6th International Conference on Advances in Experimental Structural Engineering
11th International Workshop on Advanced Smart Materials and Smart Structures Technology
August 1-2, 2015, University of Illinois, Urbana-Champaign, United States

Experimental tests of reinforced concrete frame subassemblies with buckling restrained braces in double-K configuration

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ABSTRACT

Although the unbalanced brace force at the mid-length of columns discourages the use of K- or double K-bracing in concentrically braced frames, this limitation needs re-evaluation for buckling restrained braced frames. Unlike ordinary steel braces, buckling restrained braces (BRBs) exhibit almost identical behavior in tension and compression, and to arrange BRBs in a double-K configuration may provide an efficient solution of connecting BRBs to reinforced concrete members by exempting the steel-to-concrete connections from unfavorable tension force. Three 1/2-scaled subassemblies were tested statically to examine the above idea. Each specimen consisted of two identical reinforced concrete beams framing into two columns. Two of the specimens were braced by BRBs in double-K configuration, and the other one represented a bare frame for comparison purposes. The test results show that the BRBs performed as intended in both tension and compression. The RC frames in the braced specimens were only moderately damaged at 2% inter-story drift while the BRB cores were sustaining large plastic strain. No cracks were observed at the mid-length of the columns or the mid-span of the beams where the BRBs met.

KEYWORDS: *Double K-braced frames, cyclic loading, buckling restrained brace, connections, reinforced concrete frame.*

1. INTRODUCTION

In utilizing buckling restrained braces (BRBs) in retrofitting existing reinforced concrete (RC) structures, engineers used to install buckling-restrained braced steel frames instead of individual BRBs to ease the force transfer between BRBs and RC components. The retrofitting braced frames are either attached to the façade or installed within the RC frame (e.g., [1, 2]). In both cases, dense post-installed anchors are usually required to resist the combined shear and tension at the steel-to-concrete interfaces, making the construction noisy, dusty and time consuming.

For new RC construction, it is possible to embed the gusset plates of a BRB into the RC components so that the connection can be made more compact and easier-to-construct (e.g., [3, 4]). Even though, the steel gusset plate which is usually fastened to both the adjoining RC column and the beam ends is usually subjected to a complicated 'frame action' that may lead to premature fracture of the welds or buckling of the gusset plates [5]. Such gusset plates would also have detrimental effects on the RC frame, such as reducing the aspect ratio of the adjoining RC column (e.g., [6]) and introducing considerable over-strength in the frames [7]. While fundamental tests were conducted to investigate the performance of such conventional corner gusset connections [8, 9], new solutions were proposed and tested at either component level (e.g., [10, 11]) or system level (e.g., [12, 13]).

Although currently prohibited by AISC 341-10 for buckling restrained braced frames [14], double-K bracing as shown in Figure 1.1 has several unique advantages when implemented in RC frames. First, the two BRBs that share the same gusset plate are always acting in opposite directions, that is, one in tension and the other in compression. Ideally, when identical BRBs are used in a single span, there is no residual tension force on the gusset plate. As a result, much less studs or post-installed anchors would be required for the connection to transfer the BRB axial force to the concrete members. Some residual compression force may rise from the higher compression strength of a BRB. AISC 341-10 requires that the BRB compression strength should be no greater than 1.3 times its tension strength. This sets an upper bound for the residual compression force at the mid-length of the beams and columns.

Then, in double-K bracing, the gusset connections at the mid-length of the beams and columns are free of the detrimental 'frame action', and are thus easier to proportion. In addition, the gusset connections are away from the potential 'plastic hinges' at the RC beam ends, and therefore the inelastic behavior (e.g., concrete cracking, rebar yielding) would not interact with the BRB connections in an unintended manner. The four BRBs and their gussets in a single span can be prefabricated together as an energy-dissipating package and then shipped to the site to further accelerate the on-site construction.

To assess the seismic performance of RC frames braced by BRBs in double-K configuration, static cyclic loading tests were performed on three RC frames subassemblies. Details of the tests and preliminary discussions on the test results are reported as below.

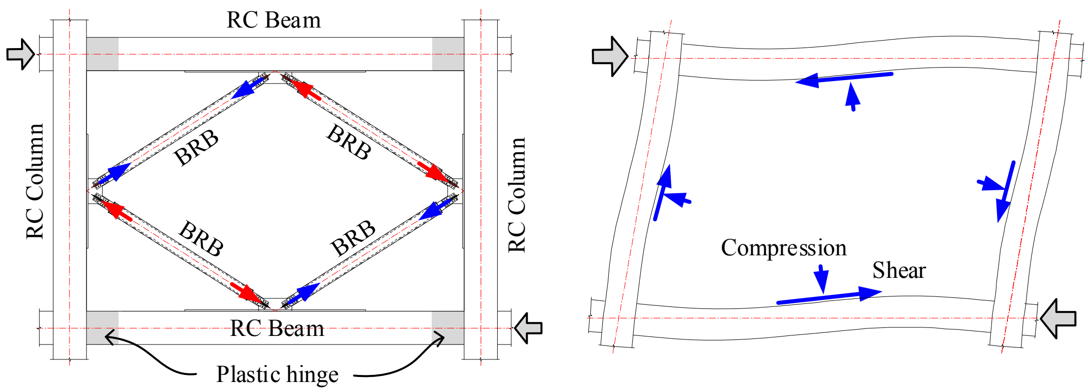


Figure 1.1 Reinforced concrete frames braced by BRBs in double-K configuration

2. SPECIMENS

Three 1/2-scaled RC frame subassemblies were subjected to cyclic loading with increasing story drift amplitudes. Two of the specimens were braced by BRBs in double-K configurations while the other one served as a bare frame counterpart for comparison. As shown in Figure 2.1, each RC frame subassembly consists of two beams framing into two columns. The RC frame conforms to the Chinese concrete structure code [15], which incorporated a strong column-weak beam concept. The beam flexural reinforcement ratio is about 1.1%, and the column overall reinforcement ratio is 2.7%. Ductile detailing was provided for both the beams and columns. The intervals of the beam stirrups and column hoops were reduced by half in the regions close to the beam-to-column joints. C40 concrete (40 MPa nominal compressive strength of cubes) and HRB400 rebars (400 MPa nominal yield strength) were used for the RC frames. The measured average compressive strength of concrete cubes is 49.7 MPa. The measured yield strength and tensile strength of ϕ14 longitudinal rebar are 563 MPa and 673 MPa, respectively.

Four identical BRBs were installed in double-K configuration for each braced specimen. The steel core was made of the Chinese Q235 steel (235 MPa nominal yield strength) and the nominal yield strength of each BRB is 132 kN. The BRBs were manufactured by Lead Dynamic Engineering Co., Ltd., a joint-venture by the Nippon Steel and another two Chinese local companies. The BRBs were bolted to the gusset plates. While the distance between the intersection points of the BRB axes is 1595 mm, the plastic segment of the BRB steel core is only 500 mm. As a result, a 1/50 inter-story drift corresponds to 2.88% strain in the plastic segment of the BRBs if assuming the rest of the BRBs are rigid.

The gusset plates were connected to the RC beams and columns by two different methods for the two braced specimens. In one method proposed for new constructions, M19 shear studs were welded to the base plate of the gusset plates, and were embedded in the RC components (Figure 2.2(a)). In the second method, ϕ12 post-installed chemical anchors were used for the connection to simulate applications in seismic retrofit of existing buildings. In this case, the RC frame was first cast without the BRB gusset plates and cured for at least 28 days. Then the chemical anchors were installed in the concrete, fit into the tapered holes on the base plates of the gusset plates, and welded to the base plates (Figure 2.2(b)). Following the capacity design concept, the number of shear studs and post-installed anchors were determined by the resultant shear force of the adjusted BRB strength at the connection interfaces, neglecting the possible compression or tension force on the same interface. The adjusted BRB strength takes into account 50% strain hardening for both BRBs connecting to the same gusset and another 30% over-strength for the BRB in compression.

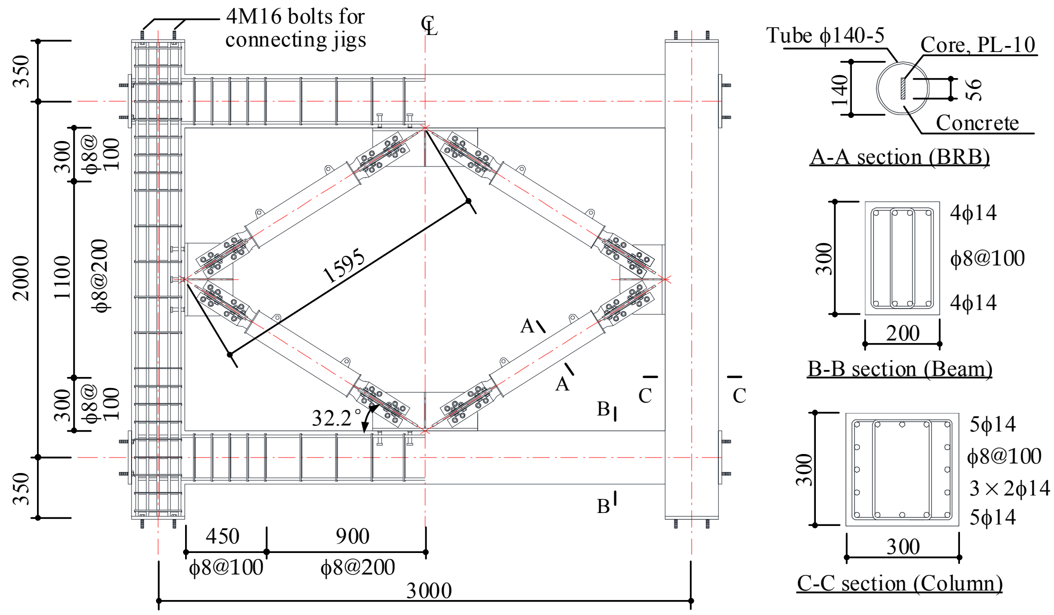
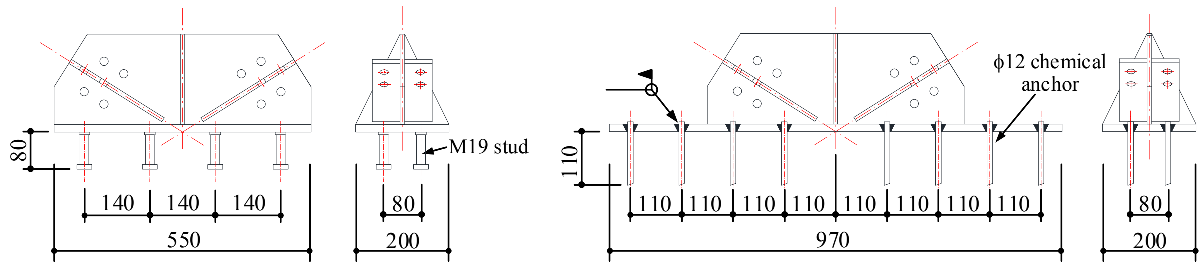


Figure 2.1 Specimen geometry and reinforcement



(a) (b)

Figure 2.2 Connection details for gusset plates on beams: (a) embedded shear studs for new construction applications; (b) post-installed anchors for seismic retrofit applications.

3. TEST SETUP AND LOADING

As shown in Figure 3.1, the specimen was mounted on two mechanical pins firmly fastened on the strong floor. Two horizontal actuators protruding from the reaction wall were employed to load the specimens. The upper actuator was displacement-controlled to impose the desired inter-story drift (IDR) on the specimen, while the lower actuator was force-controlled to counteract the upper actuator so that the bottom mechanical pins were waived from excessive shear.

For connection to the loading jigs, end plates were provided at the far ends of the beams and columns. The longitudinal rebars were welded to the end plates. Four M16 high-strength bolts protruded from the outer surface of each end plate, ready to be fastened to the steel jigs.

A spherical-headed oil jack was employed to exert axial force through a steel jig on top of each column. Roller cushions were installed between the oil jacks and the overhead reaction beam so that the jacks could move horizontally along with the columns. The steel jigs fastened to the top of the columns were restrained by pantographs for out-of-plane stability. Before lateral loading, the oil jacks applied 482 kN axial compression to each of the columns to simulate the gravity load. This corresponds to about 20% of the column’s nominal axial strength. During the test, the forces in the oil jacks were constantly adjusted to counteract the overturning moment due to horizontal loading, so as to maintain constant axial forces in the lower halves of the columns to protect the mechanical pins under them.

Characteristic inter-story drifts of 1/1200, 1/550, 1/200, 1/100, 1/67 and 1/50 were taken as the amplitude targets for the loading cycles. Among these, the 1/550 and 1/50 IDRs are the drift limits for RC moment-resisting frames at their serviceability and ultimate limit states, respectively, per the Chinese seismic code [16]. The 1/200 IDR is the drift limit stipulated by the Building Standard Law of Japan for serviceability limit state [17], and the 1/100 IDR is usually taken as an inelastic drift limit for passive-controlled structures under major earthquakes in Japan's seismic design practice. Two cycles of static loading were performed at each amplitude.

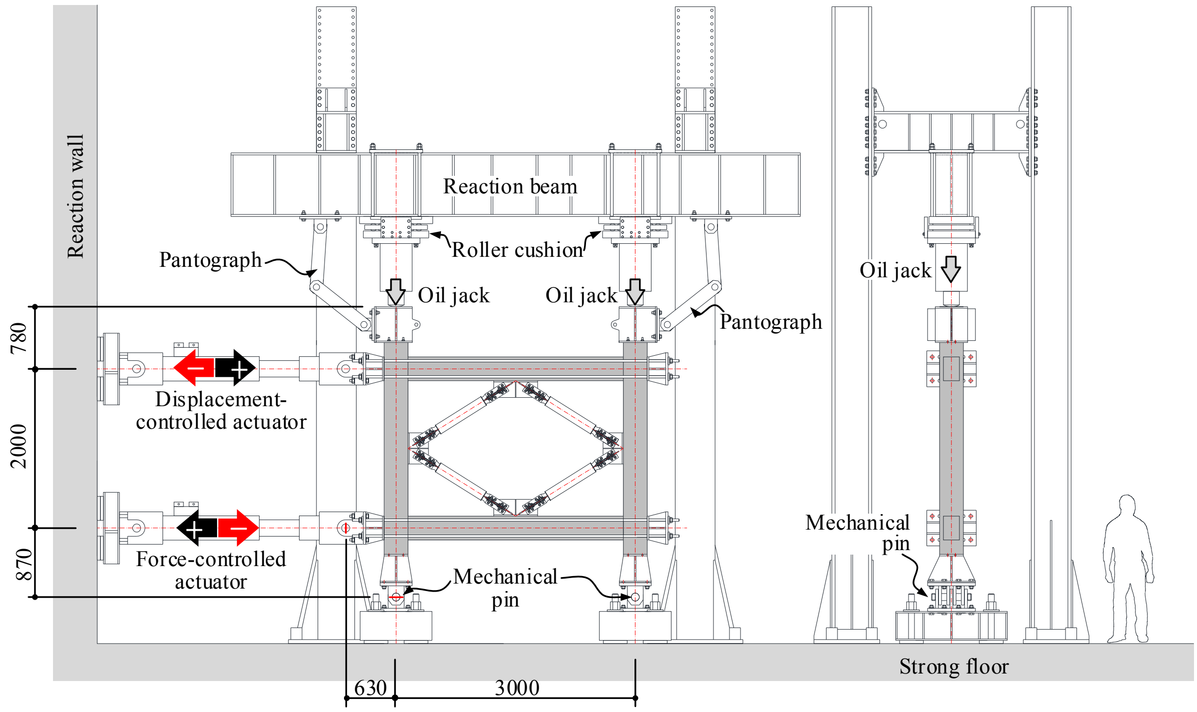


Figure 3.1 Test setup

4. TEST RESULTS

4.1 Force-displacement relationships

As compared to the bare frame specimen (No.1), the two braced frame specimens exhibited stable and full hysteresis all through the loading process up to 1/50 inter-story drift (Figure 4.1). The BRBs started to yield at inter-story drift ratios as small as 1/604 and 1/560 for the braced frame with shear studs (No.2) and the one with chemical anchor (No.3), respectively. In contrast, the bare frame specimen did not exhibit significant sign of yielding until 1/72 inter-story drift ratio. Note that, in the current setup, this drift ratio included both the chord rotation of the RC beam and the rotation of the bottom beam-to-column joints.

Before the last loading cycle of 1/50 drift amplitude of Specimen No.3, one of the four BRBs was removed at unloaded condition. Then the loading was resumed to see whether the BRB-to-concrete connections would fail when their force balance was broken. The hysteresis of this last loading cycle is depicted by the dashed line in Figure 4.1. The only significant phenomenon was that the peak forces dropped by 21% (from 821.4 kN to 650.2 kN) and 18% (from −895.4 kN to −693.8 kN) in the positive and negative loading directions, respectively. The damages to the concrete members or the steel-to-concrete connections were not exacerbated by the removal of the BRB.

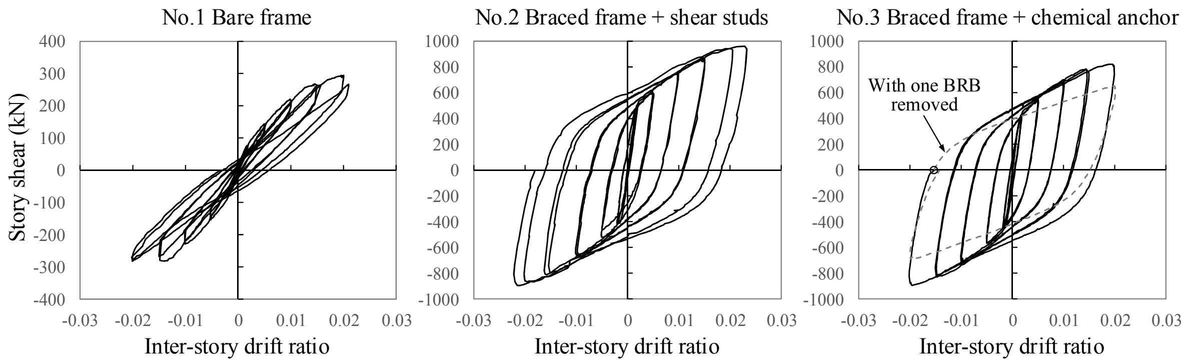


Figure 4.1 Force-displacement relationship of specimens

4.2 Damage to RC Frames

The apparent damages to the RC frames in the three specimens are summarized in Figure 4.2. As intended, most damages were concentrated in the beam ends, where major cracks developed and slight concrete spalling was also observed at the final stage of the loading. Take Specimen No.2 for example. Cracks were first observed at the beam, and no cracks were found on the columns until the second loading cycle of 1/100 drift. At 1/100 drift, a few cracks at the beam ends grew to wider than 0.2 mm. These cracks continued to open and at 1/50 drift, some of them became wider than 1.0 mm. Cracks on the columns were distributed at the beam-to-column joints and regions close to the joints. The column crack widths were considerably smaller than those of the beams.

Regardless of the existence of the BRBs, the cracking patterns (crack distribution and widths) on Specimen No.2 and 3 were similar to that of the bare frame specimen (No.1). The two braced specimens behaved quite similarly. The BRB-to-concrete connections in both specimens remained essentially elastic throughout the test.

4. CONCLUSIONS

Although currently prohibited by steel structure codes for seismic applications, double-K bracing is a promising system for buckling restrained braced RC frames, because it simplifies the design of the BRB-to-concrete connection, and helps improve the seismic performance of these connections.

Three RC frame subassembly specimens were tested statically, two of them were braced by buckling restrained braces in double-K configuration and one was a bare frame for comparison. The test results show that the buckling restrained braces performed well and the residual forces imposed by the BRBs normal to the BRB-to-concrete connection at the mid-length of the beams and columns had no significant effects on the damages of the RC frames.

In double-K bracing, four smaller BRBs are used in a braced span instead of one or two bigger BRBs. This leads to less strength demand for a single BRB gusset connection. The stud or anchor connection in the current test successfully withstood the combined tensile and shear force imposed by a single BRB, as was shown in the last loading cycle of 1/50 drift for Specimen No.3. On the other hand, however, the plastic segment of each of the smaller BRBs is much shorter than that of bigger BRBs. The length of the plastic segment of a single BRB in the current test is only about 30% of the center-to-center brace length. This leads to higher strain levels in the BRBs in double-K configuration, and thus requires higher low-cycle fatigue performance of BRBs.

AKCNOWLEDGEMENT
The experimental investigation is sponsored by the National Natural Science Foundation of China (Project No.51308514 and No. 51478441). The financial support is highly appreciated.

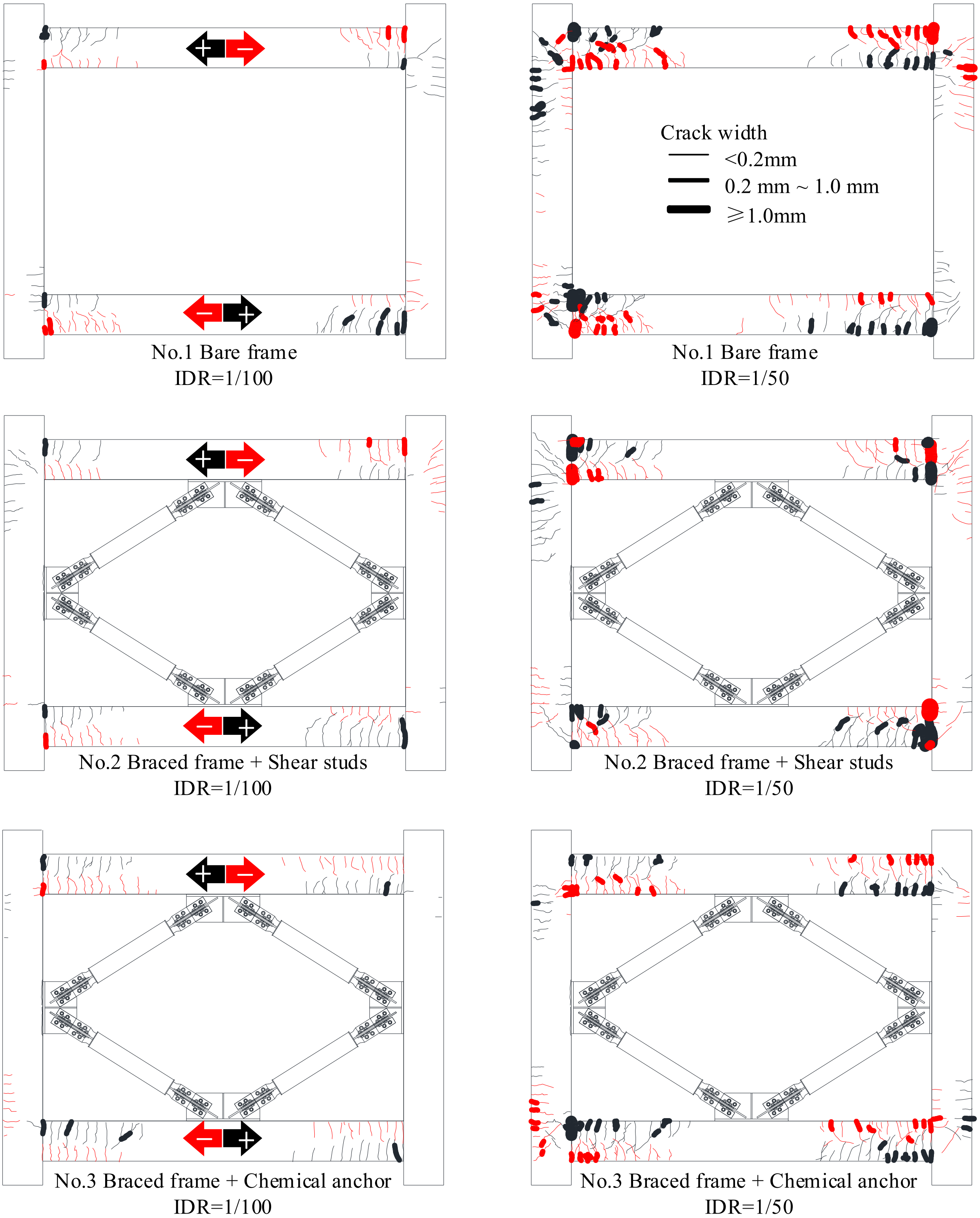


Figure 4.2 Cracks on RC frames

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