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Cyclic behavior of panel zone in beam-column subassemblies subjected to bidirectional loading

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ABSTRACT

This paper aims to examine the cyclic behavior of panels in beam-column subassemblies subjected to bidirectional and unidirectional loading and to demonstrate the differences of panel behavior under two loading modes. The specimens were composed of wide-flange beams and square tube columns, and the panel zones were designed to yield before columns and beams. Experimental results showed that specimens subjected to bidirectional loading suffered severe damage, caused by the weld fracture at the corner of panel-to-diaphragm weld, and failed at 0.06 rad and 0.04 rad story drift for specimens with panel aspect ratio of 1.4 and 2.0, respectively. Specimens subjected to unidirectional loading developed a story drift of 0.06 rad without strength reduction. The panels contributed about 60%–80% story drift and dissipated approximately 80% of total input energy. Elastic stiffness of panels correlated well with theoretical values that were considered both flexural and shear stiffness. Panels with higher aspect ratio showed smaller plastic shear strength. Finite element analysis indicates that the lower plastic shear strength was resulted from flexural yielding in panels, and the effect of flexural yielding became more considerable under bidirectional loading. Moreover, the beams were found to present plastic moments 20%–50% lower than the theoretical values, which was attributed to the small panel-to-beam strength ratio.

1. Introduction

The steel moment frame is a commonly used structural system for buildings in intense seismic regions due to its superior performance against earthquake actions. Since the plastic hinges appearing on columns may lead to severe structural damage, current seismic designs for steel moment frame usually follow the philosophy of "strong-column weak-beam" to have hinges occur in beams. However, as the panel zones of beam-column joints will bear large shear force whenever the frames are subjected to strong seismic motions, plastic distortion may occur in panels rather than in beams as expected, due to the limited strength of panel zone.

Krawinkler, Bertero and Popov conducted pioneering researches on the seismic behavior of panel zone [1–5]. Panel zones have been shown to provide stable hysteresis behavior and superior energy dissipation capacity under cyclic loading. The concept of panel yielding even prior to the hinge formation at beams was generally accepted by seismic design provisions. Moreover, the effect of panel deformation on structural behavior was investigated [6,7], and various numerical models were also developed to predict the elasto-plastic response of the panel [8–10]. In Japan, square tube columns are preferred to be used for steel moment frames, due to the advantage of identical sectional properties in both axes. Many researches have been conducted on panels of square section about the strength and ductility [11–15]. However, most studies only involved the in-plane loading test and concerned the in-plane behavior of panel. The behavior of panel under bidirectional loading should also be paid attention, as the panels may be subjected to bidirectional shear forces during the earthquake. Few researchers including Hiura et al. [16] and Ito et al. [17] carried out bidirectional loading tests on beam-column subassemblies to study the panel behavior in such condition, while the specimens were not loaded to fail in the research of Hiura et al. [16], and the cross-sections of column and panel were not same in the research of Ito et al. [17] which led to the early fracture of specimens. Therefore, further studies are still necessary to provide additional information about the elasto-plastic behavior and ultimate state of square tube panel under bidirectional loading.

To the end, the objectives of this paper are to examine the cyclic behavior of panels in beam-column subassemblies subjected to bidirectional and unidirectional loading and to demonstrate the differences of panel behavior under two loading modes. Two types of wide-flange beam-square tube column subassemblies are presented, i.e. plane

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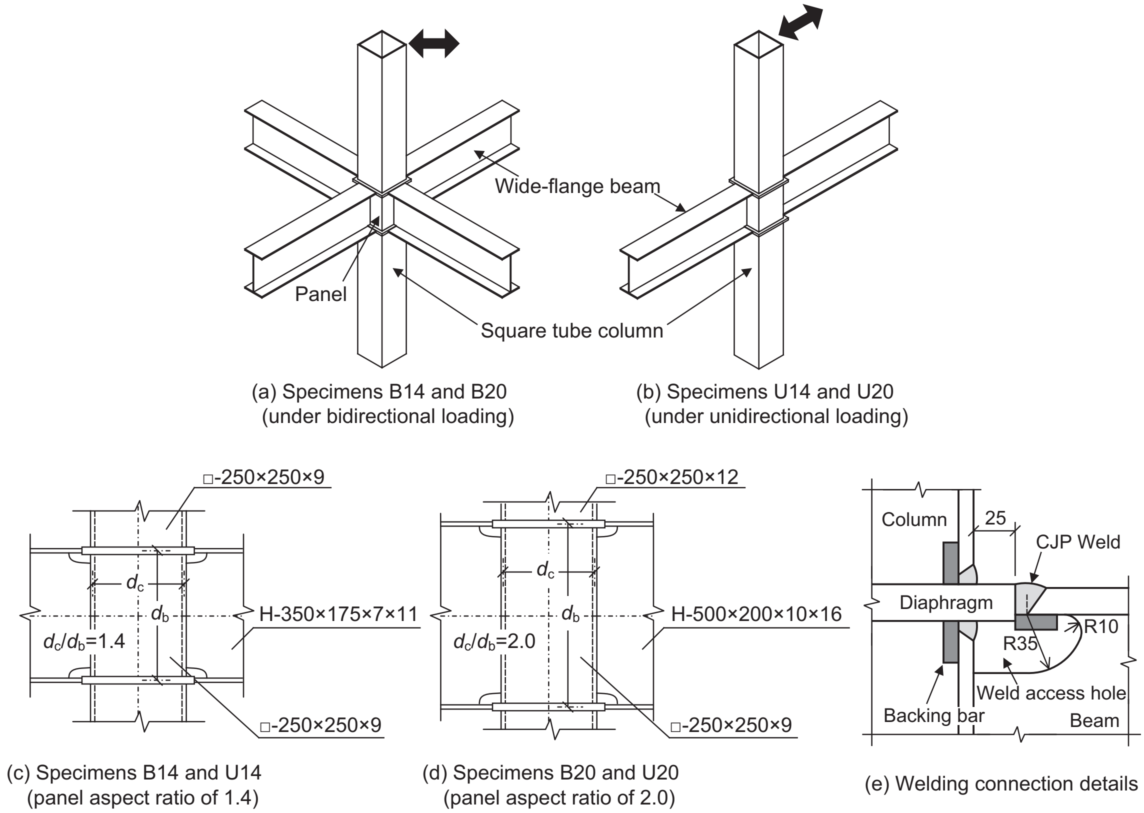

Fig. 1. Test specimen.

subassembly and three-dimensional (3D) subassembly. Each type of subassembly consists two specimens, of which the panels have varying aspect ratios. Large-scale specimens were tested under cyclic loading. The next section presents the specimen design and experimental program. The third section details the test results, including hysteretic responses, failure modes, elastic stiffness, deformation capacity and shear strength. Finally, the fourth section develops the finite element models of the beam-column subassemblies and analyzes the panel behavior under the two loading modes.

2. Experiment program

2.1. Test specimen

The test specimens represented the interior beam-column subassemblies extracted from the steel moment frame, assuming that the points of inflections are at the mid-spans of beams and mid-heights of columns. The column and beam sizes adopted were typical of low to medium rise steel buildings constructed in Japan. To accommodate the capacity of the loading facility, the specimens were fabricated at 2/3 scale in geometric dimension. A total of four beam-column subassembly specimens were fabricated. Specimens B14 and B20 with a shape of three-dimensional cruciform were subjected to bidirectional loading, while Specimens U14 and U20 with a shape of plane cruciform were subjected to unidirectional loading, as shown in Fig. 1(a) and (b). In this research, for Specimens B14 and B20, a single oil jack was used to provide a force in the diagonal direction of the panel section. It can be regarded as bidirectional loading that two oil jacks provided identical and synchronized forces in the orthogonal planes of the frame.

Fig. 1(e) shows the welding details at beam-to-column connection. Two diaphragm plates were inserted between the columns and panel. The thickness of diaphragm plate was 19 mm for Specimens B14 and U14 and 22 mm for Specimens B20 and U20, respectively, which was much thicker than the beam flanges. The diaphragm plate was extended from the column face by 25 mm for all specimens. The beam flanges, columns and panel were welded to the diaphragm by complete-joint-penetration (CJP) groove welds, and the beam webs were welded to panel using fillet welds. The weld access holes were adopted to enable the welding construction convenient to operate, the shape of which was recommended by Japanese Specification [18]. The rectangular backing bars were used at the location of welding to secure firm welding quality.

Table 1 lists the sectional dimensions of each member for all the specimens. The beams were wide-flange sections of H-350 × 175 × 7 × 11 (depth × flange width × web thickness × flange thickness, unit:

Table 1
Test specimen.

Spec.name	Cross-sectional dimension (unit: mm)			Lateral force to cause components yield				
	Beam (SN400B)	Column (BCR295)	Panel (BCR295)	Q^*_b (kN)	Q^*_c (kN)	Q^*_p (kN)	$\frac{Q^*_b}{Q^*_p}$	$\frac{Q^*_c}{Q^*_p}$
B14	H-350 × 175 × 7 × 11	Box-250 × 250 × 9	Box-250 × 250 × 9	229	172	154	1.49	1.12
B20	H-500 × 200 × 10 × 16	Box-250 × 250 × 12	Box-250 × 250 × 9	567	266	238	2.39	1.12
U14	H-350 × 175 × 7 × 11	Box-250 × 250 × 9	Box-250 × 250 × 9	229	259	161	1.43	1.61
U20	H-500 × 200 × 10 × 16	Box-250 × 250 × 12	Box-250 × 250 × 9	567	400	249	2.28	1.61