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Seismic behavior comparison of reinforced concrete interior beam-column joints based on different loading methods

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ABSTRACT

Due to the difference in loading point, experimental researches on seismic behavior of beam-column joint can be generally divided into two types, namely loading at beam ends (BL method) and loading at column top end (CL method). This paper presents an experimental investigation aimed at comparing the cyclic behavior of interior beam-column joints with different loading methods. Four groups of full-scale interior beam-column subassemblages were tested under reversed cyclic loading. Two identical specimens were tested under two different loading methods in each group. On the basis of the experimental results, the paper discusses the distinctions of cyclic behaviors under different loading methods in terms of crack pattern, joint shear strength, joint shear transfer mechanism, joint shear deformation, longitudinal bar-slip, energy dissipation, and stiffness degradation. In addition, a numerical simulation of these four groups of specimens is shown and discussed. The experimental results and numerical analyses confirm that the loading method can have certain influence on the cyclic behavior of the beam-column joints. The joint shear strength, joint shear deformation and longitudinal beam bar slip of beam-ends loading specimens (BL specimens) are considerably larger than that of column-end loading specimens (CL specimens), although the loading protocol used for CL method is more severe than BL method in terms of number of loading cycles. In consequence, the influence of loading method should be considered when the seismic behavior of the beam-column joint is evaluated according to a great number of existing beam-column joint tests.

1. Introduction

Post-earthquake inspections indicate that the severe damage or failure of beam-column joints can result in excessive drift or global collapse of the structure [1–3]. Under cyclic loading, high shear stress is concentrated in the beam-column joint region. Significant bond slip and strength degradation occur when the yielding of longitudinal bars of the beam penetrates into joint region and diagonal cracking develops. Bond slip failure or shear failure of joint are considered undesirable as they lead to strength degradation and stiffness degradation of the RC frame [4]. Thus, joint shear deformation and bar slip deformation are considered as crucial parts in experimental research.

It is essential that beam-column joint can effectively transmit the necessary shear forces through joint region. The joint shear force can be transferred across the joint by a combination of two mechanisms, namely strut mechanism and truss mechanism [4–7]. The truss counts on the forces transferred by bond of longitudinal bars, the horizontal transverse steel and the vertical column reinforcement to maintain the truss action, so that a large amount of transverse reinforcement is required in the joint region to sustain the joint strength. The diagonal compression strut primarily depends on the compression stresses acting on the concrete of beam and column critical sections and the concrete strength of strut. In this case, the requirement of joint transverse reinforcement reduces to just an amount required to confine the concrete properly. Different crack patterns can be observed under different transfer mechanisms [5–12].

A number of research teams in different parts of the world have studied the behavior of beam-column joints in order to improve its response to seismic loads. In the experimental programs, cyclic loads of the experiments can be introduced in two methods: loading on the column-end (CL method) or loading on the beam-ends (BL method), as shown in Fig. 1. Some research teams applied the cyclic loads by CL method [6,9,10,12–14]. The deflected shape of the subassemblage under CL method is similar to the deflected shape of a subassemblage in planar frame under earthquake motion, as shown in Fig. 1(a). The cyclic loading applied at the column end was generally displacement-controlled with the increasing of story drift ratio [12–14]. However, it is slightly difficult to control the boundary condition in this method.

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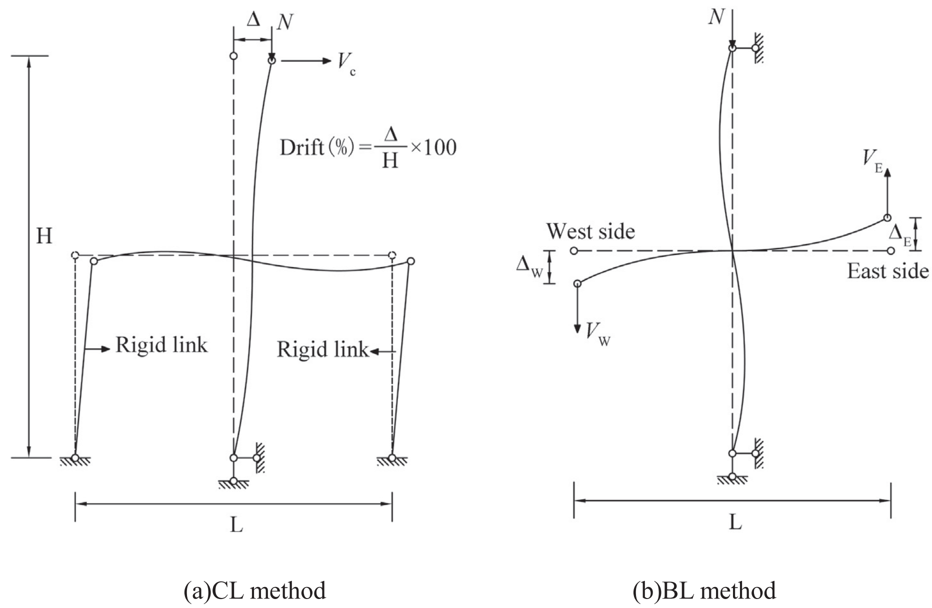

Fig. 1. Loading methods of beam-column joint.

Thus, the other research teams applied cyclic loads by BL method [8,11,15–20]. The cyclic loading applied at the beam ends was generally load-controlled at first and displacement-controlled subsequently with the increasing of displacement ductility factor [8,11,15–18]. This method is more complicated due to the requirement of two coordinated actuators (Fig. 1(b)), but the boundary condition is easier to control. A significant number of experimental studies have been performed on beam-column subassemblages by different loading methods, but it was evaluated together without dividing the loading methods, which may lead to the misjudgment of the seismic behavior [21–23].

The main objective of this research is to compare the difference in the seismic behavior between the identical specimens with two loading methods, and to quantitatively evaluate their difference. Four groups of full-scale RC interior beam-column subassemblages were designed, constructed and tested to compare the seismic behavior of the joint. There were two identical specimens (same geometry and design details) in each group, one loaded by CL method and the other one loaded by BL method to allow a performance comparison to be established. The conventional drift ratio based loading protocol and the conventional displacement ductility based loading protocol were used for CL and BL specimens respectively, in order to keep consistent with the loading protocols of these two kinds of loading methods previously used by other researchers [11,13–17]. The investigation was focused on comparing the difference of crack pattern, joint shear strength, joint shear transfer mechanism, joint shear deformation, longitudinal bar-slip, energy dissipation, and stiffness degradation, with the tested data processed using the formulations extensively used by other research groups. Then, the four groups of specimens were simulated satisfactorily using non-linear finite element analysis, and the difference in the simulated behavior between two loading methods was compared.

There are a large number of existing beam-column subassemblages experimental results that were tested using different loading methods. Therefore, they should not be analyzed together before the effects of loading method on the seismic behavior of beam-column subassemblages are investigated thoroughly. The target of this study is to compare the difference of the test results under two loading methods using their conventional loading protocol, but not to study how to change the loading protocol of this two loading methods to obtain the identical test results. Based on the research results of this paper, it is clarified that loading methods affect the seismic behavior of beam-column joint to different degrees, and the difference was quantitatively evaluated. This study contributes to combine a large number of existing test results of BL specimens and CL specimens to make a comprehensive evaluation of the beam-column joint seismic behavior considering the effects of loading methods.

2. Test program

2.1. Specimen and design parameter

A total of eight specimens including four CL specimens (named CL-n, n = 1, 2, 3, 4) and four BL specimens (named BL-n, n = 1, 2, 3, 4) were divided into four groups (Group-n included CL-n and BL-n). Two specimens in each group were designed with the same dimensional size and reinforcement details, but loads were applied in different ways. The specimens were designed based on the strong column-weak beam requirement and detailed requirements of Chinese Code [24]. The joint transverse reinforcements were close to the lower limit value calculated according to the Chinese Code [24]. Fig. 2 shows the geometry, dimensions, and reinforcement details of each group of specimens.

2.2. Material specifications

The concrete compressive strength of all the specimens at the time of testing is presented in Table 1, and the yield strength of the reinforcements is presented in Table 2. The specimens of different group were prepared separately, and two specimens in the same group were tested in different days, thus, there were differences in the strength of reinforcements and concrete.

2.3. Test setup, instrumentation and loading sequence

The loading apparatuses of two loading methods are shown in Fig. 3(a) and (b). A constant axial load was applied to the column of both CL and BL specimens through an actuator at the column top, which was maintained constant during the tests. The axial load ratio of Group I, II, III and IV are 0.25, 0.3, 0.25 and 0.25, respectively. For CL specimens, the bottom of the column was hinge support, and both ends of beams were roller supports. Loads applied at the top end of the column was measured with a load cell attached in series with an actuator that applied reversed cyclic lateral load, as shown in Fig. 3(a). The full specimen under CL method in laboratory is shown in Fig. 3(c). The test