Journal of Structural Engineering and Geotechnics,

5 (1), 21-29, Winter 2015

Numerical Analysis of Cyclic Behavior of Beam-To-Column Bolted Connections in Steel Frames

Morteza Rastian[*a], Asghar Vatani Oskouie[b], Hassan Aghabarati[c]

[a]*M.Sc. in Civil, Structural Engineering, Takestan Branch, Islamic Azad University, Takestan, Iran*

[b]*Department of Civil Engineering, Shahid Rajaee Teacher Training University, Tehran ,Iran*

[c]*Department of Civil and Architectural Engineering, Qazvin Branch, Islamic Azad University, Qazvin, Iran*

Received, 10 January 2015; Accepted, 21 March 2015

Abstract

This article considers the seismic behavior of beam-to-column joints in steel frames for different bolt arrangements by using of finite element modeling. As the most important beam-to-column joint type, the beam-to-column joints with end-plate is chosen for the analysis. Four different specimens have been analyzed. These models had some differences such as bolt arrangement and the presence or absence of end-plate stiffeners. Design of bolts arrangement and stiffeners have been done based on the AISC standards. Two vertical bolt arrangements, with or without stiffener and two other models with horizontal bolt arrangement, with or without stiffeners have been considered. Different aspects such as energy absorption, ductility, initial stiffness and effective stiffness for all specimens have been compared. Finally effect of pre-stressing of all specimens has been assessed. As a result, comparison between vertical bolt arrangement and horizontal bolt arrangement has shown that the vertical bolt arrangement is more advantageous, especially in energy absorption.

Key words*:* Beam-to-column joint, End-plate, Cycling load, Bolt arrangement, Stiffener, Pre-stressing.

1. Introduction

The behavior of [*]beam-to-column joints in steel frames can be conveniently represented by its flexural behavior which is primarily shown by the moment–rotation (M–h) relationship. This behavior is non-linear even at low load levels. In fact, moment– rotation curves represent the result of a very complex interaction among the elementary parts constituting the connection

Since the connection types are highly indeterminate, current design approaches cannot model three-dimensional (3D) systems which are governed by complex combined material and geometrical non-linearity, friction, slippage, contact, bolt–end plate interactions and, eventually, fractures. Hence, the finite element technique has been adopted as a rational supplement to the calibration of design models.

To use the finite specimens, first, a verification with the experimental results was performed. And finally, after comparing and validating the numerical results with the experimental results, based on the available and allowable standards, changes ware made to the specimen. and, the effect of the pre-stressing of bolts was also analyzed.

The main aim of this study was to consider defferent specimens in relation with the cycling load. These modeles are able to simply illustrate the effect of different changes such as bolt arrangment on the joint properties such as energy absorption, initial stiffness, effective stiffness and ductility.

2. Beam-to-column joint under cyclic load

To verify beam to column joints analysis under cycling load, by use of Abaqus software, a finite model was made. The results compared to theoretical and experimental results which are presented by Summer et al. [1–3] for the beam to column joints.

2.1. Joint configuration

The joint configuration shown in figure 1, is based on an end-plate welded to the beam section and attached to the column flange by 4 rows of 1.25 inch bolts. Of the 4 rows, 2 are in the tensile part of the beam (one row above the beam tensile flange and the other under the beam tensile flange), and two other rows of bolts in the compaction part of the beam section. The test specimen, chosen to verify the finite element model, consists of a W14x193 (A572 Gr.50) column with a single W30x99 (A572 Gr.50) beam attached to the flange.

[*] Corresponding Author Email: Morteza.Rastian@gmail.com

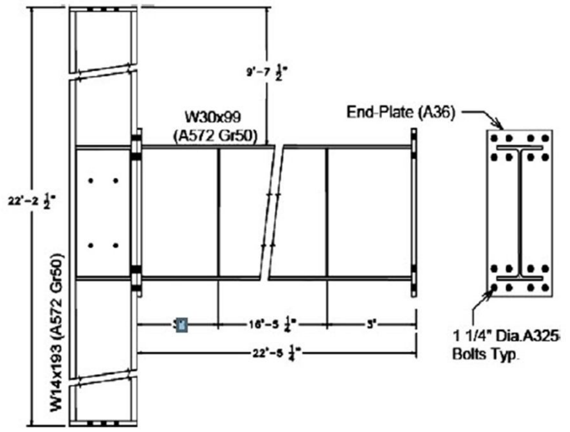

Figure 1. Connection configuration used by Summer.[4]

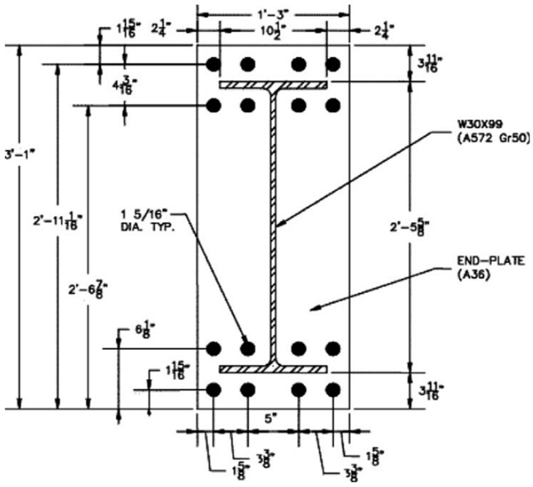

Figure 2. End-plate layout[4]

2.2. Loading protocol

The specimen was loaded cyclically based on the standard load history recommended by AISC [5]. In this protocol, the inter story drift angle, h, imposed on the test specimen is controlled as shown in Fig. 3.

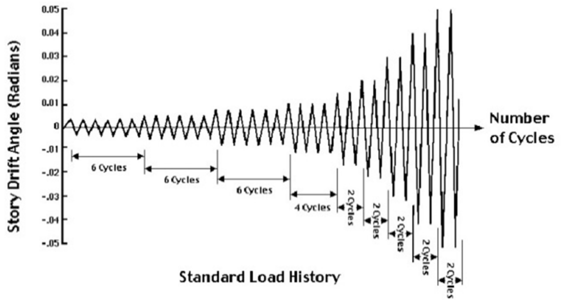

Figure 3. Standard load history recommended by AISC [6]

2.3. Finite element model

2.3.1. Boundary conditions and model properties

Young's modulus, Poisson's ratio, and Friction coefficient are equal to 29,870 Ksi, 0.3, and 0.5, respectively.

Both column ends are hinged supports. Six lateral supports for beam flanges constrained in X-direction are provided at a distance of 4 ft. 1 in., 12 ft. 1 in. and 18 ft. 9 in. from the centerline of the column. The free end of the beam is considered as a roller support in the vertical direction. The loading (displacement control) was applied to the centerline of the beam at a node located on the upper flange at a distance of 20 ft. 1 1/4 in. from the centerline of the column.

Tabe.1 exhibits a comparison between test results (experimental) and finite element results.

Table 1
Comparison between test results and finite element results

Item	Experimental results	FE results
Maximum applied moment (Kips.in)	18521	17716

Figures 4 and 5 illustrate the relation between moment and rotation in the central line on the column for both experimental and finite models.

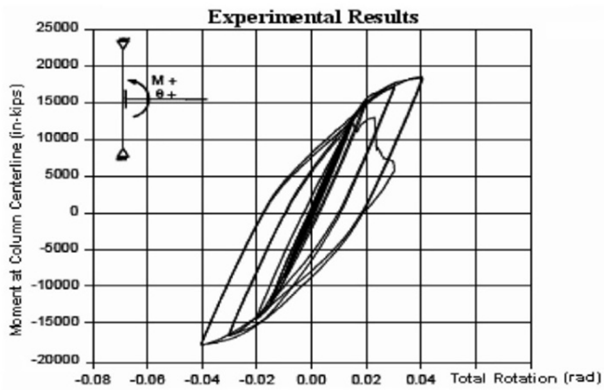

Figure 4. Relation between total rotation and moment [4]

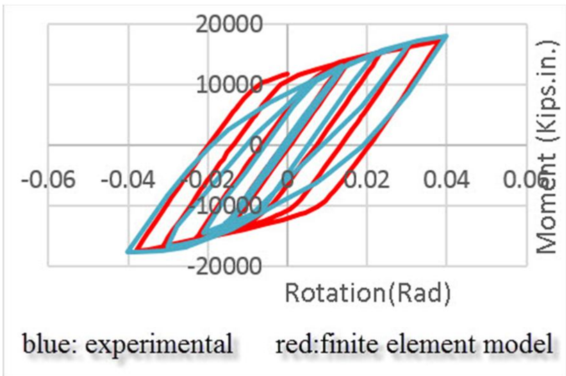

Figure 5. Relation between total rotation and moment in the FE and Experimental model

Results shown in table 1 and figures 4 and 5 illustrate a very good and proper convergence between FE model and experimental specimen.

2.3.2. Material properties

The stress-strain curves shown in figures 6 and 7 are used in modeling based on the type of the chosen material.

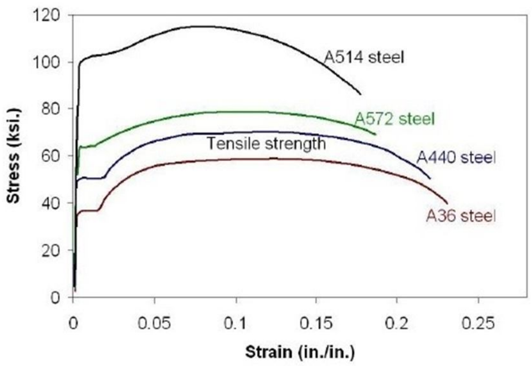

Figure 6. Steel stress-strain diagram[1] [7]

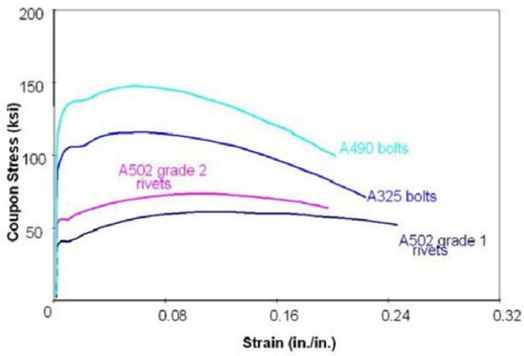

Figure 7. Steel bolt stress-strain diagram[2] [7]

2.4. Considered specimens

Four FE specimens are considered:

Specimen No.1 is a model based on 16 bolts with horizontal arrangement. There are four bolt rows with 4 bolts in each row. No end-plate stiffener is used.

Specimen No.2 vertical arrangement. 8 rows and in each row there are two bolts. No end-plate stiffener is used.

Specimen No.3 is a model based on 16 bolts with horizontal arrangement. There are four bolt rows with 4 bolts in each row. End-plate stiffener is used.

Specimen No.4, vertical arrangement. 8 rows and in each row there are two bolts. End-plate stiffener is used.

Modeling conditions are based on the reference model.

2.5. Pre-stressing

Eight specimens were created based on applying pre-stressing force to the bolts. Four specimens are based on the specimens explained in section 2.4 with the pre-stressing force value being10% of the maximum strength force of the bolt. The other four specimens used 30% of the maximum strength force of the bolt as pre-stressing force. Figure 8 shows the model No.1 after applying the pre-stressing force to the bolts.

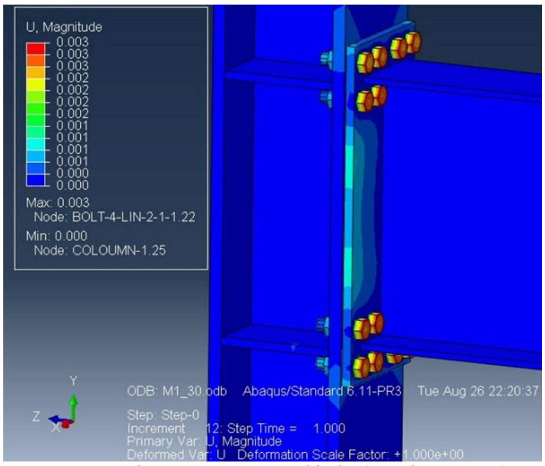

Figure 8. Pre-stressed bolts (Specimen No.1)

3. Results

The software has been run for all specimens. Energy absorption, ductility, initial stiffness, effective stiffness and finally, the effect of pre-stressing has been studied for all cycles. Moreover, the maximum moment for a special displacement equal to 9 inch was considered. The results are as follows:

3.1. Maximum tolerable moment

Under a special displacement applied to the end of the beam (in the distance of 241.25 in from the center line of the column), the tolerable moments are shown in figure 9.

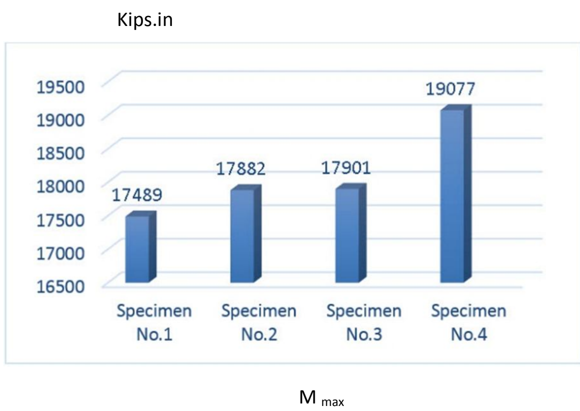

Figure 9. Maximum tolerable moment for all specimens without applying bolt pre-stressing

These results explain that the vertical bolt arrangement has a better performance when compared with the horizontal bolt arrangement. This means that, by applying more moment to the beam, the displacement of the

[1] Geoffrey L. Kulak, John W. Fisher, John H. A. Struik, Guide to Design Criteria for Bolted and Riveted Joints, Second edition

[2] Geoffrey L. Kulak, John W. Fisher, John H. A. Struik, Guide to Design Criteria for Bolted and Riveted Joints, Second edition

vertical arrangement is less than the displacement of the horizontal arrangement. Comparing models 2 and 3 illustrates that the vertical bolt arrangement without end-plate stiffener has the same results as the horizontal bolt arrangement with end-plate stiffener. It means, by changing the bolt arrangement from horizontal to vertical, it's possible to omit the end-plate stiffener and achieve the same results. Table No. 2, displays the results of maximum tolerable moments for the specimens under loading.

Table 2
Maximum moment (Kips.in) under an specific displacment (9 in.)

No.	Item	Maximum moment without applying pre-stressing	Maximum moment while applying 10% pre-stressing	Maximum moment while applying 30% pre-stressing
1	Specimen No.1	14489	17652	17680
2	Specimen No.2	17882	18171	18235
3	Specimen No.3	17901	18222	18400
4	Specimen No.4	19077	19084	19196

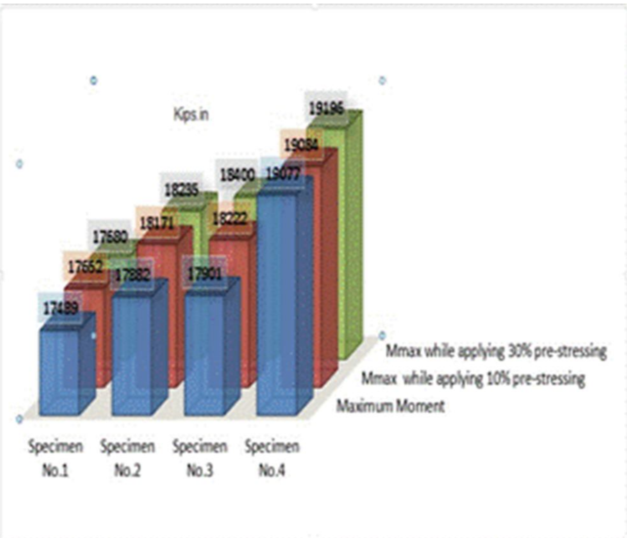

Figure 10. Maximum moment under a specific displacment equal to 9 in

Comparing the results shown in table No.2 and figure No.10 declare that by applying 10% of the bolt strength force as the pre-stressing force to the bolts, specimen No.1 exhibits only 1% performance improvement. But models 2, 3 and 4 have about 2% improvement in tolerable moment. By applying 30% of the bolt strength force as the pre-stressing force to the bolts, model No.1 which has horizontal bolt arrangement without end-plate stiffener improves about 1% and specimen No.2 which has vertical bolt arrangement without end-plate stiffener improves about 2%. Specimen No.3, the horizontal bolt arrangement with end-plate stiffener, improves about 3%. On specimen No.4, the end-plate stiffened and vertical bolt arrangement model, it seems that, applying bolt pre-stressing force has no effect on the operation of the joint. This may be because of the strength of the joint structure.

2.3. Considering initial stiffness, effective stiffness and ductility of all specimens, cycle by cycle.

All specimens have been studied cycle by cycle. By using two-lined force-displacement diagram, their initial stiffness, effective stiffness and ductility of them has been calculated. Figures 11 to 14 show the final cycle, two-lined, force-displacement diagram for all models. Moreover, tables 3, 4 and 5 illustrate the values of stiffness, effective stiffness and ductility for cycles No.6 to the end for all models. The reason for choosing cycle No.6 is due to considerable deflections that started during this cycle.

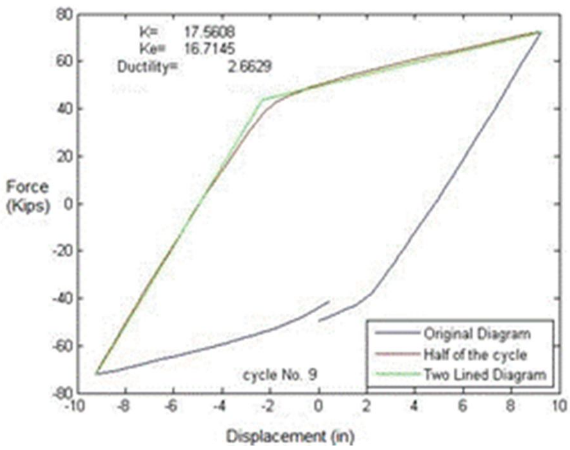

Figure 11. Two-lined diagram of the last cycle of the specimen No.1

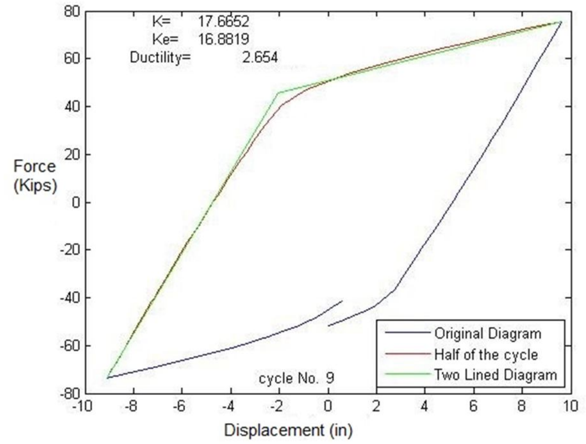

Figure 12. Two-lined diagram of the last cycle of the specimen No.2

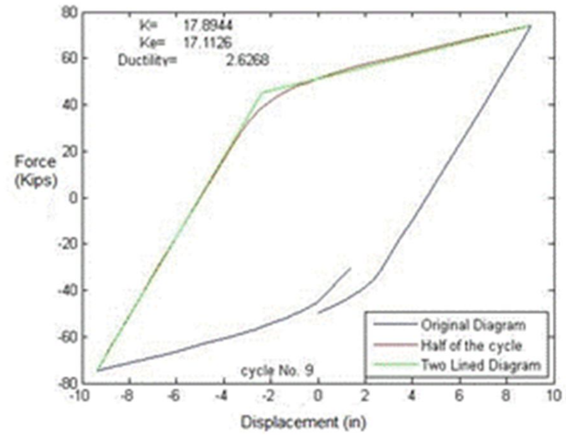

Figure 13. Two-lined diagram of the last cycle of the specimen No.3

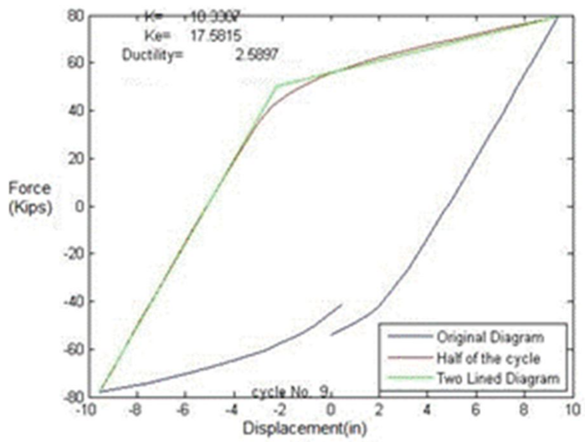

Figure 14. Two-lined diagram of the last cycle of the specimen No.4

Table 3
Comparison between initial stiffness, effective stiffness and ductility of all specimens without effect of bolt pre-stressing

cycle	Specimen	Initial Stiffness	Effective Stiffness	Ductility
6	No.1	16.19	15.93	1.15
	No.2	16.44	16.19	1.15
	No.3	16.47	16.25	1.15
	No.4	17	16.78	1.14
7	No.1	15.56	16.16	1.65
	No.2	16.73	16.38	1.63
	No.3	16.81	16.44	1.63
	No.4	17.35	16.98	1.64
8	No.1	17	16.33	2.15
	No.2	17.26	16.62	2.18
	No.3	17.30	16.72	2.15
	No.4	17.77	17.24	2.09
9	No.1	17.56	16.71	2.66
	No.2	17.66	16.88	2.65
	No.3	17.89	17.11	2.63
	No.4	18	17.58	2.59

Reviewing the values in table 3 shows that, even though changing the bolt arrangement, as well as adding or removing the end-plate stiffener, has limited impact on the ductility of the models, it does have an impact on the stiffness and effective stiffness of the models; at least in the extent of the tests on current specimens and without the effect of the bolt pre-stressing force. As an example, initial stiffness in specimen 4 compared to specimen 1 has increased by about 2.5% and effective stiffness has increased by about 4%. As it's illustrated in table No. 3, vertical bolt arrangement has been more successful when compared with horizontal bolt arrangement.

Table No. 4
Comparison between initial stiffness, effective stiffness and ductility of all specimens with applying 10% of the bolt strength force as bolt pre-stressing force.

cycle	Specimen	Initial Stiffness	Effective Stiffness	Ductility
6	No.1	16.90	17.68	1.19
	No.2	16.49	16.32	1.21
	No.3	16.44	16.24	1.17
	No.4	16.98	16.83	1.14
7	No.1	17.30	16.89	1.68
	No.2	16.85	16.53	1.68
	No.3	16.69	16.41	1.58
	No.4	17.32	17.02	1.63
8	No.1	17.77	17.09	2.2
	No.2	17.34	16.79	2.19
	No.3	17.23	16.63	2.17
	No.4	17.78	17.27	2.12
9	No.1	18.37	17.49	2.74
	No.2	17.92	17.17	2.70
	No.3	17.82	17.01	2.71
	No.4	18	17.64	2.61

Table No. 5
Comparison between initial stiffness, effective stiffness and ductility of all specimens with applying 30% of the bolt strength force as bolt pre-stressing force.

cycle	Specimen	Initial Stiffness	Effective Stiffness	Ductility
6	No.1	16.91	17.14	1.2
	No.2	16.47	16.43	1.18
	No.3	16.44	16.36	1.17
	No.4	16.97	16.95	1.16
7	No.1	17.33	17.30	1.66
	No.2	16.91	16.63	1.68
	No.3	16.81	16.53	1.68
	No.4	17.35	17.11	1.64
8	No.1	17.80	17.50	2.2
	No.2	17.34	16.90	2.2
	No.3	17.18	16.67	2.14
	No.4	17.78	17.36	2.12
9	No.1	17.68	17.9	2.65
	No.2	17.95	17.29	2.74
	No.3	17.72	17.20	2.65
	No.4	17.64	17.73	2.64

Comparison between tables 4 and 5 illustrates that initial stiffness and effective stiffness in the models without end-plate stiffener, by applying 10% of the bolt strength force as the bolt pre-stressing force, improves. This performance improvement is about 4-5 %. By applying 30% of the bolt strength force as the bolt pre-stressing force, it's been cleared that initial stiffness has not changed, but effective stiffness shows performance improvement.
Considering ductility shows that applying up to 30% of the bolt strength force as the bolt pre-stressing force improves ductility by about 3%.

3.3. Stress
Von-misses criterion has been used to consider the stress in the specimens. Table No. 6 compares the maximum stresses existing in the models.
3.4. Energy absorption
Using the Abacus software package utilities, the joint energy absorption has been calculated in all cycles of force-displacement diagram. The result of the calculations for all specimens and all cycles is presented in table No.6 for comparison.
By applying the bolt pre-stressing, the energy absorption in different cycles of all models has been calculated. The results of bolt pre-stressing equal to 10% of the bolt strength force are shown in table No.8 and the results of bolt pre-stressing equal to 30% of the bolt strength force are shown in table No.9.

Table 6
Comparison between the maximum stresses in the specimens (Kips/in^2)

Item	Maximum stress after applying 10% bolt pre-stressing	Maximum stress after applying 30% bolt pre-stressing
Specimen No.1	207.38	210
Specimen No.2	173.2	192.6
Specimen No.3	191.49	188.12
Specimen No.4	159.59	177.43

Table 7
Energy absorption in all cycles of all specimens without applying the effect of bolt pre-stressing force

Item / Cycle	1	2	3	4	5	6	7	8	9	Total Energy
Specimen No.1	0.000	0.000	0.004	0.026	0.529	27.252	290.596	686.740	1080.370	**2085.760**
Specimen No.3	0.000	0.000	0.001	0.213	0.213	33.226	287.520	677.277	1116.245	**2114.500**
Specimen No.2	0.000	0.000	0.003	0.026	0.438	40.489	284.730	737.753	1164.650	**2191.630**
Specimen No.4	0.000	0.000	0.001	0.013	0.383	36.016	310.510	706.856	1239.880	**2293.660**

Table 8
Energy absorption in all cycles of all specimens with10% of the bolt strength force as the bolt pre-stressing

Item / Cycle	1	2	3	4	5	6	7	8	9	Total Energy
Specimen No.1	0.000	0.000	0.004	0.026	0.307	42.962	300.421	723.199	1192.610	**2220.050**
Specimen No.3	0.000	0.000	0.001	0.010	0.210	32.354	319.447	730.984	1203.310	**2260.190**
Specimen No.2	0.000	0.000	0.004	0.023	0.531	36.124	312.426	697.299	1164.780	**2197.760**
Specimen No.4	0.000	0.000	0.001	0.016	0.329	18.530	298.770	742.280	1270.720	**2317.760**

Table 9
Energy absorption in all cycles of all specimens with30% of the bolt strength force as the bolt pre-stressing

Item	Cycle	1	2	3	4	5	6	7	8	9	**Total Energy**
Specimen No.1		0.000	0.001	0.004	0.025	0.560	35.865	315.546	721.389	1142.500	**2215.890**
Specimen No.3		0.000	0.000	0.002	0.016	0.191	41.515	309.568	727.041	1194.040	**2239.410**
Specimen No.2		0.000	0.001	0.003	0.026	0.432	38.100	265.685	699.789	1214.780	**2196.160**
Specimen No.4		0.000	0.000	0.001	0.013	0.343	28.159	304.783	746.061	1255.750	**2313.040**

4-Conclusion

4.1. FE results and experimental test results were compared to examine the validity and the prospect ability of the offered specimen. The FE show a good coordination and convergence with the experimental test results in all steps of loading.

Before applying bolt pre-stressing

4.1. In regards to tolerable moment, it has been shown that vertical bolt arrangement has a better performance when compared to the horizontal bolt arrangement. Its value in specimen 4 is about 10% more than its value in specimen 1. This means, by applying more moment to the beam, its deflection is less than the specimen 1. Moreover, comparing specimen 2 and 3 illustrate that the performance of the specimen with vertical bolt arrangement without end-plate stiffener has the same results as the specimen with horizontal bolt arrangement with end-plate stiffener.

4.2. Considering the initial and effective stiffness demonstrates that the vertical bolt arrangement presents better results compared to horizontal bolt arrangement even with end-plate stiffener. Due to initial stiffness, this better performance is about 3% and due to effective stiffness it is about 5%.

4.3. Energy absorption in the specimens illustrates that the vertical bolt arrangement in comparison with horizontal bolt arrangement shows a better performance. This is obvious when comparing specimen 2 with specimen 3. The performance improvement in specimen 4 is about 10% more than performance in specimen 1. Comparing specimens with horizontal bolt arrangement to each other shows that presence of stiffener improves the performance by about 5%. The improved performance in vertical bolt arrangement with end-plate stiffener compared to vertical bolt arrangement without end-plate stiffener is about 8%.

4.4. Finally, considering all parameters and comparing all tables and graphs, exhibited that vertical bolt arrangement performance is better than the horizontal bolt arrangement and that's possible to use vertical bolt arrangement instead of stiffened horizontal bolt arrangement. It's obvious that using end-plate stiffener in the vertical bolt arrangement presents better results.

After applying bolt pre-stressing

4.5. Regarding the maximum tolerable moment, by applying up to 30% of bolt strength force as bolt pre-stressing, in specimens 1 to 3, a performance improvement of about 1 to 3% can be exhibited. In the case of specimen 4, applying bolt pre-stressing up to 30% has no effect on joint performance.

4.6. By applying up to 30% of bolt strength force as bolt pre-stressing, it has been observed that joint initial and effective stiffness in the non-stiffened specimens have increased up to 5%. But in the specimens without end-plate stiffener, no changes has been observed.

4.7. Pre-stressed specimens' ductility has increased about 3% in comparison to the non-pre-stressed specimens.

4.8. Regarding the maximum stress engendered in the specimens, based on table 6 values, it's evident that in the horizontal bolt arrangement, by applying up to 30% pre-stressing, a reduction of about 20% to 30% in the specimen stress is achieved.

4.9. In the pre-stressed specimen up to 30% with vertical bolt arrangement, using end-plate stiffener causes a reduction of about 8% in the maximum stressed engendered in the whole specimen.

4.10. Comparing tables 4 and 5 illustrates that by applying up to 30% of bolt strength force as bolt pre-stressing to the specimens without end-plate stiffener, the initial and effective stiffness has improved and increased about 4% to 5%. Applying up to 30% of bolt strength force as bolt pre-stressing to the specimens with end-plate stiffener and with vertical bolt arrangement has no effect on the joint initial and effective stiffness.

4.11. Considering the specimens ductility shows that by applying up to 30% of the bolt strength force as bolt pre-stressing to the specimens, a performance improvement and ductility increase of about 3% is evident.

4.12. Regarding the energy absorption, applying bolt pre-stressing of up to 30% of the bolt strength, causes about 7% improvement on the performance of specimens without joint stiffener. This pre-stressing has no effect on the energy absorption of specimens with joint stiffener.

4.13. By applying bolt pre-stressing of 10% to 30% of the bolt strength force, it's possible to omit the joint stiffener but maintain the energy absorption as much as the energy absorption of the joint-stiffened specimens. This is a more feasible option, both economically and executively.

References

[1] Sumner, E.A., Mays, T.W., Murray, T.M. (2000). End-plate moment connections: test results and finite element method validation, in: Connections in Steel Structures IV: Steel Connections in the New Millennium: Proceedings of the Fourth International Workshop, Roanoke, VA, October 22–25, pp. 82–93.

[2] Sumner, E.A. , Mays, T.W. , Murray, T.M. (2000). Cyclic Testing of Bolted Moment End-Plate Connections, Research Report SAC/BD-00/21, CE/VPI-ST 00/03, Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA.

[3] Sumner, E.A.(2003). Unified Design of Extended End-Plate Moment Connections Subject to Cyclic Loading, Ph.D. Thesis, Faculty of the Virginia Polytechnic Institute and State University, Blacksburg, VA, USA.

[4] Mashaly,E., El-Heweity,M., Abou-Elfath,H., Osman, M. (2011). Finite element analysis of beam-to-column joints in steel frames under cyclic loading, Alexandria Engineering Journal, pp. 91-104.

[5] Specification for Structural Steel Building, AISC_360, 22 June, 2010.

[6] American Institute of Steel Construction Inc. (AISC), Manual of Steel Construction – Load and Resistance Factor Design Specification for Structural Steel Buildings, second ed., 1994.

[7] Kulak,G., Fisher,J., Struik,J. (1987). Guide to Design Criteria for Bolted and Riveted Joints. Wiley- Interscience, Second Edition.