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Behaviour of end-plate moment connections under earthquake loading

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Abstract

A series of eight full-scale structural steel beam-to-column end-plate moment connection specimens was tested under cyclic loads. The parameters investigated were end-plate thickness, bolt diameter, end-plate extended stiffener, column stiffener, type of flush and extended end-plate. The experimental results are presented in terms of moment capacity, rotational stiffness, rotation capacity and hysteretic curves. The test results indicate that extended end-plate connections have adequate strength, joint rotational stiffness, ductility and energy dissipation capacity required for use in seismic moment frames. Based on the test results and analysis, details on end-plate moment connections for seismic steel frames has been proposed, three failure mode requirements and the corresponding resistance have been recommended to assure that the end-plate connection can provide enough rotation capacity and energy dissipation capacity under earthquake loading and its ultimate failure mode is ductile. A bilinear kinematic hardening hysteretic moment–rotation (M–ϕ) model for the end-plate connection extended on both sides has been proposed.

Keywords: End-plate connection; Cyclic load; Seismic; Rotation capacity; Joint stiffness

1. Introduction

During the Northridge earthquake in California in 1994 and the Kobe earthquake in 1995, many steel buildings suffered from fracturing in the welded moment connections. A great deal of experimental and analytical research has been conducted on the behaviour and design method of steel seismic moment connections, for example the SAC steel research project [1]. One of the alternative connections investigated was the end-plate connection, especially the extended type.

The end-plate connection consists of a plate shop welded to the end of a beam and field-bolted to the connecting member. The connections can also be used to splice two beams together [2]. Because the bolted beam-to-column connection is less rigid than beam-to-column welded connections, end-plate connections offer enhanced ductility at the beam-to-column connection. Since the welding for these connections is performed in the shop under controlled conditions, high-quality welds are easier to achieve with this type of connection than with field welded connections [3]. End-plate connections also have the advantages of easy fabrication and fast erection compared to welded connections. The typical end-plate connections are flush end-plate connections and extended end-plate connections with or without stiffeners.

However, details of bolted end-plate connections vary enormously, as well as their fabrication and erection. Many variable parameters will affect their behaviour, such as bolt diameter, number of bolt rows and columns, bolt spacing, bolt grade, end-plate dimensions, stiffener, column and beam sizes, bolt pretension force, yield strength of steel, slip coefficient of contact surfaces, etc. Although many monotonic loading tests of end-plate connections have been performed, these tests cannot cover a range of so many variables and their monotonic behaviour is still not well understood. Furthermore, very limited experimental work on their behaviour under cyclic loading has been conducted and their seismic behaviour needs to be further investigated.

Ghobarah et al. [4–6] have conducted two series of end-plate connection experiments under cyclic loading, and they conclude that properly designed and detailed extended end-plate connections can be considered suitable for moment-resisting frames in areas of high seismic intensity.

Based on three tests on large-size beam end-plate moment connections to column flanges under severe cyclic loading, Tsai and Popov [7] pointed out that the end-plate extended stiffener

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and stronger bolts can improve the behaviour of end-plate connections under large cyclic loads significantly, the extended end-plate moment connections can be designed to develop the full plastic moment capacity of the beam under cyclic loading, and the effect of prying force is reduced by the use of an end-plate extended stiffener.

Bernuzzi et al. [9] conducted two series of tests on beam-to-column connections under cyclic reversal loading. The tests results indicate that two cycles at the same maximum amplitude are sufficient to quantify the resistance deterioration. The cyclic response of end-plate connections including flush and extended on both sides and only one side of the beam can be generally considered quite satisfactory in terms of stiffness, strength and rotational ductility.

An experimental investigation of 15 cyclically loaded extended end-plate connections was undertaken by Adey et al. [3] to assess the significance of some design parameters. According to the tests results, medium-sized beam connections are more ductile than larger beam connections, and the relaxed bolt configuration provided more energy dissipation and connection ductility.

Yorgun et al. [10] conducted two tests to investigate the effect of a gap between the end-plate and the column face on the cyclic behaviour of the extended end-plate connection. It was concluded that an end-plate connection with a gap provided by placing an I-shaped element showed better performance than the standard one.

Eight beam-to-column flush end-plate connection specimens were tested by Broderick et al. [11] under monotonic and cyclic loading conditions. These specimens displayed a stable cyclic response up to a determinable rotation limit and their performance of the test specimens indicates that this joint type could be applied to earthquake-resistant design.

Sumner and Murray [2,12] have conducted eleven full-scale cyclic extended end-plate beam-to-column moment connection tests. The experimental results demonstrate that extended end-plate moment connections can be detailed and designed for use in seismic force resisting moment frames, and a strong column, strong connection and weak beam philosophy should be utilized: the four bolt unstiffened extended and the eight bolt stiffened extended end-plate moment connections can provide the required strength, stiffness and ductility required for use in seismic regions.

The available tests are not always sufficient. Research to date indicates that end-plate moment connections can be designed with sufficient strength to develop the beam plastic moment capacity and the required beam inelastic rotation capacity. But the amount of cyclical loading experimental investigation on the four-bolt extended stiffened end-plate connection reported up to now is limited. Moreover, it is rare that several types of end-plate connection are loaded in the same series of cyclic loading tests in order to compare and study the influence of various factors, for example, flush and extended type, end-plate stiffener, column flange stiffener (i.e. continuity plate), bolt size, end-plate thickness, etc. Another important situation is that welded-plate beams and columns are widely used as elements of moment-resisting frames in many countries due to the possibility of producing variable cross-sections along the beam or column length so as best to fit the stress condition. Welded-plate sections can be most economically designed in the critical cross-sections and result in savings of steel.

In this study, eight specimens of beam-to-column bolted end-plate connections with various details and welded-plate columns and beams were tested under cyclic loads. The contribution of the panel zone and the gap between the end-plate and column flange to the connection rotation has been investigated. Bolt force responses have also been monitored by a special method. The objective is to investigate the influences of connection details, for example, flush and extended type, end-plate stiffener, column flange stiffener, bolt size, end-plate thickness, etc., on the connection strength, stiffness, ductility, failure mode and earthquake-resistant behaviour, and then propose standard connection details and a ductility design method for end-plate connections in order to obtain excellent behaviour under earthquakes.

2. Test specimens

A typical extended end-plate connection used for tests is shown in Figs. 1 and 2. The out-of-plane deformation of the specimens was restrained during tests. These eight specimens are all beam-to-column connections originated from typical multistory steel frames. The details of these eight specimens are shown in Table 1 and Fig. 3. The beam and column sizes with welded-plate I-shaped cross-sections were unchanged for all these eight specimens. The depth, web thickness and flange thickness of columns and beams are 300 mm, 8 mm and 12 mm, and the column and beam width are 250 mm and 200 mm respectively. The thickness of the column flange is taken as the same as the end-plate within the range of 100 mm above and below the extension edge of the end-plate. The thickness of the column stiffener and end-plate extended stiffener is 12 mm and 10 mm respectively.

The welds between the end-plate and beam flanges and the welds for the column flange splices are full penetration welds, and all the other welds, including the welds between flanges and webs of beams and columns, end-plates and beam webs, are fillet welds with 8 mm leg size.

The steel is grade Q345 with nominal yielding strength $f_y = 345$ MPa and the bolts are high strength friction-grip bolts (grade 10.9). The actual material properties of the steel and bolts are obtained from tensile tests on coupons and from the bolt certificate of quality as shown in Table 2. The nominal elastic modulus of the bolts is 206 000 MPa.

One column of the bolts in each connection was instrumented using strain gauges. As shown in Fig. 4, two shallow slots were grooved symmetrically on the unthreaded portion of the bolt shank, and in each slot a strain gauge was fixed and covered with resin to protect it. When tightening bolts, the line of the two strain gauges is secured perpendicular to the beam flange, so that the strain of the bolt in the connection moment plane can be measured. The bolt axial force can be calculated by the mean value of the two strain gauge measured values.