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FINITE ELEMENT ANALYSIS OF THE EFFECT OF WEB PANEL-ZONE STIFFENERS ARRANGMENT ON CONNECTION BEHAVIOR

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ABSTRACT: In this paper, the effect of different arrangements of stiffeners for connecting two beams with different heights to a column is studied under cyclic loading. This load applies to the top of the column. The connection of the beams to the column is considered to be rigid, so that the moment in the beam creates a shear and bending effect in the connection web panel-zone. The support condition in modeling is such that horizontal and vertical movement is prevented at the bottom of the column, in other words, its support is hinge. After modeling half of the structure in ABAQUS software, the sample is verification. Samples with different arrangements of stiffeners are then analyzed and hysteresis loops representing the system's behavior against cyclic loads are drawn. From these rings, the state of resistance and stiffness of the system in each loading period can be observed. Any general or local instability in the members of the system manifests itself in can be observed at any time of loading and hysteresis loops, if any. In the end, it was concluded which kind of arrangement makes the transfer of stress, as well as the effect of the arrangement on the rate of increase stress concentration and the ability to withstand the amount of force.

KEYWORDS: ABAQUS; Bridges; Hysteresis; Rigid connection; Web panel-zone.

1 INTRODUCTION

In buildings and bridges, connections play a crucial role in maintaining structural integrity. In fact, the primary function of connections is to properly transfer forces between structural members based on the desired performance. In the Northridge earthquake, significant damage was inflicted on the beams and columns of moment frames. Before this earthquake, it was believed that rigid and semi-rigid connections with full penetration welds could withstand significant plastic deformation. However, cracks and failures in the connections indicated that the actual ductility in these connections was less than what was specified in the design codes. Therefore, extensive tests and research have been conducted on various types of connections, especially rigid connections.

Ali Reza Moradi Grousi and colleagues [1] conducted experiments on reduced section beam rigid connections. They demonstrated that the reduced section connection minimizes the damage to the panel zone. However, after a moderate-intensity earthquake, due to extensive damage, the entire beam would need to be replaced, which is practically impossible. Zhaofeng and James [2] conducted experiments on reduced section beam rigid connections to deep columns. The experiment on reduced section beam connections with stiffeners was also carried out by Roodsari and colleagues [3]. They also performed a numerical analysis of this connection.

Montouri and Sagarsi [4] used steel strips to increase the ductility of timber beams. Lee and colleagues [5] investigated the effect of connection stiffness on the seismic performance of moment frames. They tested eight reduced-section beam connections and considered connection stiffness as a key variable. They also explained the reasons for the failure of the samples. Jahanbakhshi and colleagues [6] conducted experiments on the connection flange in box columns. They tested three real-scale specimens made of I-shaped beams and box columns.

Several European research centers focused on the characteristics of welded connections and the expansion of the panel zone analysis range (web panel zone) by modeling the effects of loads as the effect of forces from beams connected to the connection flange. A study by Zutomjarr [7] was conducted to investigate the relevant stress effects in the connection flange area of the column web. Jardao and colleagues [8] studied the performance of unequal-height beam connections for high-strength steel without using column stiffeners. Based on this study, the stresses due to compression, tension, and shear in the web panel-zone area were combined.

Hashemi and Jazani [9] investigated the details of unequal height beam connections under seismic loads. According to one of their conclusions, it is necessary to use high-strength stiffening plates in the column web and the upper and lower flange of the beam connected to the column in a sloping manner relative to the horizon. The behavior of the connection moment-rotation diagram depends on a large number of parameters, including materials, geometry, and loading conditions. Using stiffeners can reduce the impact of tensile, compressive, and shear forces present in the connection web panel-zone. The moment-rotation diagram should be used to model the behavior characteristics of the connection. Relevant mathematical relationships for the structural model of the connection web panel zone are used for resistance and deformation variables.

In this article, the specifications of the samples are first introduced. Then, the loading methods and different arrangements of the connection web panel-zone stiffeners are described. Subsequently, the accuracy of the modeled sample in the software is validated using the laboratory test results. Finally, different samples are subjected to loading and are investigated for the analysis results.

2 SAMPLE SPECIFICATIONS

In this article, the effect of different arrangements of connection web panel-zone stiffeners is studied under cyclic loading. For this purpose, half of the structure span is modeled in the Abaqus software. The boundary conditions in the modeling are such that lateral and vertical movements are prevented at the bottom of the column, and in other words, its support is a pin joint. In order to investigate the behavior of the connection web panel zone and the absence of stress concentration in a specific part of the structure, cyclic loading is applied to the top of the column. The connection of the beams to the column is considered to be rigid, so the moment in the beam introduces shear and bending effects into the connection web panel zone. It should be noted that the purpose of this research is to compare the effect of different arrangements of stiffeners at the location of the connection web panel zone on the column web. Therefore, besides the changes in the arrangement of these stiffeners, the other modeling parameters need to be consistent. For this reason, the dimensions of the beams and columns studied in all samples are assumed to be the same. Table (1) and Figure (1) provide a representation of the dimensions of the fixed sections of the model.

Table 1. Dimensions and specifications of the model members

Element	Web		Flange		Length (cm)
	Thickness	Width	Thickness	Width	
Column C1	1	36	2	20	310
Beam B1	1	36	2	20	180
Beam B2	1	56	2	40	180

The stiffeners in the connection web panel zone cause a change in stress distribution in the connection and significantly influence the behavior of the structure. To compare the effect of the arrangement of stiffeners, four different layouts are used in this study. It is worth mentioning that different arrangements of stiffeners in the connection flange are denoted by "st" and indicated by numbers 1 to 4. Figure (2) illustrates the layout and location of the stiffeners.

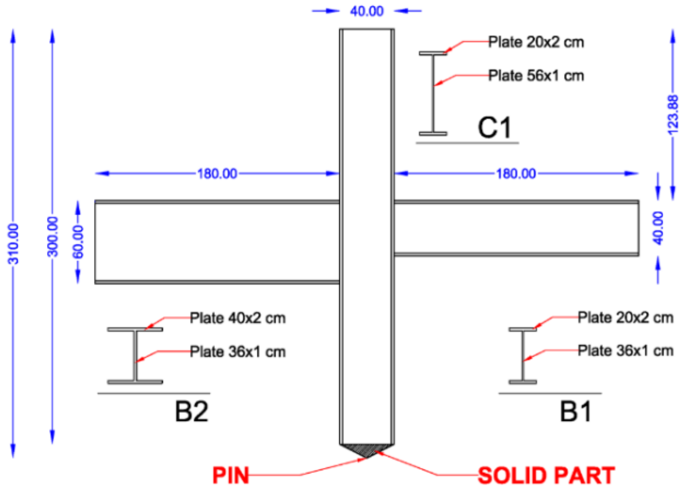

Figure 1. Overall dimensions of the modelled beam and column

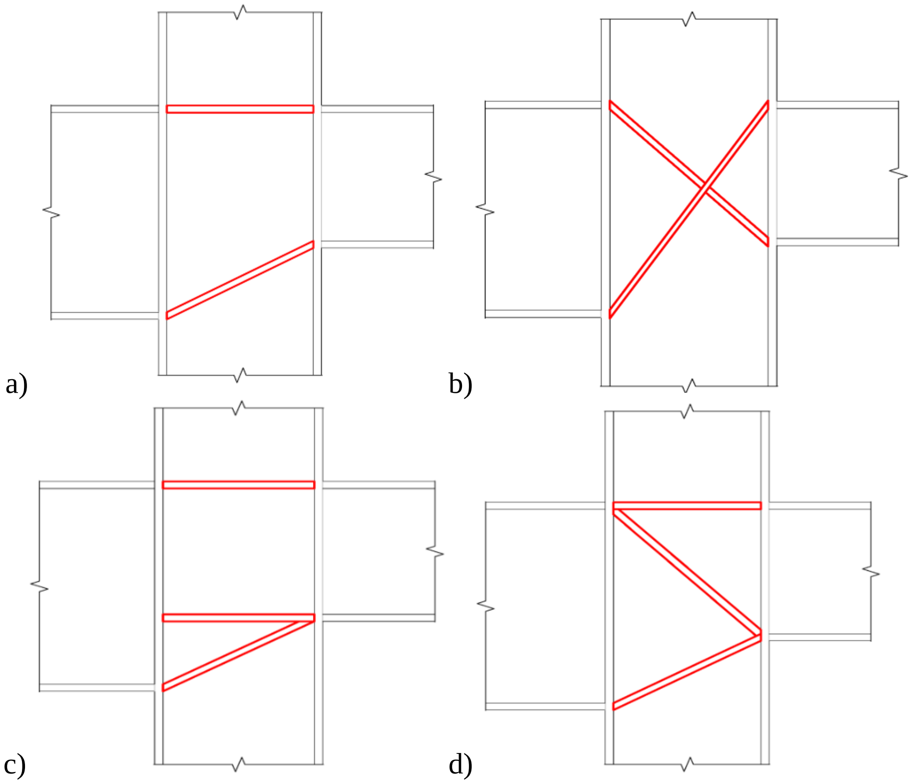

Figure 2. Arrangement and location of stiffeners: a) Sample st1 b) Sample st2 c) Sample st3 d) Sample st4

The purpose of providing a constant loading is to enable result comparison and to establish an acceptance criterion for connection verification, as the loading method significantly affects the behavior of the connection and its seismic criteria. The loading pattern used for the connection samples is cyclic loading, as shown in Figure (3). The loading steps, number of cycles, and column end displacements are presented in Table (2). Cyclic loading is based on the amount of rotation of the connection web panel zone, the displacement at the top of the column in each cycle, and the number of cyclic loads used in the structural analysis.

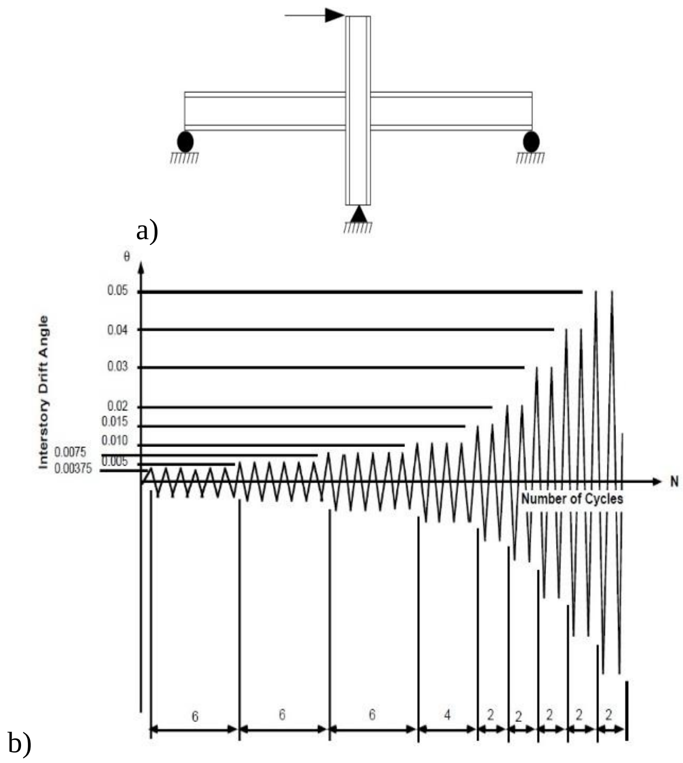

Figure 3. a) Loading application method, b) Loading history

The mechanical properties of the steel used in the connections for structural modeling in the software are required. In the connection modeling, used steel with a yield strength of 240 MPa and an ultimate strength of 370 MPa. The elastic modulus in the linear region of the stress-strain diagram is E=206000 MPa. For modeling the nonlinear behavior of materials, a two-linear elastoplastic diagram is used, where the ultimate strain (ε_u) is twenty times the yield strain ($20\varepsilon_y$), and the Poisson's ratio is $\upsilon=0.3$. Figure (4) shows the two-linear elastoplastic diagram for steel.

In the present study, all samples have pin joint supports at both ends of the column, so that the column is free to rotate about an axis perpendicular to the beam plane. Additionally, the end of the beam is restrained only in terms of lateral displacement. The samples are loaded with reciprocating displacements at the end of the beam (Figure 5). A 4-node C3D4 pyramid element is used for meshing the samples. Figure (6) illustrates the meshing of the connection in the software.

Table 2. Connection loading method

Loading step	Number of cycles	Relative floor displacement angle (Rad)	Column end displacements (mm)
1	6	0.00375	5.63
2	6	0.005	7.50
3	6	0.0075	11.25
4	4	0.010	15.00
5	2	0.015	22.50
6	2	0.020	30.00
7	2	0.030	45.01
8	2	0.040	60.03
9	2	0.050	75.06
10	2	0.060	90.11

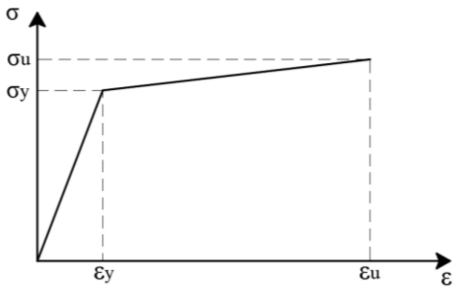

Figure 4. Two-linear elastoplastic diagram

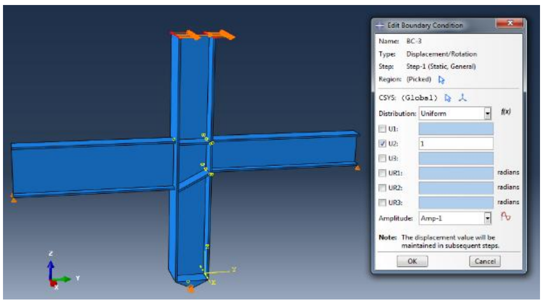

Figure 5. Loading application method and assignment of supports to the samples

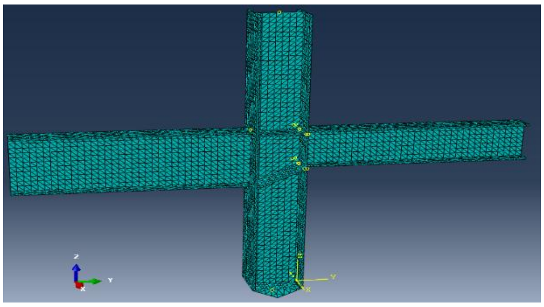

Figure 6. Meshing of the connection sample

3 VERIFICATION

Bayou and his colleagues [10] conducted a study on an experimental sample of a trapezoidal-shaped connection web panel zone formed by connecting two beams with different heights to a column. They utilized the results of the experimental sample to validate the model created in the software. They modeled half of the frame span in the software and then subjected the model to nonlinear static loading. The model specifications are described in Figure (7). Additionally, the section dimensions and materials specifications are presented in Tables (3) and (4) respectively.

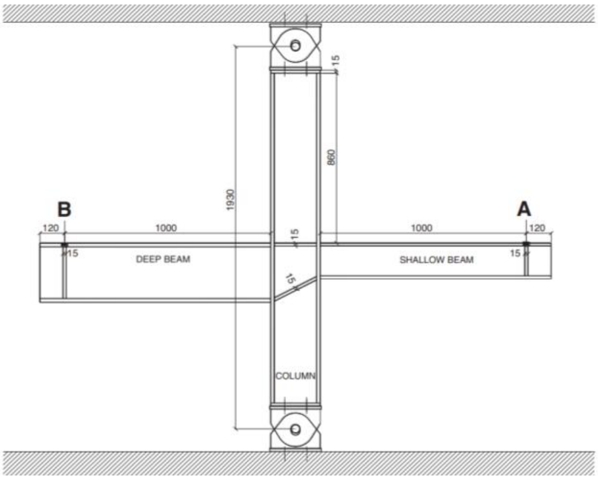

Figure 7. Dimensions of the model used by Bayou and his colleagues [10]

Table 3. Section dimensions and loading used [10]

Column Section	Deep Beam Section	Shallow Beam Section	Loading point	Load Quantity (kN)	Thickness of Stiffener (cm)
HEA 240	HEB 300	HEB 160	A	230	1.5

Table 4. Material specifications used [10]

Part	σ_y (MPa)	σ_u (MPa)	E (MPa)
HEA 160	328	494	210000
HEA 240	328	494	210000
HEA 300	328	494	210000
Stiffener	300	446	210000

The stress contour presented after analyzing the model using Abaqus software by Bayou and his colleagues [10] is shown in Figure (8). For the validation of the model regarding the analysis method, and connection boundary conditions, and to ensure the accuracy of the Abaqus software results, the specifications presented in Bayou's study and his colleagues [10] are used. Then, the results obtained from the modeling are compared with the work of Bayou and his colleagues [10]. Figure (9) illustrates the von Mises stress contour for the modeled connection in the software. Carefully in Figures (8) and (9), we can see a relatively high agreement between the von Mises stress results of the two modeled connection springs, which confirms the correctness of the modeling method in this study.

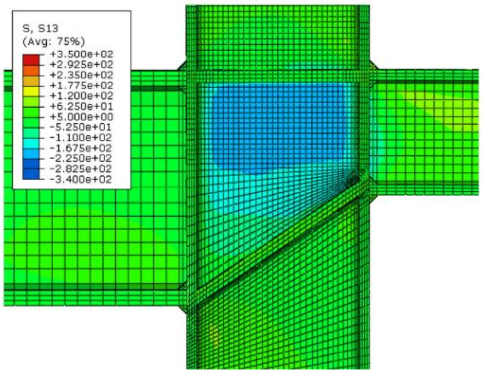

Figure 8. Von Mises stress contour by Bayou and his colleagues [10]

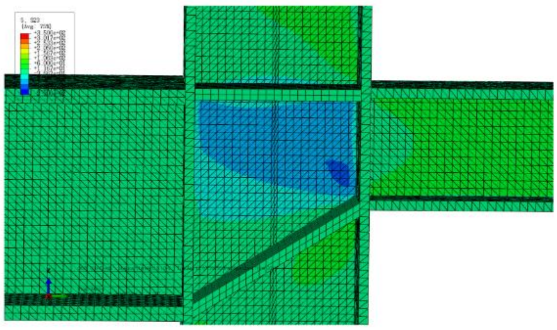

Figure 9. Display of validated modeling results

4 NUMERICAL RESULTS

Bayou and his colleagues [10] conducted a study on an experimental sample of a trapezoidal-shaped connection web panel zone formed by connecting two beams with different heights to a column. They utilized the results of the experimental sample to validate the model created in the software. They modeled half of the frame span in the software and then subjected the model to nonlinear static loading. The model specifications are described in Figure (7). Additionally, the section dimensions and materials specifications are presented in Tables (3) and (4) respectively.

The addition of stiffeners in the connection web panel zone increases the stiffness and consequently the degree of connection rigidity. Different methods are proposed for creating stiffeners in the column connection web panel zone, each having its own specific advantages and disadvantages. What is important in this regard is to understand the precise behavior of connections with different types of stiffeners and to investigate the load-bearing capacity of each type of connection. Detailed investigation of this behavior is so important and complex that extensive research has been conducted to thoroughly understand the behavior of these connections under different loading conditions. Researchers have sought to determine the stiffness and ultimate capacity of connections with various stiffeners using experimental or semi-experimental methods.

The behavior of I-shaped beam-to-column connections is influenced by several factors, including the dimensions of the beam, column flange, connection details, and the thickness of stiffener plates inside the column web. From experiments on stiffener samples inside the column, it is clear that the failure of the samples may occur with buckling or yielding of the column web or the beam flange. There is no precise solution available that can definitively account for these failure modes, and therefore, available finite element methods are used for modeling. In this section, investigate the results of the cyclic loading analysis of the column, performed using Abaqus software modeling. Then, are compared the results of analyzing these stiffener placement scenarios inside the column.

Hysteresis loops occur as a result of cyclic loading. These loops characterize the system's behavior under cyclic loads, allowing the system's resistance and stiffness to be observed in each loading cycle. The area under these loops represents the amount of energy absorbed by the system. Therefore, by calculating it in each loading cycle, the increase or decrease compared to previous cycles can be determined. Any general or local instability in the constituent members of the system is reflected in these loops, and they can be observed in each loading cycle if present. The number of loops a system can withstand against cyclic loads somewhat reflects its performance.

To compare the effect of the presence of stiffeners in the connection web panel zone, are studied their hysteresis curves. One of the criteria for determining a structure's energy absorption capacity is the area under the hysteresis curve. Therefore, one of the goals of structural strengthening is to increase the area under the hysteresis curve so that the structure can absorb more energy during an earthquake by undergoing greater deformation and entering the nonlinear material region.

Figures (10) to (13) depict the hysteresis curves of each of the connection web panel zones.

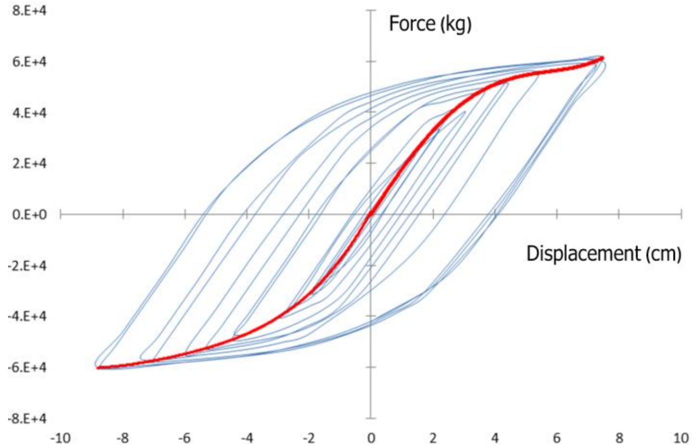

Figure 10. Hysteresis diagram of sample st1

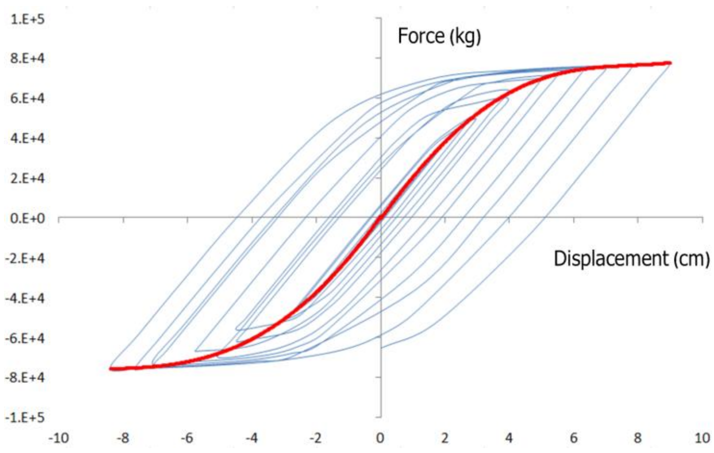

Figure 11. Hysteresis diagram of sample st2

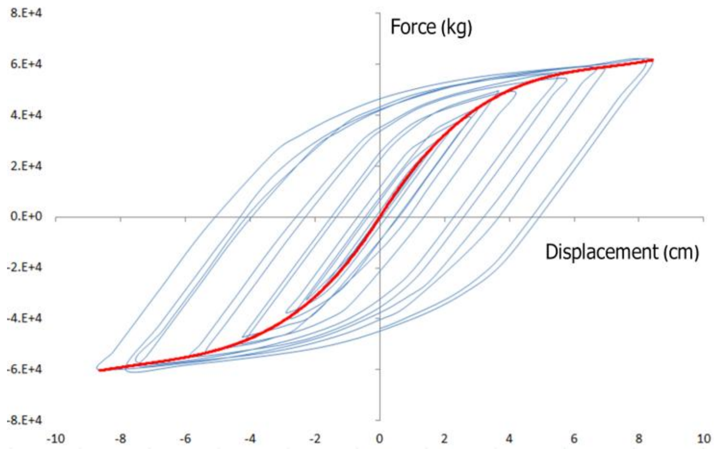

Figure 12. Hysteresis diagram of sample st3

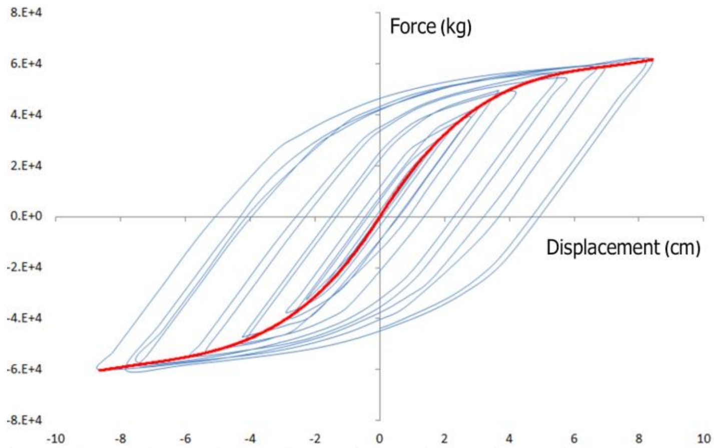

Figure 13. Hysteresis diagram of sample st4

As seen in the above diagrams, in sample st2, its hysteresis loop has the highest displacement and force, indicating lower stiffness in the connection web panel zone of this sample. Furthermore, by carefully examining its behavior, instantaneous and step-by-step yielding can be observed, as stress is concentrated only in the connection flange, and all structural members bear the stress. This can indicate excessive deformation of the structure during cyclic loading. However, connections such as samples st1 and st3, unlike samples st2 and st4, have approached their maximum displacement after a few initial loops, as the arrangement of the stiffeners confines the stress within the connection web panel zone. As a result, the strain in the elements in this area causes sudden structural deformation. This underscores the importance of the connection flange in the lateral deformation of the structure in this type of stiffener arrangement. Figure (14) presents the envelope hysteresis curve for comparing the performance of the samples.

Figure 14 - Presentation of the envelope hysteresis curves of the samples

By plotting the maximum points on the hysteresis curve of each sample, it can be observed that in samples st2 and st4, the slope of the envelope hysteresis curves gradually enters the nonlinear region, as in these two samples, stress and consequently elements undergo deformation (elastic and plastic) changes. They also have less concentration on the connection web panel zone area and are distributed throughout the model. Comparing all the samples, it can be expected that samples st2 and st4 can withstand more force at a uniform displacement, as, due to the delayed yielding of the elements in the connection web panel zone area, other structural members play a greater role in load-bearing. Additionally, the hysteresis loops of sample st2 have expanded more regularly. This is indicative of a more uniform deformation expansion in the entire model. Considering the uniform loading in all four models, an equal number of loops can be observed in the hysteresis curve of the samples.

One of the important objectives of examining the behavior of the connection web panel zone is to determine the ductility of this area. In structures with rigid connections, the amount of displacement and lateral movement of the structure under lateral loads is greatly influenced by the rotation of the connection web panel zone. In this study, after comparing the envelope curves of each of the samples, the rotation of the connection web panel zone is obtained using a third-degree polynomial interpolation for each of the samples. Figure (15) shows the obtained rotations for each of the samples.

Figure 15 - Rotation results for the samples

One of the important components in the investigation of lateral displacement is the rotation of the connection web panel zone. In moment frames, the connection web panel zone plays the most important role in the displacement of the structure because as this area yields, the connection exits its rigid state and with the increase of lateral force, is provided the possibility of significant structural displacements.

In Figure (15), the rotation in samples st1 and st3 at the beginning of loading is less compared to the other samples, as the stiffness of the connection flange in these samples is higher than in the other samples. As a result, the connection web panel zone has good rigidity. However, with increasing time and load, due to the stresses present in the connection web panel zone area, the rotations of samples st1 and st3 gradually increase due to stress confinement in the panel area. So, at the end of the loading cycle, with the yielding of most elements in the desired area, the connection stiffness decreases and significant rotations occur. However, in samples st2 and st4, with increasing loading, the stress in the panel area, due to the arrangement of the stiffeners, is redistributed to other structural members such as beams. As a result, the rate of rotation increase in these two samples is less compared to samples st1 and st3.

5 CONCLUSIONS

In structures, especially steel structures, connections play a crucial role in maintaining structural integrity. In fact, the primary function of connections is to properly transfer forces between structural members and components. Therefore, examining the performance of the connections plays a significant role in understanding the overall behavior of the structure. To understand the performance of the connection, the hysteresis curve is a suitable tool. Hysteresis loops occur as a result of cyclic loading. In these loops, any general or local instability in the constituent members of the structure can be observed in each loading cycle. The number of hysteresis loops that a structure can withstand against cyclic loads somewhat reflects its performance.

The amount of deformation and lateral movement of the structure under lateral loads in structures with rigid connections is greatly dependent on the rotation of the connection web panel zone. In this study, the rotation of the connection web panel zone was obtained using a third-degree polynomial interpolation for each of the samples. The important results of this study are as follows:

- The arrangement of stiffeners in samples st2 and st4 facilitates easier transfer of stress to other structural members. The rate of stress concentration in the panel area decreases.
- In samples st1 and st3, with the confinement of the panel area, as the loading increases, the entire panel area yields, affecting the overall behavior of the structure. Additionally, the steps of the hysteresis loops increase.
- Under uniform displacement, samples st2 and st4 have the ability to withstand a greater amount of force. At the end of the loading, samples st2 and st4 tolerated approximately 1.2 times the load compared to samples st1 and st3.
- Due to the possibility of stress redistribution from the panel area to other structural members in samples st2 and st4, there is the possibility of yielding a greater number of elements in the entire structure. With this distribution, the energy dissipation due to the plastic deformation of the structural members increases.

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