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Experimental study of end-plate joints with box columns

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ABSTRACT

Bolted joints between I-section beams and I-section columns have been widely adopted in prefabricated steel frames to avoid field welding, but it is difficult to use bolted beam-to-column joints when box columns are used because of the lack of constructional spaces and the absence of practical design methods. In order to solve this problem, a new end-plate joint form with box columns and I-section beams, as well as three prefabrication techniques for this connection form, are proposed in this paper. Four full-scale specimens were tested: one of the specimens was subjected to monotonic loads, and the other three, constructed with different prefabrication techniques, were subjected to cyclic loads. On the basis of the test results, the resistance, stiffness, rotation capacity, energy dissipation capacity and failure modes of the end-plate joints with box columns were analyzed, and the influences of different prefabrication techniques on the seismic behaviours of the joints were compared. Parametric analysis was conducted with finite element models. The joint specimens prefabricated with different techniques showed similar macro-mechanical properties, and the joint rotations were mainly caused by bulges of the column flanges. All the specimens showed satisfactory deformability and ductility, developing storey drift angles of >0.07 rad before initial fractures. The prefabrication techniques notated XW and NW were recommended as preferred because of their superior seismic performance compared to that of the technique notated YW.

1. Introduction

Prefabricated steel frames have been widely adopted in multi-storey buildings because of their convenience of construction [1]. To avoid field welding and reduce the erection period, bolted joints, such as extended end-plate joints, have been considered one of the satisfactory joint types adopted between I-section beams and I-section columns in prefabricated steel frames. A considerable number of investigations have been conducted into extended end-plate joints with I-section columns [2–7], proving that extended end-plate joints can develop satisfactory moment resistance and rotational stiffness provided they are properly designed [8–12]. Practicable design methods for end-plate joints with I-section beams have been proposed and specified in the Eurocode [13], the American code [14] and the Chinese code [15]. In these codes, the flexural yielding resistance of the column flanges is checked by the same methods as that used for the end-plates, and T-stub analysis is the basic method for checking the thickness of the end-plates and the column flanges [16].

When prefabricated steel frames are used in seismic design, box columns are preferred because they have excellent capacity to resist biaxial bending and torsional buckling [17–19]. However, when bolted end-plate joints are used in prefabricated steel frames with box columns, the flexural yielding resistance of the box column flanges cannot be analyzed directly by the method used for I-section flanges because the support conditions of the box column flanges differ from those in the I-section columns. Before application in the design of end-plate connections with box columns, existing design methods for end-plate joints with I-section columns need supplementation to check the resistance of the box column flanges [20,21]. Yet such supplementation cannot be found in the existing design codes, and investigation of this issue is also limited because it is difficult to apply bolted connections between I-section beams and box columns without spaces for bolt installation.

The use of blind bolts has provided a constructional technique for bolted connections with box columns. Experimental studies and numerical analyses of blind-bolted joints with box columns have been conducted [19,21–24], but blind bolts are quite different from standard high-strength structural bolts in their contact behaviours and pretension forces [21], such that the performance of blind-bolted connections is not well understood [25]. Investigations of bolted connections between steel beams and concrete-filled steel columns have provided suggestions for the design of end-plate connections in composite structures [26–28], but the design methods cannot be applied directly to end-plate joints with box columns, because the filled concrete influences the rotational stiffness as well as the failure modes of the connections [28].

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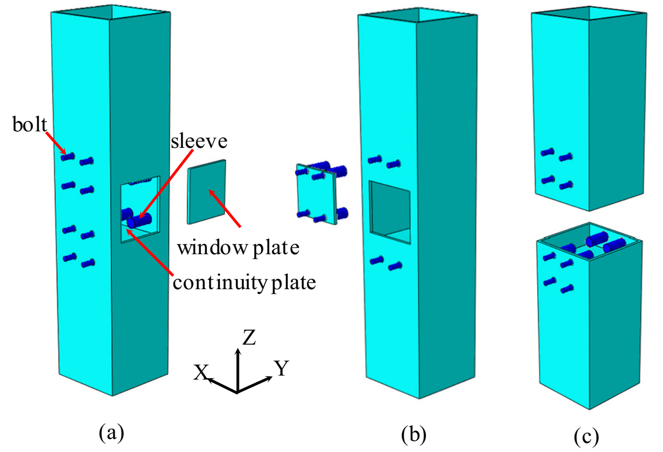

Fig. 1. Prefabrication techniques for end-plate joints with box columns: (a) XW; (b) YW; (c) NW.

In order to apply end-plate joints in prefabricated steel frames with box columns, three prefabrication techniques, which have been patented by the authors, for bolted end-plate joints with box columns are presented in this paper, In the first technique, a window is opened on one of the column-web walls and the window plate is welded back after all the bolts and continuity plates [14] have been installed. This technique is notated XW, signifying that an X-direction window is needed, as shown in Fig. 1(a). The second technique, notated YW, is similar to the first except that the window is opened on one of the column flange walls which are vertical to the Y direction. In the third technique, notated NW, no windows are used but the column must be severed in the middle, providing construction conditions for the necessary bolts and continuity plates, and subsequently welded together. The bolts used in these joint configurations should be twist-off high-strength bolts, each of which is protected by a sleeve fixed on the inner side of the column wall, as shown in Figs. 1 and 2(a), so that the pre-embedded bolts do not fall away from the holes during transportation. It should be noted that if a window is used in practice, both XW and YW would exist if

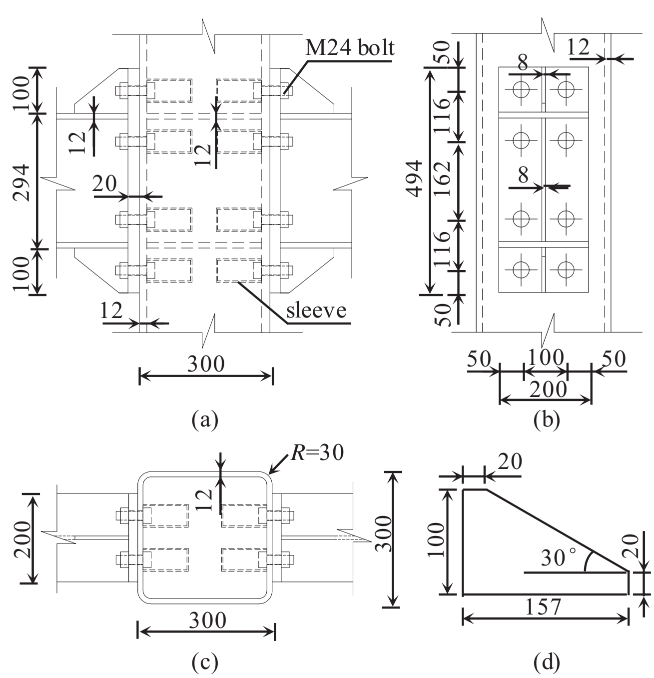

Fig. 2. Dimensions of the tested joints: (a) front view; (b) lateral view; (c) vertical view; (d) details of the extended stiffeners (units: mm).

Table 1
Summary of joint specimens.

Specimen	Beam section	Column section	Prefabrication technique	Loads
1-XW-M	H294 × 200 × 8 × 12	□300 × 12	XW	Monotonic
2-XW-C	H294 × 200 × 8 × 12	□300 × 12	XW	Cyclic
3-YW-C	H294 × 200 × 8 × 12	□300 × 12	YW	Cyclic
4-NW-C	H294 × 200 × 8 × 12	□300 × 12	NW	Cyclic

the box column is connected with four beams around, but in the analysis of plane frames these two techniques could be quite different because the welds of the window plate might affect the shear resistance of the panel zone and the flexural resistance of the flange walls in different ways. In this investigation, therefore, XW and YW are identified as two different techniques.

The cutting and welding procedures for the three techniques introduced here should be conducted in workshop, and at the construction site the beams and columns can be connected by bolt tightening without any field welding, demonstrating that this joint configuration can be conveniently applied in prefabricated steel frames. To investigate the behaviour of the end-plate joints with box columns and estimate the seismic performance of the joints with different prefabrication techniques, four full-scale specimens were tested, with one specimen subjected to monotonic loads and the others subjected to cyclic loads.

2. Experimental program

2.1. Specimens

Four cruciform end-plate joint specimens, fabricated with HN294 × 200 × 8 × 12 hot-rolled I-section beams and 300 × 12 cold-formed box columns, were designed as typical middle-column joints in a multi-storey prefabricated steel frame. The bolts used in the specimens were Grade 10.9 M24 twist-off type high-strength bolts. Continuity plates were used in the panel zone, and extended end-plate stiffeners with the configurations recommended in the American code [14] were used to obtain greater rotational stiffness. The dimensions of the connections and the members are shown in Fig. 2, where the details of all four specimens are coincident except for the prefabrication techniques as shown in Table 1. Two different loading protocols were used for these specimens, and the identifiers of the specimens, as listed in Table 1, consisted of a serial number, a prefabrication technique symbol (XW, YW or NW) and a loading protocol symbol (M for monotonic loads or C for cyclic loads).

2.2. Materials

The steel of all the columns and beams was Q345 and the nominal yield strength was 345 MPa [29]. Tensile tests were conducted with three identical coupons for the beam flanges, the beam webs and the column walls. For the 20 mm thick plate used as end-plates, as well as the 8 mm thick plate used as extended stiffeners, the material properties were tested with three coupons. The test results are summarised in Table 2, and the typical stress-strain curves of the coupon tests are shown in Fig. 3. Generally, it was expected that the mechanical

Table 2
Summary of coupon test results.

Plate	Thickness (mm)	E (MPa)	f_y (MPa)	ε_y	f_u (MPa)	ε_{st}	Elongation
Beam flange	12	216,134	367.8	0.0017	557.8	0.1371	31.1%
Beam web	8	207,658	396.8	0.0019	562.2	0.1401	28.8%
Column wall	12	205,827	547.5	0.0027	605.5	–	19.4%
End-plate	20	212,757	419.4	0.0020	589.2	0.1519	27.3%
Extended stiffener	8	218,172	340.9	0.0015	513.9	0.1571	–