Nonlinear Behavior of Bolted Extended End-Plate Beam to Column Connections Subject to Cyclic Loading

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Abstract. Bolted extended end plate beam-to-column connections are one of the most commonly used moment connections. In Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications (AISC 358-16), bolted extended end plate beam-to-column connection details are available to be utilized accordance with the limitations specified in special and intermediate steel moment frames. These limitations are mainly suitable for American I-shapes and do not cover some European I-shapes commonly used in Turkey. According to the study conducted by other researchers, beam-to-column connections with some of these European I-shapes used as beams that do not meet the limitations per AISC 358-16 have been tested and behavior of the connections has been found satisfactory. In this study, a further investigation is made for steel I-shapes used as beams that are not included in the scope of aforementioned study. To widen the availability of I-shapes used as beams and thus limitations specified for the beams, a numerical study is performed through 3D finite element models constructed using ABAQUS software.

As a result of finite element analyses, rotational and moment capacities of the connections are obtained. According to moment-rotation curves obtained, it is observed that these considered bolted extended end-plate beam-to-column connections comply with the requirements stipulated in Seismic Provisions for Structural Steel Buildings (AISC 341-16).

Keywords: Cyclic behavior · bolted extended end plate beam-to-column connections · finite element model

1 Introduction

As studied by many other researchers, due to their effectiveness and ability of transmitting large amount of moments under seismic loads bolted extended end plate beam-to-column connections are widely preferred in seismic regions. Many researchers conducted various studies to investigate the conformity of these connections in seismic applications. Adey et al. (2000) examined the effect of varying bolt arrangement and beam sizes on energy absorption capacity and ductility for moment connections and resulted that deep beams and tight bolt placement caused a decrease in the energy absorption capacity of the joint.

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Sumner and Murray (2002) conducted an experimental study to examine the performance of end plates of beam-to-column connections under cyclic loads. Experimental results emphasized that end plate moment connections can be designed for use in moment frames that transmit seismic loads, and the philosophy of strong column, strong joint and weak beam should be considered. They concluded that moment-transmitting connections with extended end plates can provide the sufficient strength, stiffness and ductility required for use in seismic regions. In addition, Sumner (2003) proposed a design procedure for the extended end plate beam-column connections for different connection configurations in his research. Haghollahi and Jannesar (2018), conducted finite element analyses using ABAQUS software and investigated the effects of different end plate thicknesses, bolt diameter and different geometry to nonlinear behavior of four-bolt extended end plate connections consisting of H-shape columns and I-shape beams. ElSabbagh et al. (2019) performed finite element analyses to investigate the parameters; shear force, geometry and loading type, affecting the behavior of extended end plate bolted connection and compared the results with two different experimental studies. Radmehr and Homami (2020) investigated the plastic hinge characteristics of extended end plate beam-to-column connections by performing finite element analyses and comparing the results with the experimental study Shi et al. (2007) conducted. They stated that the plastic hinge moves towards the beam when four-bolt extended end plate connections are designed in accordance with AISC 358-16 design criteria.

In accordance with AISC 358-16 and other specifications, use of extended end plate beam-to-column connections in moment frames under seismic loads require to meet various conditions in terms of geometry, material properties, stiffness, energy absorption and strength degradation. Furthermore, seismic application of such connections requires sufficient rotation angle capacity in accordance with AISC 341-16 under cyclic loads and flexural strength of 80% of the plastic bending moment capacity (M_p) of the connecting beam corresponding to 0.04 rad inter-story drift angle. However, geometrical limitations required by AISC 358-16 are mainly proposed for American shapes, so the limitations especially given for the connecting beam height and flange width limit the use of some European I-Shapes in moment frames transmitting seismic loads.

In addition to many other researchers, experimental and numerical studies are performed by Akgönen et al. (2015) to investigate the conformity of end-plate moment connections consisting of European I-Shapes which do not meet the aforementioned limitations to the seismic application. As a continuation to this experimental study, this paper will provide a numerical study for IPE300 and IPE330 beams which Akgönen et al. did not include in scope of their research.

2 Analysis Models

2.1 Finite Element Models

Finite element models developed to investigate the cyclic behavior of four-bolt extended end-plate beam-to-column moment connections with IPE300 and IPE330 connecting beams are prepared by using ABAQUS software. First, a confirmation model is developed and the analysis results are compared with experimental test results performed by

Akgönen et al. (2015). In light of the results obtained from the confirmation model, conservative approximation of hysteresis loops is observed.

IPE300 and IPE330 beams to HEB360 column connections are designed in accordance with AISC 358-16 and geometry of each connection is provided in Fig. 1. The width-to-thickness ratios for the flanges and web of the sections for connecting members conform to the requirements of the AISC 341-10 seismic provisions. Yield stress and modulus of elasticity were assumed to be equal to 275 N/mm^2 and 200000 N/mm^2, respectively for all connecting members except for bolts. Bolts connecting the end plates to column flange are chosen as M24-10.9 and M27-10.9 for IPE300-HEB360 and IPE330-HEB360 connections, respectively.

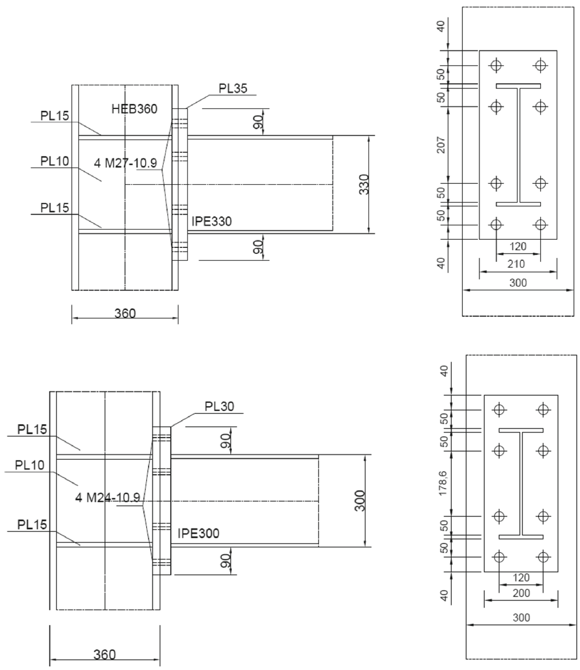

Fig. 1. Geometry of four-bolt extended beam-to-column connections for IPE300-HEB360 and IPE330-HEB360

In this study, beams, columns, end plates, bolts, continuity plates and stiffeners in finite element models are represented with solid finite elements present in ABAQUS element library. No welding is included in the analysis model (Fig. 2). Instead, tie constraint available in ABAQUS is utilized. Threaded lengths and washers are not included in the representation of the bolts in the model. Hexagon nuts and bolt body are modeled connected to the circular part (Fig. 3). Standard bolt hole diameters given in AISC360-16 are used for the bolt holes in the column flange and end plate. In finite element models, connecting members (which connecting members) are represented with C3D8R or C3D20R solid elements. In ABAQUS software, the letter "C" stands for "continuum element".

“3D” indicates that the elements are modeled in three dimensions, the number following indicates the number of nodes, and the letter “R” denotes “reduced-integration”.

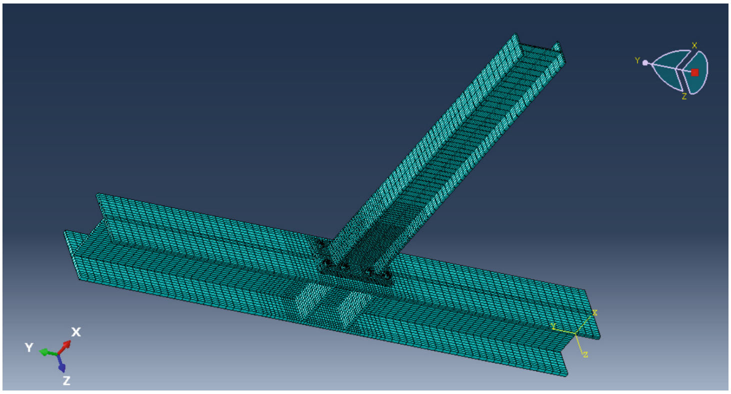

Fig. 2. Typical finite element model of connections

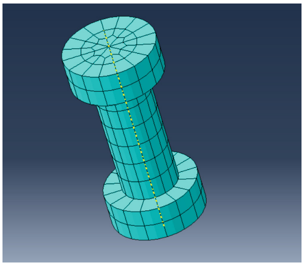

Fig. 3. Finite element model of bolts

While creating finite element meshes, different mesh sizes are considered for different members. The density of the finite element mesh is increased in regions where strains and stresses are expected to intensify on connecting members.

In finite element analysis models, it is very important to identify the interaction between the surfaces of the connecting members properly and correctly. In the finite element models prepared within the scope of this study, the interaction between surfaces that are in contact with each other is provided by the “general interaction” definition in ABAQUS software. Necessary parameters for normal behavior and tangential behavior are presented into this definition. To represent the normal behavior, “hard contact” definition is used, that is, the elements are prevented from interfering with each other and are allowed to be separated from each other if the stress is zero or less on the surfaces in contact with each other. For the tangential behavior of the surfaces, the “penalty” option is applied with friction coefficient of 0.44. Pretension is applied to bolts according to AISC 360-16.

2.2 Material Properties

The material model of connecting members in finite element models is defined separately for the elastic and plastic region. Elastic modulus (E) and Poisson ratio (γ) are defined as 200000 MPa and 0.30, respectively for the elastic region where material behavior is linear elastic. Therefore, it is specified with which slope value the stress-strain curve of the material will continue until the yield stress value.

In order to represent the plastic behavior appropriately, many material models were tried and their effects on the behavior were observed during the determination of the proper material model. In the ABAQUS software, it is possible to define the hardening behavior in various ways. In the first stage, the isotropic hardening model was tested and it was observed that the growth in the yield surface area of the curves did not reflect the behavior characteristics of the experimental results. In the second stage, the behavior was observed by selecting the "kinematic hardening" module in the ABAQUS software, and concluded that this model also did not reflect the real material behavior properly, since there was no decrease in strength in this model where the yield surface was displaced. In order to represent the material behavior under initial yield stress and cyclic loads for the plastic region where permanent deformations will be seen after yielding, the "combined hardening" module was employed in the ABAQUS software and the kinematic hardening parameters were defined by the "parameters" method. The initial yield stress value is taken from the stress-strain curve obtained from the material tests. Kinematic hardening was modeled in the theory of plasticity by the movement of the yield surface in the stress space. In the finite element models, the displacement of the yield surface is defined by the parameters C and γ. Here, C is the kinematic hardening modulus, and γ is a coefficient that determines the rate of decrease of the kinematic hardening modulus with increasing plastic deformation. In Table 1, plastic material properties defined for column, end plate, continuity plates, stiffeners and doubler plates are given. These material properties are calculated by utilizing true stress-true strain relations.

Table 1. Plastic material characteristics for connecting member except for beams and bolts

F_y (MPa)	F_u (MPa)	ε_u
275	479	0.155

The hardening parameters defined for the beams are given in Table 2. The yield stress of the beam at zero plastic deformation of 275 MPa, is increased with the ratio of the expected yield stress to the characteristic yield stress, R_y.

Table 2. Kinematic hardening parameters for beams

σ_0(MPa)	C_1(MPa)	γ_1
357.5	7993	175

2.3 Cyclic Loading Protocol

In order to evaluate the conformity of IPE300-HEB360 and IPE330-HEB360 beam to column connections in seismic application, SAC cyclic loading protocol is applied to beam end according to AISC 358-16. SAC cyclic loading protocol includes the given number of cycles for certain inter-story drift angles (Fig. 4). According to this loading protocol, the definition of the inter-story drift angle is the ratio of the vertical displacement of the beam end to the distance between the column center and the beam end. This definition is also given in Fig. 4. In the analysis models, the loading protocol is defined by the displacements acting on the beam end. While applying the loading protocol to the finite element models, out-of-plane displacement of the beams are prevented.

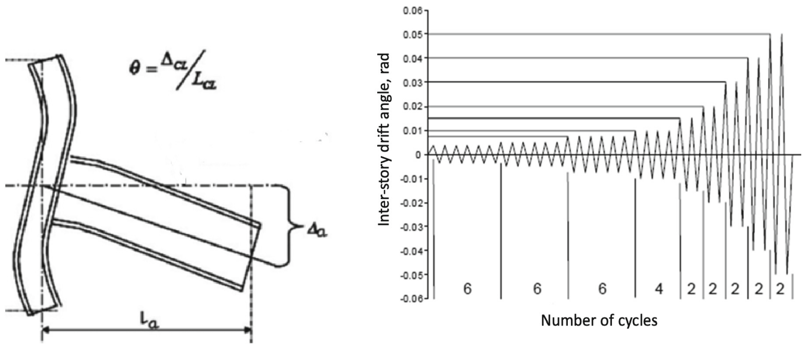

Fig. 4. SAC cyclic loading protocol and definition of inter-story drift angle

2.4 Verification of Analysis Models

Experimental test results of the study performed by Akgönen et al. (2015) are used to validate the finite element models since no experimental studies are conducted within the scope of this study. Akgonen et al. (2015) carried out experimental studies on four specimens in order to examine four bolted extended end plate beam column connections in terms of rotational capacity and strength under cyclic loads. Monotonic loading protocol is applied to one of these four connections and SAC cyclic loading protocol is applied to the remaining three samples. In the test setup, the height of the column is 3 m and the distance of the beam end from the column face is approximately 1.75 m. In the experimental setup, the out-of-plane movement of the beams is limited and no axial load is applied to beams or columns. In order to verify the finite element models, the P3 specimen is selected from the experimental study. In P3 specimen, IPE270 beam is connected to the HEB320 column with M24-10.9 bolts. IPE270 beam cross-section does not meet the beam height and flange width criteria according to AISC 358-16 Table 6.1, as do IPE300 and IPE330 beams. In the P3 specimen, end plate thickness is 35 mm, continuity plates are 20 mm thick and doubler plates are 8 mm thick (Akgonen 2015). In order to represent the plastic behavior of the IPE270 beam, the kinematic hardening parameters are defined as given in Table 3. Bilinear material model is used to define the material characteristics for elements that are expected to remain elastic, in other words, where no yielding is expected essentially. In this material model, true stress-strain values obtained from test results (Akgönen et al. 2015) are defined to finite element model.

Table 3. Kinematic hardening parameters used for P3 specimen

σ_0(MPa)	C_1(MPa)	γ_1
337.25	7993	175

According to the experimental study, the P3 specimen showed elastic behavior up to the 0.01 rad inter-story drift angle. It is also observed that the moment capacity of the P3 specimen is 224.89 kNm and −245.58 kNm. The specimen lost its strength as a consequence of local buckling of the beam flange at 0.05 rad cycles. The test is terminated at 75% of 0.07 rad cycle due to complete rupture of the beam flange. it is also demonstrated that the location of the plastic hinge region is formed at a distance of 75–110 mm from the column face. (Akgönen et al. 2015). Figure 5 shows that the post-yield failure mode of the P3 specimen is local buckling and tearing of the beam flange. With the finite element models, it is aimed to accurately represent the behavior of the connections. Therefore, before the finite element models of the connections used for the investigation, the modeling technique followed for the connections is verified by comparing the results from the analysis with those from the experimental study. For this, failure modes and hysteresis loops from the test and finite element analysis are compared in Fig. 5 and 6, showing failure modes and hysteresis loops, respectively. Consequently, the modeling technique is found to be acceptable to develop finite element models in order to represent the behavior of the connections.

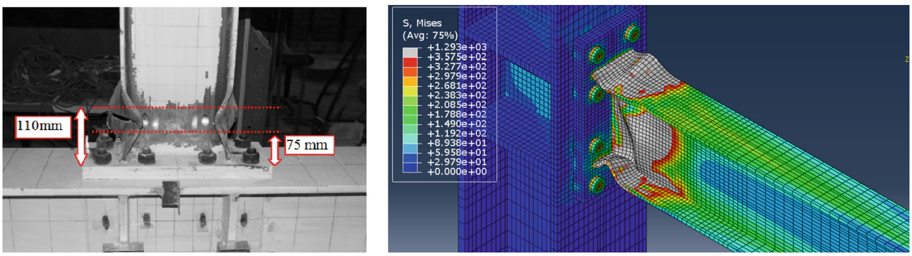

Fig. 5. Comparison of failure mode of P3 specimen at the end of the test with Failure mode of the P3 sample as a result of cyclic loading (FEM)

Hysteresis loops obtained from finite element analysis under cyclic loading for P3 specimen are represented quite reasonably with the material parameters defined for the elastic region. In the inelastic region, the moment capacity value of the connection corresponding to the rotation angle of 0.04 rad is found to be conservatively compatible with the experimental study. Finally, modeling principles and material models are found to be appropriate based on conservative approximation of hysteresis loops observed. Thus,

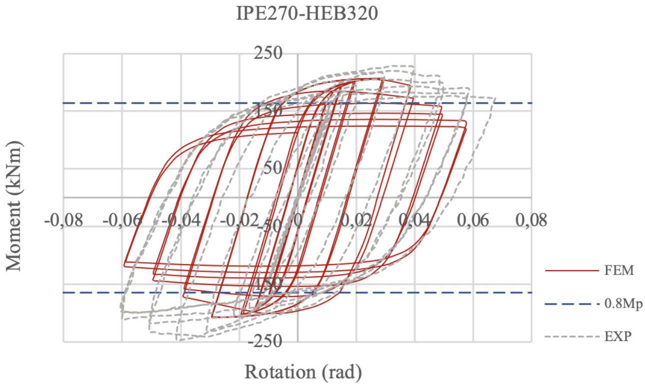

Fig. 6. Comparison of experimental and FEM results for P3 specimen moment-rotation curves under cyclic loading (Akgönen et al. 2015).

it is acceptable to analyze the behavior under cyclic loads with finite element models for IPE300-HEB360 and IPE330-HEB360 connections which have similar characteristics.

3 Evaluation of Analysis Results

In this section, analysis results of finite element models for IPE300-HEB360 and IPE330-HEB360 four-bolt extended end plate moment connections are given. The nonlinear behavior of the connections, designed in accordance with AISC 341-16, under SAC cyclic loading protocol is examined. The analysis results for both connections are evaluated in terms of rotational capacity and flexural strength.

The moment-rotation curves obtained from the finite element analyses are shown in Fig. 7 and Fig. 8 for IPE300-HEB360 and IPE330-HEB360. It is observed that both connections exhibit elastic behavior up to 0.01 rad inter-story drift angle under cyclic loading. Failure modes and stress distributions of connections are given in Fig. 9 and Fig. 10. As given in the figures, the plastic deformations localized in the beam flanges and the failure mode for both joints occurs by local buckling of the beam flanges after yielding (Fig. 7).

It is observed that the behavior of the connections is compatible with the strong column-strong connections-weak beam philosophy, and all other connecting elements remain in the elastic region in the cycle corresponding to the rotation angle where the beam reaches the bending moment capacity.

The failure modes and moment-rotation curves of the IPE300-HEB360 and IPE330-HEB360 beam-to-column connections analyzed within the scope of this study are found to have the same characteristics as the behavior of the IPE270-HEB320 connection found in the test conducted by Akgönen et al. (2015), and for these two connections, it is demonstrated that the bending moment capacity corresponding to a rotation angle of 0.04 rad is greater than 80% of the plastic bending moment strength of the beams. In both connections, the plastic hinges formed at a distance from column face approximately half of the beam height. And in accordance with the design principles, the elements involved in the connection other than the beam remained in the elastic region.

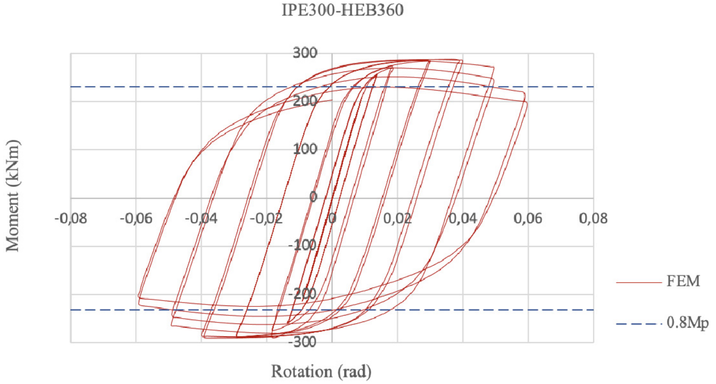

Fig. 7. Moment-rotation curve of IPE300-HEB360 connection

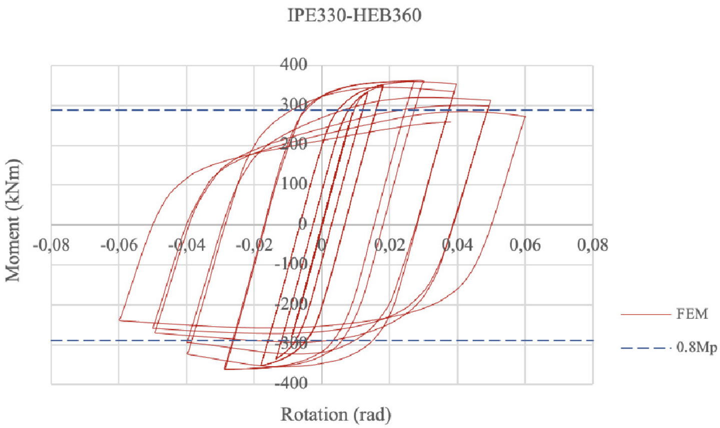

Fig. 8. Moment-rotation curve of IPE330-HEB360 connection

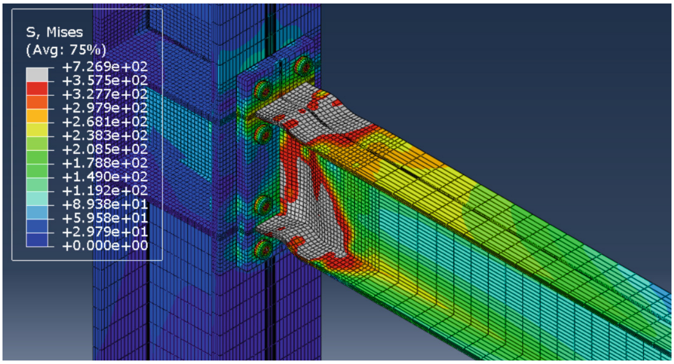

Fig. 9. Deformed shape and stress distribution of IPE300-HEB360 connection

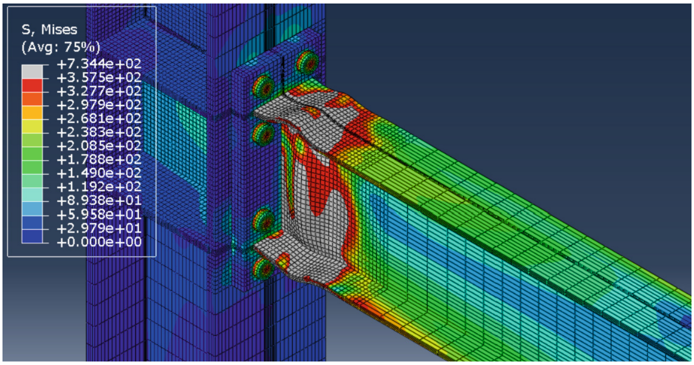

Fig. 10. Deformed shape and stress distribution of IPE330-HEB360 connection

4 Conclusion

In this study, the behavior of bolted extended end-plate beam-to-column connections consisting of European I-Shape beams which do not meet the geometric limitations given for seismic application in accordance with AISC 358-16 are numerically investigated by finite element models in terms of rotational capacity and strength under cyclic loading. Within the scope of this study, ABAQUS software is used to develop finite element models, and no experimental study is carried out. However, the technique followed in developing finite element models is verified with the results of the experimental study performed by Akgönen et al. (2015). In the light of the analyses results, the findings are as follows:

- In order to simulate the behavior of the connections considered by using finite element models, a detailed study is required to determine the proper material parameters. In addition, representing the strength degradation is found challenging since many parameters are involved.
- Analysis results show that, plasticity occurred only in the plastic hinge region on the beam and the other connecting elements remained in elastic, as expected and predicted within the design principles.
- It is observed that the IPE300-HEB360 and IPE330-HEB360 four-bolt extended end-plate beam to column connections meet the rotational capacity requirement and the flexural strength of 80% of the plastic bending moment at 0.04 rad rotation angle as per AISC 341-16.

In order to expand the scope of the study presented in this paper, it is recommended to conduct studies and research in the following areas:

- Supporting the finite element analysis results with experimental studies,
- For the finite element models studied in this study, investigation of the effect of material models defined with different parameters and finite element type and/or adding welds to the models on the behavior of the connections under cyclic loads,

– Conducting a similar study for wide-flanged European profiles as beams, both experimentally and numerically, to investigate whether the application limits in AISC 358-16 can be extended.

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