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Performance enhancement of eight bolt extended end-plate moment connections under simulated seismic loading

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A B S T R A C T

Extended end-plate (EEP) moment resisting connections provide the advantage of eliminating field welding and by virtue of this, facilitate fast field erection of building frames. The eight bolt stiffened (8ES) EEP connection is one of the prequalified moment connections in the AISC 358 standard for special moment frames (SMFs) in seismic regions. In this connection, a stiffener plate is welded between the end plate and the beam flanges to strengthen the extended portion of the end plate. This stiffener reduces prying action and more uniformly distributes flange forces among the bolt group. In experimental studies, the 8ES connection has shown ductile response to simulated seismic loading with test specimens typically failing due to beam buckling and gradual strength degradation. However, cracks initiating at the toe of the stiffener leading to brittle fracture of the beam flange has also been observed due to the high stress concentration in this region. The study reported herein proposes an eight-bolt EEP connection in which the end plate stiffener is removed and the bolt arrangement is modified to promote uniform distribution of flange forces among the bolt group. The proposed connection was developed through detailed finite element analysis in which various bolt arrangements for stiffened and unstiffened eight-bolt EEP connections were considered. The proposed connection displayed reduced beam flange stress and strain concentrations, delayed or reduced rate of strength degradation from local buckling and more uniform distribution of bolt forces when compared to the alternatives. Furthermore, when compared to the currently prequalified 8ES connection, despite requiring thicker end plates, the proposed connection is anticipated to result in cost savings from the removal of the end plate stiffener. Future analytical and experimental needs for further development of the proposed connection are discussed.

1. Introduction

In bolted extended end-plate (BEEP) moment connections, steel plates are shop welded to the ends of a beam which is then field bolted to the connecting members. Though shop fabrication of BEEP connections may be more costly than field welded connections, they offer the advantage of eliminating the difficulties associated with field welding, and may provide rapid erection of moment frames [1]. Simulated seismic testing of BEEP moment connections have shown them to be capable of providing considerable ductility and seismic resilience and as a result, they have been included in the 2010 ANSI/AISC 358 [2] prequalified connections for special and intermediate moment frames for seismic applications. The 2010 ANSI/AISC 358 [2] prequalifies three types of BEEP connections, the four bolt unstiffened (4E), four bolt stiffened (4ES) and the eight bolt stiffened (8ES) (Fig. 1).

The cyclic performances of the prequalified BEEP connections have been evaluated through large scale experimental and analytical studies. Early cyclic testing on four bolt unstiffened (Fig. 1a) and four bolt stiffened (Fig. 1b) extended end-plate connections demonstrated that ductility and energy dissipation are improved if connection components (end plate, end plate stiffener and bolts) are designed to undergo limited inelastic action, forcing beam yielding and panel zone deformation to provide the inelastic rotation [3–6]. Sumner and Murray [7] and Sumner et al. [8] corroborated these findings for the four bolt unstiffened extended end-plate connection and validated the eight bolt-stiffened extended end-plate connection (Fig. 1c) for seismic applications. Test results from these studies have been used in the development and verification of design equations for seismic applications [1,2,9].

In stiffened connections (4ES and 8ES) a triangular stiffener is welded between the outer surface of the beam flange and the extended portion of the end plate. This stiffener serves the main

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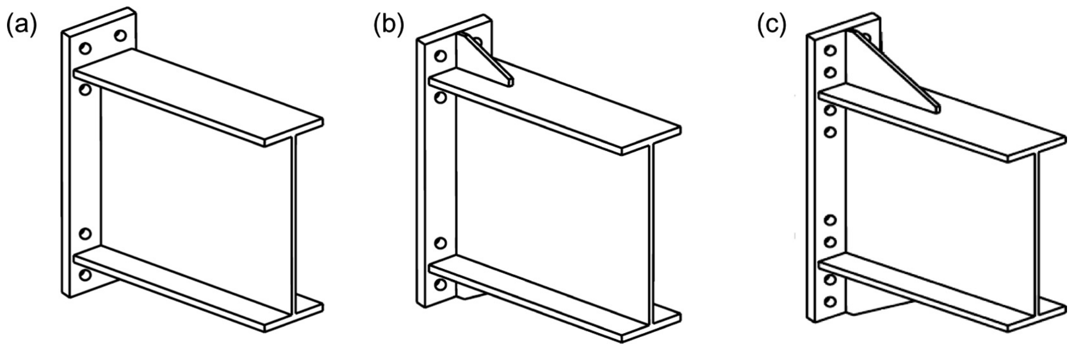

Fig. 1. ANSI/AISC 358 Prequalified Extended End Plate Connections (a) Four bolt unstiffened (4E), (b) four bolt stiffened (4ES), (c) eight-bolt stiffened (8ES) [9].

purpose of increasing the strength and stiffness of the end plate. Experimental and analytical studies show that bolt force distribution is more uniform and end plate deformations as well as prying forces are reduced with the addition of the stiffener [3,10]. End plate design equations in the 2010ANSI/AISC 358 standard which are derived from yield line analysis of the end plate account for this added strength and as a result, four bolt stiffened (4ES) connections require thinner end plates than do four bolt unstiffened (4E) connections with all else equal [1,2,9].

Experimental investigation by Sumner et al. [8] on the cyclic behavior of 8ES connections designed to develop 110% of the nominal plastic moment capacity of the beam, have shown them to display ductile behavior achieving 5 or 6% story drift prior to the end of testing. In these experiments, loading was terminated due to excessive lateral displacement of the beam, at which point, the measured flexural resistance of the connections had gradually reduced to below 80% of the plastic moment capacity of the beam. However, in a recent study [11], small cracks initiating at the welded junction between the end plate stiffener and the beam flange were observed in all 8ES specimens. In one specimen, this crack led to a brittle overload fracture of the beam flange during cycles at 4.7% interstory drift. Despite the fact that this specimen attained the required 4% interstory drift angle required by AISC 341 for use in special moment frames, the failure mechanism resulted in sudden, rather than the gradual strength loss observed in other eight bolt stiffened extended end-plate connection tests [7,8]. This failure was attributed to the high strain demands and high stress triaxiality at the stiffener toe, which are the result of the stress concentration from the sharp change in geometry (reentrant corner), and the local restraining effect at the welded junction of the stiffener and the beam flange respectively.

While the cyclic performance of 8ES connections in laboratory tests meet the requirements of AISC 341, the endplate stiffener introduces a stress concentration and adds complexity to connection fabrication and inspection. Therefore, the motivation of this study is to develop an improved *unstiffened* eight bolt extended end-plate moment connection for seismic applications. The primary feature of this connection is an octagonal bolt arrangement that provides relatively uniform distribution of bolt forces. In addition, this connection eliminates both the unfavorable stress concentration due to the end plate stiffener in the 8ES connection and the non-uniform distribution of bolt forces that contributed to bolt failures in the previously studied unstiffened eight-bolt four wide (4W) connection [8,9]. Despite requiring thicker endplates than the 8ES in order to resist endplate shear forces and limit bolt prying forces, the proposed connection reduces additional welding and fabrication associated with the end plate stiffener while also providing more usable floor space above the concrete slab. These features may make the proposed BEEP connection more economical and attractive for use in new construction.

It must be noted that during the development of the proposed BEEP connection, Kiamanesh et al. [12] investigated a circular bolt arrangement for eight bolt extended end-plate connections which is similar to the octagonal bolt arrangement proposed in this study. In the study by Kiamanesh et al. [12] finite element analysis (FEA) was used to show that a circular bolt arrangement was effective at reducing hysteresis pinching, consequently improving connection strength and energy dissipation when compared with the traditional rectangular bolt arrangement. Their study concludes that these benefits are appreciable in connections with large bolt diameters and end plate thicknesses and in general are a result of more uniform distribution of bolt forces.

Although Kiamanesh et al. [12] demonstrated the effectiveness of the circular bolt arrangement at reducing hysteresis pinching and improving connection strength and energy dissipation, the necessity of the bolt arrangement has not been addressed with comparison to the prequalified eight bolt stiffened (8ES) connection and, the potential failure mechanisms of the proposed connection, particularly the low cycle fatigue mechanism, were not considered. The study reported herein presents the systematic development of the proposed octagonal bolt arrangement through observations of the behavior of the eight bolt stiffened (8ES), eight bolt unstiffened (8E) and eight bolt-four wide unstiffened (8E-4W) extended end-plate connections. The improved connection was therefore developed with the primary objective of addressing the specific shortcomings of existing extended end-plate (EEP) connection designs.

The presentation of the study begins with the description and validation of the finite element modeling (FEM) of EEP connections. This is followed by the presentation of systematic finite element analysis of existing eight bolt extended end-plate designs and comparison of these with the proposed improved design. The analysis investigates the influence of details such as end plate stiffener, bolt configuration and end plate thickness on the performance and potential failure mechanisms of eight bolt extended end-plate connections under simulated seismic loading. Potential failure mechanisms are studied through various response indices which are calculated from the finite element model results. Finally, the results of a parametric study to examine the influence of bolt spacing parameters on the bolt force magnitudes and distribution are presented.

2. Finite element modeling of extended end-plate connections

The use of finite element modeling to simulate BEEP connection behavior dates back to 1978 with efforts of Krishnamurthy [13]. However, early studies focused mainly on simulating the monotonic response of BEEP connections [14–17] with very limited study on cyclic behavior [18]. In the last two decades, several stud-