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Experimental study on seismic behavior of full-scale fully prefabricated steel frame: Members and joints

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ABSTRACT

In a full-scale seismic test conducted by the present authors on a fully prefabricated steel frame, strains on the surfaces of beams, columns, braces and slabs were monitored, and the deformations in nine bolted end-plate joints were detected. The global responses of the frame and the composite action of the slabs were analyzed and discussed in the first companion paper. The seismic behavior of members and joints in the frame test were studied in-depth in this paper. Real boundary conditions of joints assisted more accurate study of the cyclic responses of end-plate joints compared with the general experiments on T-shape joints and cruciform joints. Seismic responses of flexible braces, beams and columns were analyzed. Hysteretic performance, backbone curves, the components of story drift ratios and energy dissipation of bolted end-plate joints were discussed. Based on these previous contents, the plastic development sequences and failure modes of the frames were summarized. The results indicate that satisfactory cyclic behavior, deformation capacity and energy dissipation were exhibited in members and joints. Over 65.3% of story drifts were induced by member bending in the elastic stage, but the increments of story drift were dominated by joint deformations after the 1.44% overall drift ratio loading stage, and the cumulative story drifts caused by joint rotations reached the proportions of 57.9–83.9% at the ultimate displacement. The maximum percentages of joint cumulative energy dissipation were 69.7%, 59.0%, 56.4% and 18.2% for the first, second, and third story and the whole specimen, respectively. The plastic development sequence and the failure mode of the frame were yielding of braces (0.36–0.72% overall drift ratio), yielding of end-plate joints (0.72–2.16%), yielding of column bases (1.80–2.16%), yielding of panel zones (≥1.80%), and yielding of several beam ends and column tops (≥4.32%).

1. Introduction

In the Key Laboratory of Civil Engineering Safety and Durability at Tsinghua University, the authors performed a quasi-static test on the seismic behavior of a full-scale three-story fully prefabricated steel frame. This paper contains part of the test results and in-depth analysis of the seismic performance of members and bolted end-plate joints. A detailed introduction of the research purposes, materials, test setup, instrumentation, and test observations is provided in the first companion paper [1]. Global responses including hysteretic behavior, strength, stiffness, deformation and energy dissipation were analyzed [1]. The composite action of prefabricated slabs under horizontal cyclic loads was also studied [1].

The loading performance, cyclic behavior and design methods of the bolted end-plate joints were studied in depth through experimental [2–10] and numerical [3,7,11–13] means. Tests or simulations were conducted of T-shape or cruciform specimens in which the inflection points of members were assumed to remain at their midpoints. Several structural tests of the seismic behavior of steel frames were conducted and reported [14–18]. Due to constraints of the test conditions, however, limited experimental study was focused on the seismic performance of the bolted end-plate joints in the full-scale framework tests. In this test, 66 displacement transducers or inclinators were arranged in the nine joints of the east frame (Fig. 1(a)). Thus, unlike the traditional joint tests, the seismic performance of the bolted end-plate joints in this frame test could be obtained directly, without any hypothesis as to

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Nomenclature

θ_b	beam-end rotation
θ_{pz}	panel zone shearing rotation
θ_{ep}	end-plate opening rotation
Δ_s	end-plate vertical slippage
γ_b	beam bending induced story drift ratio
γ_{pz}	panel zone shearing induced story drift ratio
γ_{ep}	end-plate opening induced story drift ratio
γ_s	end-plate vertical slippage induced story drift ratio
γ_c	column bending induced story drift ratio
γ	story drift ratio
H	story height
L	span
Δ	story drift
f_{yc}	yield strength of columns
E	Young's modulus
M	moments
M_{yc}	yield moments of columns
N	axial forces
N_{yc}	yield axial forces of columns
W	elastic section modulus
A_c	area of column cross-section
y	inflection point ratio
h	distance of the inflection point from the basement or the bottom beam centerline
M_m	maximum moment
M_p	full plastic moment
M_y	effective yield moment (M_{yP} for positive bending and M_{yN} for negative bending)
θ_m	maximum joint rotation
θ_p	plastic joint rotation (θ_{pP} for positive bending and θ_{pN} for negative bending)
θ_{yP}	yield joint rotation (θ_{yP} for positive bending and θ_{yN} for negative bending)
$\theta_{P\text{-}0.02}$	positive joint rotation corresponding to 0.02 story drift ratio
$\theta_{N\text{-}0.02}$	negative joint rotation corresponding to 0.02 story drift ratio
K_e	elastic unloading stiffness (K_{eP} for positive bending and K_{eN} for negative bending)
K_{eff}	effective elastic stiffness
k_b	ratio of K_e to the linear stiffness of beam [22] (k_{bP} for positive bending and k_{bN} for negative bending)
μ	ductility coefficient (μ_P for positive bending and μ_N for negative bending)
E_n	normalized energy dissipation

boundary conditions.

In this paper, a brief introduction of the testing program and the method of measuring joint deformation is given in Section 2. In Section 3, the seismic responses of braces, columns and beams are analyzed, and comparisons are drawn of the column inflection point ratios between the results obtained from the test, the portal method and the D-method. The seismic responses of the joints, including hysteresis behavior, strength, stiffness, the components of the story drift ratio, and energy dissipation are studied and presented in Section Section 4. Finally, the plastic development sequence and the failure mode of the frame are summarized in Section Section 5, based on the contents of Sections 3 and 4.

2. Experimental program

2.1. Test specimen

As shown in Fig. 1(a), the specimen in this test is a three-story, two-bay fully prefabricated composite structure consisting of two parallel placed flexibly braced frames spacing 4500 mm: the west frame and the east frame. Details and specific dimensions of a typical joint are shown in Fig. 1(b)–(e), and the names of members and joints are shown in Fig. 2. More details of the test such as actuators, material properties and construction process were provided in the first companion paper [1].

2.2. Loading protocol

As was illustrated in paper [1], a three-stage loading protocol was used based on the laboratory conditions, consisting of the symmetric quasi-static test (28 cycles), the offset quasi-static test (14 cycles) and the pushover test (monotonic loading). The entire test was controlled by the displacements (overall drift ratio/%rad) of the top actuators. Table 1 shows the details and a sketch of the loading protocol.

2.3. Instrumentations

Strains at the sections located at the midpoints of braces and the trisection points of columns were monitored throughout the testing, with further details introduced in the first companion paper [1].

For the frames using end-plate joints, the story drifts consisted of five components [8,10]: beam bending induced drifts, end-plate opening induced drifts, panel zone shearing induced drifts, end-plate slippage induced drifts, and column bending induced drifts. Joint displacements or deformations in the east frame were monitored by displacement transducers or inclinators throughout the test. As shown in Fig. 3, displacements δ_1–δ_6 and δ_9–δ_{10} were measured by displacement transducers T_1–T_6 and T_9–T_{10} respectively and beam-end rotations δ_7 and δ_8 were measured by the inclinators T_7 and T_8 respectively.

The five components of story drift are shown in Fig. 4. It is assumed that the inflection point of the beam was kept at the midspan; moreover, the midpoint of the panel zone was always at the same height as the midpoint of the cross-section at the midspan. The beam bending induced drift ratio γ_b was measured by inclinator T_7 or T_8, and the beam-end rotation θ_b was equal to γ_b, as shown in Fig. 4(a). Therefore, γ_b could be derived as:

$$\gamma_b = \delta_7 \quad \text{or} \quad \gamma_b = \delta_8 \tag{1}$$

Displacement transducers T_3–T_6 were installed on brackets that were welded on the end-plates with guide rods placed against the column flanges. Based on Eq. (2), the measured relative displacements δ_3–δ_6 between the end-plates and the column flanges were used to calculate the end-plate opening rotations θ_{ep}, which were equal to the end-plate opening induced drift ratios γ_{ep} (as shown in Fig. 4(b)). h_b is the height of the steel I-section and t_{bf} is the thickness of the beam flanges (shown in Fig. 3(a)).

$$\gamma_{ep} = \theta_{ep} = \frac{\delta_3 - \delta_4}{h_b - t_{bf}} \quad \text{or} \quad \gamma_{ep} = \theta_{ep} = \frac{\delta_5 - \delta_6}{h_b - t_{bf}} \tag{2}$$

The panel zone shearing induced story drift ratio γ_{pz}, which was equal to the panel zone shearing rotation θ_{pz} as shown in Fig. 4(c), could be calculated using the method suggested in Ref. [19]:

$$\gamma_{pz} = \theta_{pz} = \frac{\delta_1 - \delta_2}{2} \frac{\sqrt{b_{pz}^2 + h_{pz}^2}}{b_{pz} h_{pz}} \tag{3}$$

where b_{pz} is the spacing of the column flange centerlines and h_{pz} is the spacing of the internal diaphragms (beam flanges) centerlines (shown in Fig. 3(a)). Further, the end-plate slippage induced story drift ratio γ_s