid connections, and the post-Northridge connections were developed. In these connections, the main objective is to transfer the plastic hinge into the beam and at a certain distance from the column face, as this transfer of the plastic hinge from the column face reduces the concentration of

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strain in the weld region, thereby reducing the degree of weld cracking and brittle failure in the connection.

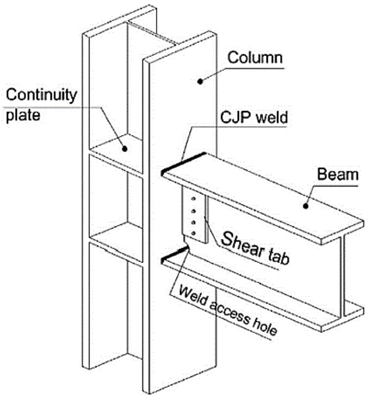


Figure 1. Example of conventional connection in Northrich [1]

Various methods have been proposed for the transfer of the plastic hinge, which are generally classified into two main categories: connection reinforcement and beam weakening. In the connection reinforcement method, with the aim of preventing premature failures, by adding components to the existing connection, a stronger connection than the beam is created, and the plastic hinge is formed in the beam and away from the column face, preventing the beam rotation relative to the column to reduce the stress in the weld region. Examples of this category include the use of local flange reinforcement, reinforcing the connection joint by adding components such as various stiffeners [2-7]. The use of the connection reinforcement method can significantly reduce the stress in the connection and is an effective rehabilitation technique for increasing the ductility of rigid connections. However, despite the mentioned advantage, it often requires costly and difficult welding operations.

The second category is the reduced beam section (RBS) method, where the beam section is weakened at a specific and predetermined location with the aim of forming a plastic hinge in that region, to reduce the stress levels in the vicinity of the beam flange-to-column groove welds. This method has been able to address the deficiencies of the pre-Northridge connections to a considerable extent. Given that this method can reduce the stress demand in the areas near the weld and connection components, including the connection source, weld, bolts, and so on, it has received much attention and research, and various methods have been proposed for its implementation, mainly through the creation of different shapes of cuts, slots, and holes in the beam flange at a suitable distance from the column face or the use of various replaceable reduced sections [7-19].

Another method of beam weakening to improve the performance of steel connections is the heat-treated beam section (HBS) method, which was recently proposed by Morrison et al. in 2015. This method involves the application of a specific heat treatment process to a defined range of the beam flanges using specialized pads. This heat treatment process reduces the yield strength of the steel and, consequently, the strength in the heat-affected zone, leading to the transfer of the plastic hinge onto the beam [20-23]. Another method for creating a reduced beam section is the slotted-flange (DF) connection, where a series of holes are created on the beam flanges instead of cutting the flanges, creating a controlled weak zone for the formation of the plastic hinge to reduce the stress concentration in the beam flange-to-column welds [24-28].

Since the flanges are the main components of the beam for resisting bending, some researchers have proposed the reduced web section (RWS) method, which is generally achieved through web cutting and creating holes in the web with different geometric shapes, such as circular, elliptical, semi-circular, or rectangular [29-36], replacing the flat web with different sections such as accordion-like or tubular [37-39], or using replaceable reduced sections [40-42], as an alternative approach to reducing the beam section. The use of RWS connections has recently gained particular attention, especially for steel moment frames in existing buildings, as the reduction of the beam section through flange cutting is accompanied by the difficulty of cutting the upper part of the beam flange due to its location in the floor slab. Therefore, in this aspect, RWS connections are more practical when used as a rehabilitation technique [41-42].

In the present study, with the aim of investigating the cyclic behavior and performance of other RWS connection designs, after the validation of the finite element model, seven non-uniform beam web weakening patterns are proposed and compared against the uniform vertical slotting pattern (RWS-1) to evaluate their influence on the cyclic behavior of the beam-to-column connection through analytical and finite element modeling.

2. Beam Web Weakening Patterns Investigated

Figure 2 shows the details of the non-uniform RWS-2 to RWS-8 beam web weakening patterns studied to evaluate their impact on the seismic behavior and performance of the beam-to-column connection compared to the uniform web slotting pattern (RWS-1). All these designs result in an equal reduction of the beam cross-section area by 7189 mm².

3. Finite Element Model Validation and Modeling

3.1. Finite Element Modeling of the Connection

To evaluate the impact of the different web reduction patterns on the seismic performance of the connection, the

Abaqus software was used for the three-dimensional modeling and nonlinear analysis of the direct beam-to-column connection with complete joint penetration (CJP) welds. The beam section was taken as 270 IPE with a free span of 1500 mm, and the column section was IPB200 with a free span of 1500 mm. To obtain accurate stress and strain conditions close to the actual conditions, the finite element model components, including the column, beam, doubler plate, and continuity plates, were modeled using shell elements, which have the capability to consider large deformations, nonlinear behavior, and the simulation of buckling and its effects on the reduction of the analytical model's strength. Additionally, the "NLGEOM" option was activated to consider the geometric nonlinearity effects. Rigid shell elements were also used to model the support plates at the two ends of the column and the beam. The steel material was ST37 with the nominal mechanical properties listed in Table 1, with a nonlinear behavior using a combined hardening model that can consider both isotropic and kinematic hardening behavior of the steel.

The loading was applied according to Figure 3, based on the displacement history protocol following the SAC loading protocol [43, 44], through the gradual application of a series of cyclic pseudo-static incremental displacements at the beam tip. To simulate the boundary conditions in the finite element model, including the supports and load application points, a reference point (RP) was first defined on the rigid end plates of the column and beam, and then the corresponding boundary conditions were assigned to this point, as shown in Figure 3.

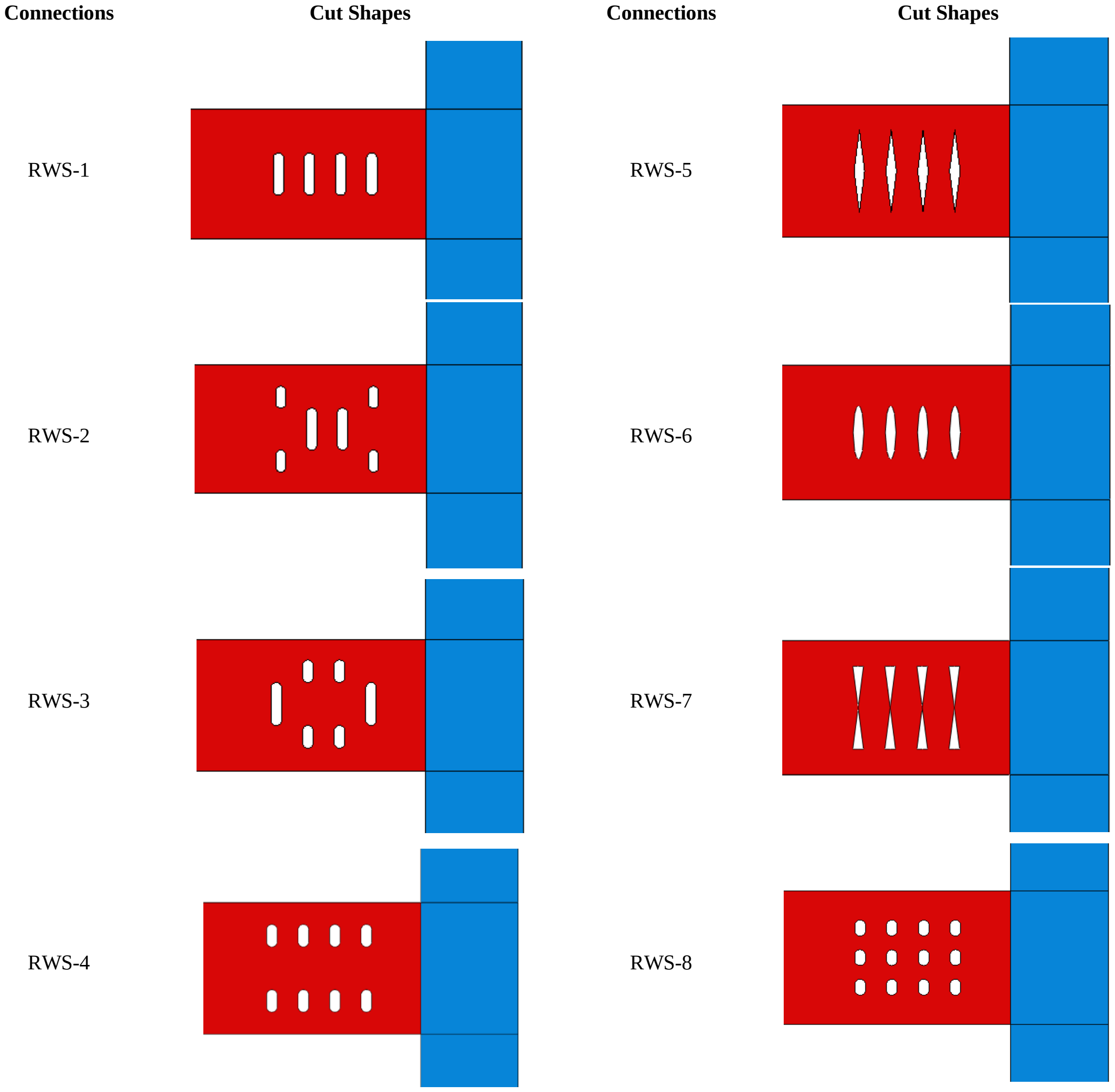


Figure 2. Details of the different web reduction patterns

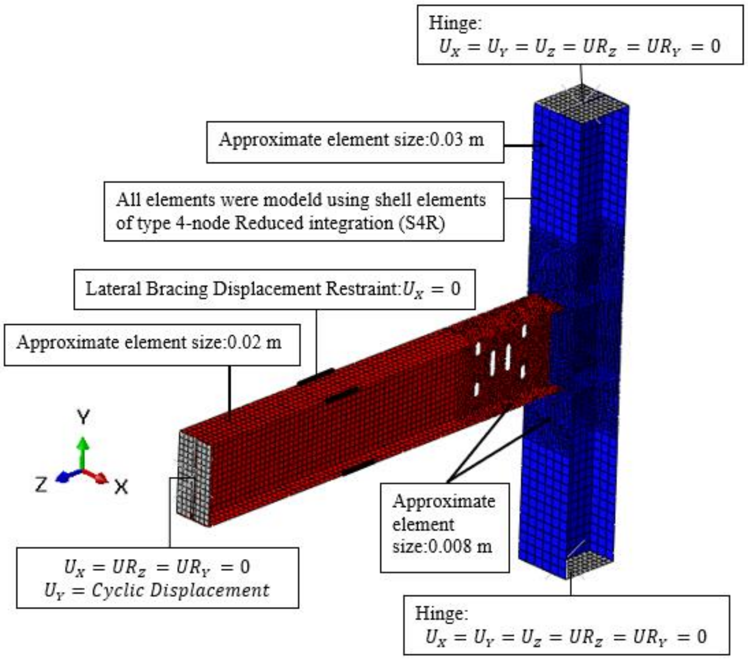


Figure3. 3D FE model for Specimen B3

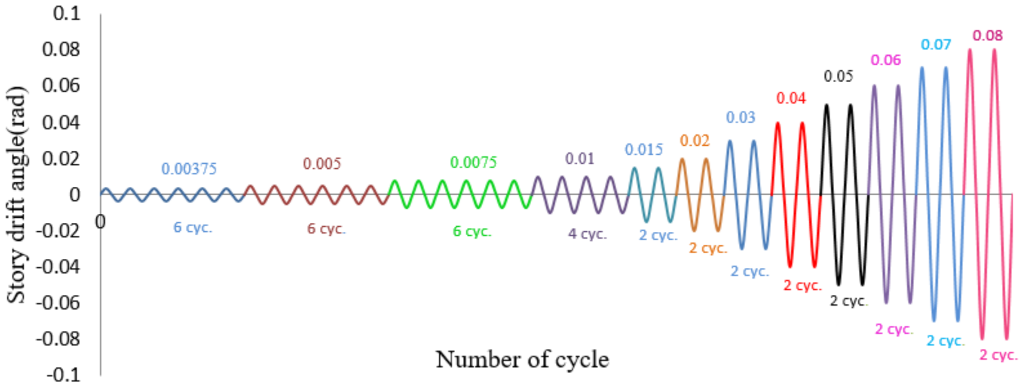


Figure 4. Loading protocol based on FEMA 351 [43, 44]

Additionally, lateral bracing of the beam was modeled to prevent out-of-plane buckling. The meshing of each connection component was performed separately using S4R elements, and a finer mesh was used in the vicinity of the connection, the connection joint, and the web weakened region to provide a more accurate representation of the buckling behavior and the high stress and strain rates in these critical areas. Figure 3 shows a three-dimensional view of the finite element model and the meshing details and boundary conditions for the RWS-1 connection. It should be noted that in this study, the modeling and the influence of factors such as the concrete slabs were neglected, and only the modeling of the steel beam-to-column connection was performed, assuming high-quality complete joint penetration (CJP) welding of the beam to the column, and the weld modeling was not considered, and the beam-to-column connection was modeled directly.

Table2.
Mechanical Properties of Structural Steel – St37[45]

$\sigma_y^{nominal}$	$\sigma_u^{nominal}$	Elongation(%)	E	υ
240 Mpa	360 Mpa	30.8	210 Gpa	0.03

3.2. Model Validation

The overall validity of the finite element modeling approach in Abaqus and the accuracy of the numerical analysis results in predicting the seismic behavior, strength degradation, and stiffness reduction due to the formation of the plastic hinge and the buckling of the connection components are evaluated by comparing the numerical analysis results of the experimental specimen DB700-SW, whose seismic behavior under the SAC loading protocol was investigated in the studies by Lee et al. [46, 47]. Figure 5 shows the geometric details, and Table 2 presents the material properties used for the construction of the aforementioned model.

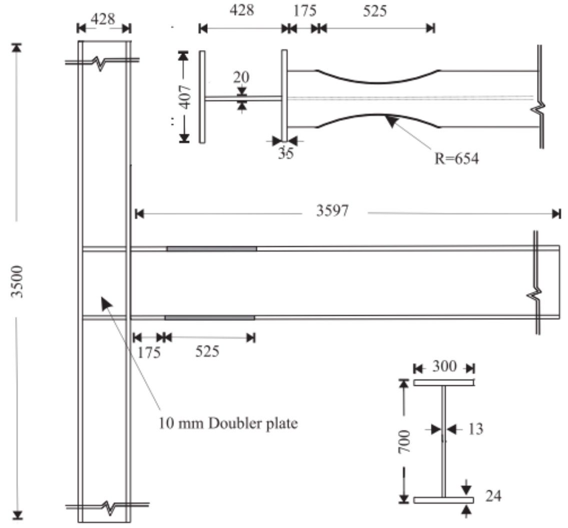


Figure 5. Specimen DB700-SW tested by lee et al(units in mm) [46,47]

Table 2.
Physical properties of the DB700-SW connection materials [47]

Member	Coupon	σ_y	σ_u
Beam (SS400)	Flange	304 Mpa	455 Mpa
	Web	364 Mpa	480 Mpa
Column(SM490)	Flange	343 Mpa	512 Mpa
	Web	358 Mpa	520 Mpa

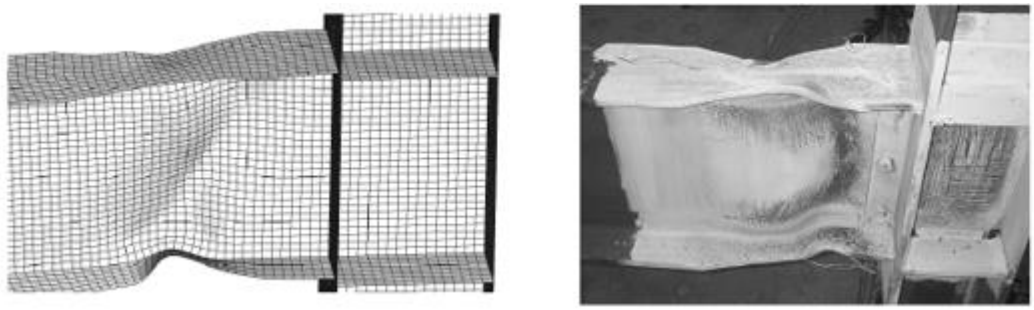
3.3. Validation Model Analysis Results

After the finite element analysis under cyclic loading, the accuracy of the results is compared with the experimental and numerical results of the DB700-SW connection. As shown in Figure 6, the cyclic response, Bauschinger effect, strain hardening, and strength degradation due to local and torsional buckling obtained from the finite element model of the DB700-SW specimen in the present study show acceptable agreement with the seismic response and deformation of the experimental and finite element reference specimen [44].

4. Finite Element Analysis Results

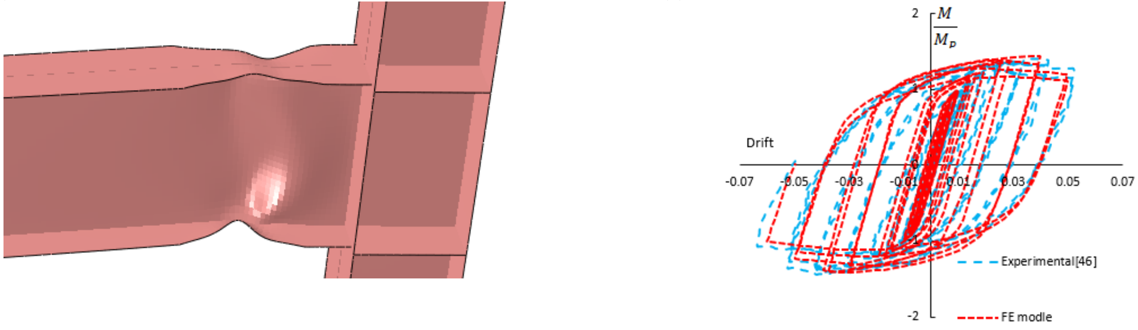
4.1. Moment-Rotation and Hysteresis Curves

Accepting the von Mises criterion as the basis for evaluating the performance and ultimate failure of the steel, to assess the impact of the different web cutting patterns on the seismic behavior of the connection, the normalized moment-rotation hysteresis curves of the studied connections are compared in Figure 7 up to the end of the loading (6% rotation). The total beam rotation is calculated by dividing the tip displacement at the load application point by the distance to the column center (1600 mm).



(a) FE[46]

(b) DB700-SW at 6% drift [46]



(c) Local buckling of the beam at 6% drift

(d) hysteresis response

Figure 6. Comparison of the FE model and test results of specimen DB700-SW tested by lee et al[46].

As observed, although all models exhibit suitable hysteretic behavior, some of these curves are significantly influenced by the beam web weakening patterns. The hysteresis curves show that the connection strength in all models decreases due to the local buckling of the beam. However, this strength reduction is not significant, as the connection strength in all models is still greater than 80% of the beam plastic moment at 4% rotation.

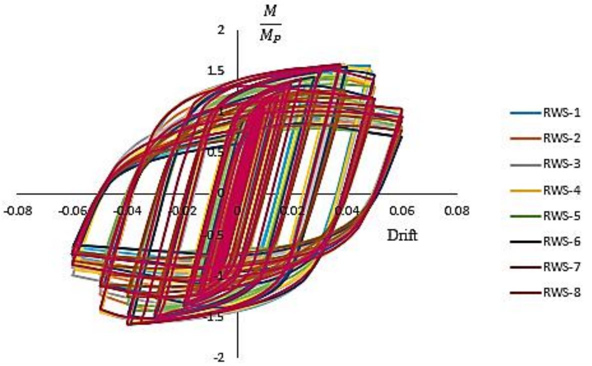


Figure 7. Cyclic moment-rotation curves of the specimens

4.2. Investigation of the Equivalent Plastic Strain Distribution

In the seismic analysis of connections, parameters should be used to identify the potential failure or crack initiation locations. One of the damage indicators used to evaluate the potential for failure and fracture in fillet welds and steel elements is the equivalent plastic strain (PEEQ), which is defined as:

$$PEEQ = \sqrt{\frac{2\epsilon_{ij}^{pl}\epsilon_{ij}^{pl}}{3}} \qquad (1)$$

where ϵ_{ij}^{pl} are the plastic strain components in the i and j directions.

This indicator of energy dissipation during cyclic loading and as a measure of the extent of residual strains in the materials and locations in the connection that are susceptible to tearing and fracture is considered, and it directly represents the degree of progression and expansion of plastic deformations in the connection during cyclic loading. Therefore, in the evaluation and comparison of the changes in plastic strain in different regions of the connection, particularly in the vicinity of the complete joint penetration (CJP) weld to the column, considering the different beam web weakening patterns can also be useful.

In Figures 8 and 9, the distribution of the equivalent plastic strain (PEEQ) for two critical and determinant parts of the connection behavior, namely the fillet welds connecting the beam flanges to the column flanges and the weakened region of the studied connections, were investigated at the end of the loading cycle corresponding to 6% rotation. The selection criteria for the mentioned sections are based on the failure location in the Northridge earthquake connections and the evaluation of the ability of each weakening pattern to transfer and reduce the strain from the column surface to the weakened region.

The results shown in Figure 8 indicate that in terms of reducing the plastic strains in the fillet welds and the potential for connection failure, the weakening pattern (RWS-7) can reduce the equivalent plastic strain in the CJP weld of the direct beam-to-column connection by an average of 48% compared to the uniform web slotting pattern (RWS-1) as the reference connection. In contrast, the (RWS-2) pattern has resulted in an average 42% increase in the equivalent plastic strain in the CJP weld compared to the (RWS-1) connection. The asymmetry of the PEEQ values at the two ends of the weld line in the (RWS-2) connection is also due to the significant increase in beam buckling compared to the other patterns studied. Therefore, the appropriate performance of this type of connection can be expected by selecting a suitable beam web weakening pattern.

Figure 9 also shows that, in terms of the ability of each weakening pattern to transfer and reduce the strain from the column surface to the weakened region, the (RWS-3) pattern has the best performance among the studied patterns in concentrating the plastic strains in the weakened region.

5. Conclusion

Due to the inaccessibility of the top beam flange, which is usually embedded in the concrete slab, and the high cost of slab demolition to cut the top flange, one of the methods for the rehabilitation of existing moment-resisting frame connections is the use of beam web weakening. This research describes the numerical investigation of the cyclic performance of steel beam-to-column connections rehabilitated by the web section reduction method with different patterns. To provide a preliminary evaluation of the behavior of the mentioned connections, seven new web section reduction patterns were considered for finite element modeling in Abaqus, and the effect of their implementation on the changes in the equivalent plastic strain, moment-rotation curves, and the potential for failure were investigated, disregarding the influence of factors such as the presence of concrete slabs. A summary of the results of this study is as follows:

1. The research results showed that the creation of beam web weakening with a suitable pattern can shift the strain concentration region from the CJP weld near the column to the weakened region.

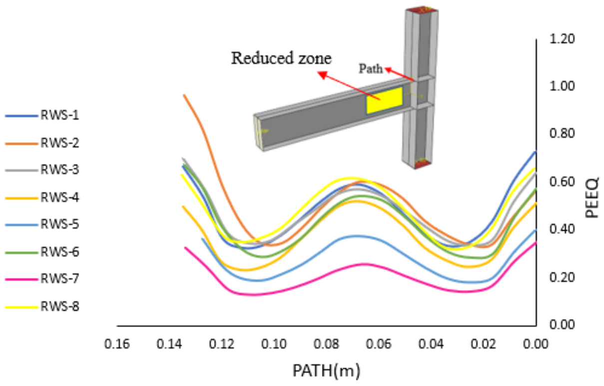


Figure 8. PEEQ strain changes at the end of the loading cycle corresponding to 6% rotation above the weld line

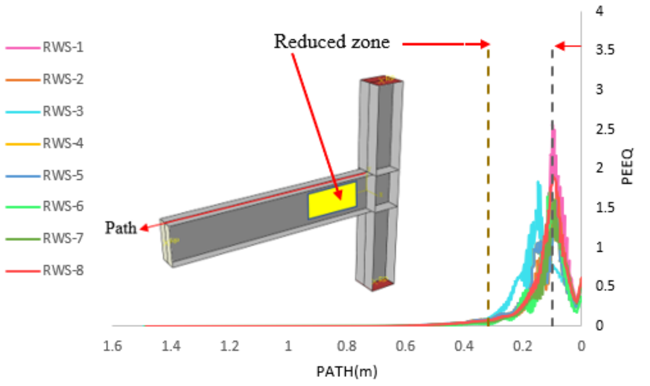


Figure 9. PEEQ strain changes at the end of the loading cycle corresponding to 6% rotation along the central axis of the beam wing

2. The investigations showed that the connection with the web weakened in a suitable pattern can reduce the equivalent plastic strain in the beam-to-column CJP weld by 48% compared to the reference analytical specimen.

Despite the above results, it should be noted that further research and studies are necessary to identify the behavior of the mentioned connections.

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