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EFFECT OF CIRCULAR BOLTS CONFIGURATION ON THE BEHAVIOR OF EXTENDED END PLATE CONNECTIONS

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Abstract

The goal of this investigation is to demonstrate through finite element (FE) studies the effect of circular bolts configuration on the behavior of eight bolted unstiffened extended endplate connections when subjected to monotonic loading. FE models incorporating pretension of fasteners, full contact interactions and nonlinear material and geometric characteristics of extended endplates are developed and validated against experimental results available in the literature. Moreover, eight models on extended endplate (four having circular bolt configuration, and four having rectangular bolt configuration) are tested under monotonic loading. A parametric study is conducted varying column flange thickness and bolt configuration (circular and rectangular) to investigate their effect on the induced prying forces, bolt force, and force total-deformation responses. Contributions from endplate deformation (inducing primary prying forces) and column flange deformation (inducing secondary prying forces) are quantified for both extended endplate connections with circular and rectangular bolt configurations. The results show that extended endplates with circular bolts configurations. This study sheds the light on the behavior and strength of eight bolted unstiffened extended endplate with circular bolt configurations. Future experimental research work will be conducted to collect data that will lead to the prequalification of this connection typology for use in moment resisting frames.

Keywords: Extended endplate; Circular bolts configuration; Finite element; Prying; Secondary prying.



1. Introduction

Extended endplate connections have become the choice of many structural engineers in designing connections for moment resisting frames in seismic areas. Full scale experimental tests on stiffened and unstiffened eight bolted extended endplate connections with rectangular bolt configuration are reported in the literature. The most important ones include the experiments conducted by Chasten et al. [1], Sumner and Murray [2] and Katula and Dunai [3]. It is concluded that stiffened eight bolted extended end-plate connections have the rotational stiffness, ductility and strength required for use in seismic applications when compared to their unstiffened counterparts. Analytical studies on the behavior of endplate connections with rectangular bolt configuration are presented in the literature. The most important ones include Tarpy and Cardinal [4], Kukreti et al. [5], Murray [6], and recently Ghassemieh et al. [7], and Liu and Wang [8]. Previous analytical studies consider that the endplate thickness is a major parameter that affects the stiffness of the connection and its global response. These studies proposed design guidelines for improving the ductility and strength of endplate connections. However, column flange deformation causing the additional bolt force in the absence of continuity plates was not explicitly addressed in the existing design of extended endplate connections. Continuity plates are often used in extended endplate/column systems to stiffen the column flange and web, in order to resist large forces transmitted by the beam flange. On the other hand, detailing columns without continuity plates reduces the cost and effort needed for fabrication. Thus, extended endplates without continuity plates should be investigated for use in seismic design.

Very few experimental tests and FE models are conducted on eight bolted extended endplate connections with circular bolt configuration subjected to cyclic loading. The most important ones include Kiamanesh et al. [9] and Schweizer [10]. Experimental and FE results show that positioning the bolts in a circular pattern around the flange alters the distribution of the tensile force, and therefore increases the overall capacity and ductility of the connection. Despite all experimental and analytical tests conducted on endplate connections under seismic loadings, eight bolted unstiffened extended endplate with circular bolt configuration behavior was not addressed thoroughly as far as strength, stiffness, and ductility. Also, the effect of prying forces was not considered in predicting the response of such connections subjected to cyclic loading.

One of the main behavioral characteristics of extended endplate connections in predicting the ultimate strength and response is the prying phenomenon. Total prying is defined as the amount of tensile force that is added to the bolts due to a significant deformation of extended endplate/column flange system. In particular, secondary prying is defined as the additional force induced in the tension bolts due to excessive column flange deformation (Hantouche et al. [11] and Hantouche et al. [12]). Several models for predicting the ultimate strength and response are reported in the literature and the important ones include those suggested by Kulak et al. [13], Swanson [14], Eurocode 3 [15], and recently Hantouche et al. [16] and Bai et al. [17]. Therefore, it is necessary to develop a model to quantify the amount of prying forces and to predict the force-deformation response of eight bolted extended endplate connections with circular bolt pattern subjected to seismic loading.

In summary, this research aims at investigating the strength and behavior of eight bolted unstiffened extended endplate connections with circular bolt configuration through FE modeling. First, preliminary design guidelines are proposed for extended endplate connection with circular bolts configuration. Second, FE models are developed and validated against experimental results available in the literature. Third, FE component models of eight bolted unstiffened extended endplate connection with circular and rectangular bolts configurations are tested under monotonic loading. Results show that extended endplate connections having circular bolts configuration, consistent with the proposed design guidelines, exhibit more ductile behavior and lower secondary prying forces when compared to those with rectangular bolt configuration.



2. Preliminary design of extended endplate connection with rectangular and circular bolts configurations

2.1 Connection preliminary design

Eight bolted extended endplate connections with circular and rectangular bolt configurations are designed and detailed using guidelines available in the AISC 358-10 [18]. The extended endplate is welded to the beam and the beam/endplate system is field bolted to the column flange (Fig.1). A rectangular matrix of 8 bolts (2 columns and 4 rows) is provided at the level of each beam flange as shown in Fig.2(a). The connection is designed such that the plastic hinge occurs in the beam at a distance, d, from the face of the column. Note that the beam and column are made of A992 steel, the plate material is made of A36 with A325 bolts. The beam is designed as a seismically compact element.



Fig. 1 – Extended endplate connection

The connections considered in the design consist of the equivalent of W18 beam connected to columns with the flange thicknesses, t_{cf} , varying from 1.0 cm (0.375 in.) to 5.0 cm (2.0 in.). The preliminary connection configuration is based on the following steps:

1. First identify the independent geometric parameters of the extended endplate. Select values for the gauge distances $(g, p_{fi}, p_{fo}, p_b, d_e, b_p)$ shown in Fig.2(a) within the range of acceptable values given in table 6.1 of the AISC 358-10 [18]. After choosing the geometric parameters, h_1 , h_2 , h_3 , and h_4 (mm) can be calculated (see Fig.2(a)).

2. Assume there is no prying. Determine the minimum bolt diameter d_b (cm), with capacity to resist the applied moment at the face of the support M_f .

3. Select the extended endplate thickness, t_p (mm), based on endplate yielding mechanism. Select the minimum required thickness to the nearest 0.3 cm (1/8 in.).

4. The endplate should not extend from the top of the beam flange by more than 12.7 cm (5 in.), avoiding any local buckling behavior at both edges of the plate.

For the circular bolt configuration, the designer would start with a preliminary rectangular bolt design, and then proceed in accordance to the proposed assumptions and modifications:

1. It is assumed to have equal gage distance $(p_{fo} = p_{fi})$ for the bolts to get a perfectly symmetrical circular configuration.

2. The bolt gage distances shown in Fig.2(b) are calculated as $g_1 = (b_p - 2e)/2$ and $g_2 = b_p - 2e$, where b_p (cm) is the plate width and e (cm) is the minimum edge distance defined in section J of the AISC 360-10 [19].



3. The 4 far bolts (Sets 1 and 3) are moved vertically, rearranged on the circle centered at the beam flange and passing by the bolts in Set 2 giving a symmetric circular configuration as shown in Fig.2(b).

4. The minimum bolt spacing requirements are in accordance to section J in the AISC 360-10 [19].



Fig. 2 – Extended endplate with: (a) rectangular bolt configuration, (b) circular bolt configuration

2.2 Cases selected for analysis

The independent geometric and force related parameters for extended endplate connections are identified. The endplate thickness t_p , the column flange thickness t_{cf} , and the bolts vertical gages h_1 , h_2 , h_3 , and h_4 reflected by the bolts arrangement are three geometric parameters that impact the amount of prying and deformation in extended endplate connections. The force-related parameter is the applied tension load T on the extended endplate resulting from the axial loading applied at the beam tip. The minimum required thickness of the extended endplate, t_p , is calculated based on the applied moment encountered in the beam. Furthermore, two types of columns are investigated, ranging from rigid columns (column flange is thicker than the endplate), to flexible columns (column flange thinner than the endplate). The study covers columns with flange thicknesses, t_{cf} , ranging from 1.0 cm (0.375 in.) to 5.0 cm (2.0 in.). Every case is associated with an extended endplate having circular and rectangular bolt patterns to study the effect of bolt distribution on the response. Note that, the endplate thickness, t_p , is a dependent parameter, incorporated in the design according to the existing design restrictions defined in the AISC 358-10 [18].

In order to study the amount of total prying in endplate/column systems for a given load T, a total of eight extended endplates component models are studied and listed in Table 1. Figure 3 shows a sample of the FE component models that were designed to be tested under monotonic loading. Note that the column and beam components are built up from welded plates representing one flange and half the web.



Specimen Number	Bolt diameter	Endplate thickness	Column flange thickness	Loading	Bolt configuration
1	1.6 cm (5/8 in.)	1.6 cm (5/8 in.)	1cm (3/8 in.)	Monotonic	Circular
2			1.6 cm (5/8 in.)		
3			2.5 cm (1 in.)		
4			5 cm (2 in.)		
5			1cm (3/8 in.)		Rectangular
6			1.6 cm (5/8 in.)		
7			2.5 cm (1 in.)		
8			$5 \mathrm{cm}(2 \mathrm{in})$		

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Fig. 3 – Endplate with circular bolts configuration: (a) Top view, (b) Front view.

3. FE Modeling

Using ABAQUS, 3-D FE models are developed for typical extended endplate connections which incorporate the following characteristics: (1) nonlinear material behavior for base and bolt material; (2) full pretensioning of fasteners; and (3) contact interaction between the extended endplate and column flange, bolt head and column flange, and bolt nut and endplate.

The FE modeling technique described in this section is to be used (1) for validation against experimental results available in Sumner and Murray [2] and Schweizer [10], and (2) for running FE simulations to predict the response and strength of extended endplate connection having rectangular and circular bolts arrangement which conform with the designed component models.

3.1 FE modeling vs. Experiment (Sumner and Murray [2] and Schweizer [10])

FE models are developed, using ABAQUS, to reproduce the experimental results available in the literature. Details of the geometric configuration and material model used in the FE analysis can be found in [2] and [10].



3.1.1 Mesh design

Eight-node linear brick elements with reduced integration (C3D8R) are used to mesh the endplate/column system. Figure 4 shows a full 3-D model representing the extended endplate/column system with rectangular bolts configuration. The length of the column is equal to 305 cm (120 in.). The model consists of a column, a beam, an endplate and 16 tension bolts. The beam is attached to the endplate using tie constraint representing the CJP welds in order to allow full load transfer between the elements. The tie constraint fuses together two elements having different mesh constitution. The interaction between the plate, bolt head, bolt shank and column flange are modeled as surface to surface contact with finite sliding and a coefficient of friction equal to 0.2.

3.1.2 Material properties

The von Mises yield criterion is used in the analysis. The bolts are modeled in ABAQUS using their gross area, rather than their effective area. A490 bolts are modeled with a yield stress of 811 MPa (117.5 kips) and an ultimate stress of 872 MPa (126.5 kips). The yield strain is 0.00405 and the ultimate plastic strain is 0.03084. The yield and ultimate stress used for the base material are 385 MPa (55 ksi) and 500 MPa (71.5 ksi), respectively. The yield strain used for the base material is 0.00189, and its plastic strain is 0.09827. For all the steel members of the connection, Young's modulus is assumed as 203,000 MPa (29000 ksi), and Poisson's ratio as v = 0.30. In conclusion, a bilinear model with isotropic hardening for both base and bolt material is used in the analysis.

3.1.3 Boundary conditions and loading

The analysis is divided into two steps: (1) pretension step, where the 16 bolts are pretensioned to the minimum required force defined in the AISC 360-10 [19], and (2) loading step, where the monotonic load is applied at the beam tip. In the pretension and loading steps, the degrees of freedom of the column edge are constrained against any translation and rotation. The lateral sides of the beam flange are assumed to be fixed against translation along the x-direction. The outer and inner faces of the beam flange are fixed against translation in the y-direction to avoid any bending action on the connection (Fig.4).

To compute the net primary prying force, Q_p , the column flange is assumed to be fully rigid and is fully constrained against any translation and rotation. However the column flange is free to deform when computing the total prying force, Q_T . During the first step, the pretensioning force is generated by applying a bolt force on the shank equal to the minimum pretension force. Throughout the loading step, surface pressure is applied on the flange section at the beam tip.

3.1.4 Validation with experimental results

Figures 5(a) and 5(b) show a comparison of the FE moment-rotation response of the extended endplate connection with experimental results of Sumner and Murray [2] and Schweizer [10], respectively. The FE model predicts with excellent agreement the experimental moment-rotation envelope curve as far as stiffness, strength and ductility. In addition, the FE models exhibited similar failure modes as described in the experimental results.

The FE model developed in this study to reproduce the experimental results conducted by Schweizer [10] shows that buckling of the beam flange and web occurs in the extended endplate connection with circular bolt configuration as shown in Fig.5(b). It can be seen that the endplate is still in its elastic range; however yielding occurs in the bolts which conforms to the experimental results reported in Schweizer [10]. Hence, it can be concluded that the FE modeling technique can be used to study extended endplate connections.



Fig. 4 – 3-D model of endplate connection with rectangular bolt configuration.



Fig. 5 – FE vs. experiment: (a) Extended endplate with rectangular bolt configuration moment-rotation curves [2], (b) Extended endplate with circular bolt configuration moment-rotation curves [10].



3.2 FE modeling of component tests

Using ABAQUS, FE models of eight bolted extended endplate connections with circular and rectangular bolt configurations are developed. The main objective is to highlight the difference between the circular and rectangular bolts configurations.

The component model developed in ABAQUS is shown in Fig.6. C3D8R brick elements are used to mesh the system. The beam is attached to the endplate using tie constraint representing the CJP welds. A coefficient of friction equal to 0.2 is used. A325 bolts are modeled with a yield stress of 680 MPa (98.6 kips) and an ultimate stress of 749.1 MPa (108.65 kips) with a plastic strain of 0.0045. The yield and ultimate stress used for the plate are 293 MPa (42.5 ksi) and 448 MPa (65 ksi), respectively, with a plastic strain of 0.07. The yield and ultimate stress used for the column and beam are 391.5 MPa (56.78 ksi) and 493.8 MPa (71.62 ksi), respectively, with a plastic strain of 0.1.

The component models are loaded in two steps: (1) pretension step, where the 8 bolts are pretensioned, and (2) loading step, where a monotonic load is applied at the beam tip as an induced displacement. Boundary conditions are shown in Fig.6.



Nodes on the top and bottom edges of the column, plate, and beam are fixed against translation in the y-direction

Fig. 6 – 3D model of endplate connection with circular bolt configuration.

3.2.1 Investigation of primary and secondary prying

The prying force is calculated at the step where the first bolt row fails causing the failure of the connection. The bolt force exhibited in every bolt, B, is calculated by multiplying the von Mises stresses by the gross section area of the bolt shank. The prying force, Q, is calculated by subtracting the total bolt force B from the total applied force, T, at failure: Q=B-T. Two models are generated in ABAQUS to calculate the secondary prying, Q_s . In the first model, the column flange is free to deform used to calculate the total prying, Q_T . The second model is developed to calculate the primary prying, Q_P , with rigid column flange. The percentage secondary prying is obtained by subtracting the primary prying from the total prying at the same load step T where failure occurs, as shown in Eq. (1).

$$\left(\frac{Q_s}{T}\right) = \left(\frac{Q_T}{T}\right) - \left(\frac{Q_p}{T}\right) \tag{1}$$

The primary, secondary, and total prying percentages are calculated for each column flange thickness of as shown in Table 2. Results show that the extended endplate/column system with circular bolt configuration exhibit lower secondary prying forces (Table 2). On the other hand, endplate with rectangular bolt configuration exhibit lower primary prying forces when compared to its circular counterpart. More generally, as the column flange thickness increases, the secondary prying force decreases in both endplates with circular and rectangular bolt configurations.



t_{cf} (cm)	Percent prying (%)	Circular	Rectangular
	Primary	11.6	10.8
1	Secondary	13.9	16.3
	Total	25.5	27.0
	Primary	16.1	14.2
1.6	Secondary	1.8	2.9
	Total	17.9	17.1
	Primary	14.0	14.0
2.5	Secondary	0.2	0.3
	Total	14.2	14.3
	Primary	13.8	13.9
5	Secondary	0.1	0.2
	Total	13.9	14.1

Table 2 – Percentage of total, primary, and secondary prying

3.2.2 Bolt force variation

To further investigate the effectiveness of the circular bolt pattern, the bolt force history is investigated for extended endplate connections having circular and rectangular bolt configurations with t_{cf} equal to 1.0, 1.6, 2.5 and 5 cm as shown in Fig.7 and Fig.8, respectively. It can be seen that for all column/endplate systems with circular bolt configurations, bolts D are involved in carrying the load earlier and more effectively than bolts D in rectangular bolt configurations. This is because in connections with circular bolt pattern, the far bolts (D) carry equal or more load than the near bolts (bolts B and C), which are subject to higher bending moments in rectangular bolt configuration and carry more load than the other bolts (bolts A and D) for thick column flange (2.5 cm and 5.0 cm) with circular bolts configuration, the force is equally spread across bolts B, C, and D while for rectangular bolt configuration the force is spread across bolts B and C only.

Based on FE results, in the circular bolt pattern the bolts are more effective and reach higher capacity than the bolts in the connection with rectangular bolt configurations. This is because the load is efficiently spread across the bolts, developing a more ductile behavior.

3.2.3 Force displacement

The force-total displacement response of eight bolted extended endplate connections with circular and rectangular bolt configuration is shown in Fig.9. The total displacement is defined as the displacement between endplate and column flange (Fig.9(a)). Results show that thicker column flange exhibits higher force and lower total displacement. Also, specimens with circular bolt pattern are stiffer then their rectangular counterparts as they undergo smaller displacement for the same load. However, specimens with rectangular bolt configuration sustain larger total displacement for thin column flange (1.0 cm and 1.6 cm) when compared to their circular counterparts this is because the force is distributed equally among bolts B, C, and D while for their circular counterparts bolts D develop the highest force.



Fig. 7 – Bolt force history for circular configuration: (a) 1.0 cm column, (b) 1.6 cm column flange, (c) 2.5 cm column flange, (d) 5.0 cm column flange.



Fig. 8 – Bolt force history for rectangular configuration: (a) 1.0 cm column, (b) 1.6 cm column flange, (c) 2.5 cm column flange, (d) 5.0 cm column flange.



Fig. 9 – (a) Total displacement, (b) Force- total displacement

5. Conclusion

In this research, a detailed design procedure is proposed for extended endplate with circular bolt configuration associated with deep girders. 3D nonlinear FE models were developed and validated against experimental results available in the literature. Also, a parametric study was conducted on 8 connections to investigate the effect of the circular bolt configuration on the prying phenomenon, bolt-force distribution, and force total-displacement. The prying force was quantified and analyzed based on FE results. Extended endplate with circular bolt configuration exhibited smaller secondary prying forces when compared to its rectangular counterpart. Furthermore, adopting a circular bolt configuration provides more overall ductile behavior and allows the bolts to be engaged more equally in the tensile axial load. This study provides engineers with guidelines to design extended endplate connections with circular bolt configuration.

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7. References

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