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Experimental study of ultra-large capacity end-plate joints

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ABSTRACT

When bolted joints are required in steel structures involving large spans or heavy loads, ultra-large capacity end-plate joints with 12 bolts or 16 bolts in tension should be applied if ordinary end-plate joints or large capacity end-plate joints cannot meet the resistance requirement. Four full-scale specimens of ultra-large capacity end-plate joints were tested subjected to monotonic load. The moment-rotation curves of all the specimens were obtained, and the moment resistance, rotational stiffness, and distribution of the bolt strain increments in tension were analyzed when the bolt diameter, the end-plate thickness, or the layout of the bolts changed. The tested ultra-large capacity end-plate joints shared the failure mode of end-plate yielding followed by bolt fracture or necking, and the thickness of the end plate had an obvious influence on the joint resistance. A significantly inhomogeneous distribution of bolt strain increments was observed. Bolts in corners, which made little contribution to the moment resistance in the tests, could be removed or considered as shear-resistant bolts. In the design of this kind of joint, the resistance of the panel zone can be decided according to the Chinese code, the American code, or the Eurocode, and the equivalent number of the bolts in tension is recommended to be 7.0 based on a proposed distribution model of the tension load resisted by bolts in tension, derived from the tests.

1. Introduction

The extended end-plate joint, with an end plate welded at the end of the beam and connected to the flange of the column by bolts, is among the widely adopted beam-to-column joints in steel frames. This joint form has an advantage in construction without field welding. Also, large rotational stiffness and satisfactory ductility can be developed in this joint provided it is properly designed [1,2,3,4,5,6,7]. Conventional configurations of extended end-plate joints are shown in Fig. 1, with eight bolts in total, four of which are arranged in tension. End-plate stiffeners are often applied to improve joint performance when the joint is designed as a rigid one. Many investigations on the performance of conventional extended end-plate joints have been conducted [8,9,10,11,12,13], and several design methods have been proposed in different design codes or guides [14,15,16,17,18,19].

The design method in the Chinese code [14] and that in the American code [18] regard conventional extended end-plate joints as rigid, so only the moment resistance needs to be checked. In both methods the four bolts in tension are considered to share the tension force equally and the T-stub analogy method is employed to check the resistance of end plates. Also, yield line models based on plate theories are specified in several design codes or guides [15,16,17,18] with equations to check the end-plate thickness provided. In Eurocode 3, all joints must be estimated to determine whether they are rigid, semi-rigid, or just pinned, based on the ratio of rotational stiffness to beam line stiffness [19], so both the moment resistance and the rotational stiffness must be checked. The component method is adopted to predict the joints' moment resistance and initial rotational stiffness, and the basic component in extended end-plate joints is the T-stub [10]. It also should be noted that the specified ultimate states of the high-strength bolts in the Chinese code are different with that in the other two codes above. In the Chinese code the employment of slip-critical high-strength bolts is recommended in end-plate connections and it is specified that the ultimate state of such bolts in tension is the state when the connected plates separate from each other around the bolts [14], whereas in the American code and the Eurocode, the bolt reaches its ultimate state when it fails.

As the moment resistance demand for beam-to-column joints is increased in steel frames involving large spans or heavy loads, conventional extended end-plate joints might not meet the resistance requirement, being limited by the axial tension capacity of the bolts. Two improved configurations, both referred to as large capacity end-plate joints with eight bolts arranged in tension, have been proposed and investigated [20,21,22]. The first configuration, illustrated in Fig. 2(a), features a wide end plate and two 4-bolt rows in tension, and the component method in Eurocode with T-stubs can be adopted in the design of such joints in theory if the stiffeners are ignored. The second configuration, illustrated in Fig. 2(b), features a long end plate and four bolt-rows in tension. A method based on the research of Murray and Kukreti [20] was proposed in the American code for the design of stiffened long-end-plate joints [16,18], and the component method can also be applied to design this kind of joint theoretically. Based on

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Notation

$t_{ep\text{-}nom}$	nominal thickness of end plate
b_b	width of beam
h_b	depth of beam
t_{bf}	thickness of beam flange
t_{bw}	thickness of beam web
t_{ep}	thickness of end plate
b_c	width of column
h_c	depth of column
t_{cf}	thickness of column flange
t_{cw}	thickness of column web
E	Young's modulus
f_y	yield strength
ε_y	yield strain
ε_{st}	strain at the end of yielding plateau
f_u	ultimate tensile strength
φ_c	connection rotation
φ_{pz}	panel zone shear rotation
M	moment at beam end
M_u	ultimate moment resistance
M_y	yield moment resistance
φ	joint rotation
φ_u	joint rotation corresponding to ultimate moment resistance
φ_{up}	plastic join rotation corresponding to ultimate moment resistance
φ_y	joint rotation corresponding to yield moment resistance
K_φ	rotational stiffness
γ	engineering principal shear strain in plane
N_t	tension load resisted by the bolt most likely to fail
N_{eq}	equivalent number of tension bolts
N_b	tension resistance of a single bolt

the existing investigations, large capacity end-plate joints can show heightened rotational stiffness [22] but the axial forces in different bolts in tension develop quite inconsistently, with the stress increments of the outer bolts significantly lower than that of the inner bolts close to the web or extended stiffeners [23].

The moment resistance of large capacity end-plate joints may still be insufficient in situations with special requirements. Therefore, a new end-plate joint called the ultra-large capacity end-plate joint is proposed in this paper. As illustrated in Fig. 3, this new joint form has an arrangement of 32 bolts or 24 bolts in total, with half of the bolts located in the tension side. As in large capacity end-plate joints, bolts in tension in

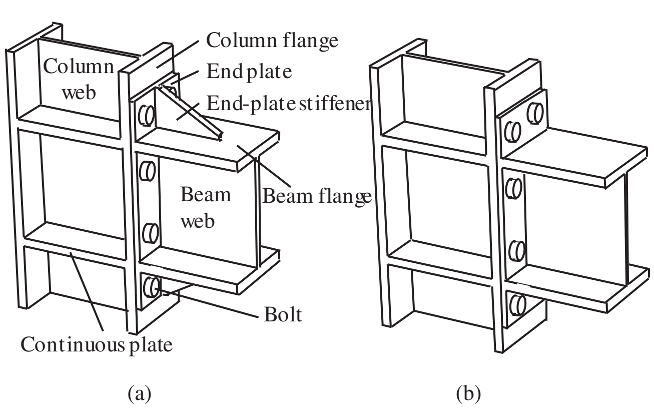

Fig. 1. Conventional configurations of extended end-plate joints: (a) with end-plate stiffeners; (b) without end-plate stiffeners.

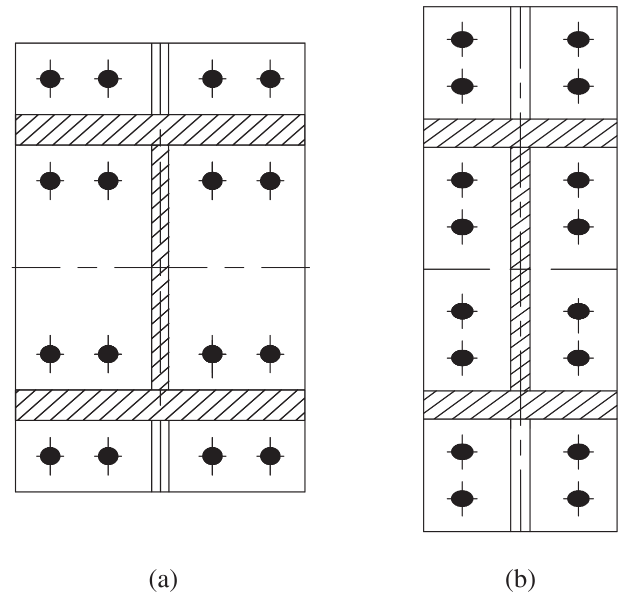

Fig. 2. Configurations of large capacity end-plate joints: (a) with wide end plate; (b) with long end plate.

ultra-large capacity end-plate joints are considered to develop a complex distribution of axial force. It should be noted that end plates with stiffeners, which are recommended to improve joint performance, can experience a complex stress state, so that ultra-large capacity end-plate joints cannot be properly divided into conventional T-stubs, indicating that the existing design methods given above for end-plate joints cannot be applied in the design of this joint form directly. Also, the yield line models in existing codes are all corresponding to connection configurations with one bolt column in each side and cannot be applied in design of the two-column bolt group in ultra-large capacity end-plate joints. To determine a proper design method for the tested joint form, it is necessary to analyze the performance of this kind of joint.

In this paper, four full-scale specimens of ultra-large capacity end-plate joints with different end-plate thickness, bolt diameter, or bolt layout were subjected to monotonic loads to investigate the performance of this new joint form. Failure modes as well as moment-rotation curves are discussed and the distribution of the tension strain increments in the bolts is analyzed.

2. Experimental program

2.1. Specimens

Four ultra-large capacity end-plate joint specimens, fabricated with welded H-section beams and columns, were designed with different joint parameters. The beams and the columns shared the same welded section H800 × 500 × 60 × 30. The total length of 5 m for the columns was determined based on a typical steel frame design, and the cantilever beam, connected to the flange with end plate and bolts in the middle of the column, was 3 m in length. The parameters of the joints are shown in Table 1 and the measured dimensions of all the specimens are given in Table 2. The name of each specimen is constituted by the sequence number (1–4), the nominal thickness of the end plate (EP32 for the 32 mm thick end plate and EP25 for the 25 mm thick end plate), the nominal bolt diameter (M30 bolt or M27 bolt) and a letter for the bolt layout (A or B). The specimen 1-EP32-M30-A was designed as a standard specimen whereas specimens 2–4 changed end plate thickness, bolt diameter, and bolt layout respectively compared to the standard specimen. The bolt layout types are illustrated in Fig. 3, where layout type A has 32 bolts in total and layout type B removes 8 of the bolts. There are 8 bolt rows and 4 bolt columns, and for convenience in the