Paper IFHS-211

Experimental Evaluation of The Seismic Behavior of Steel-Braced RC Frames

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ABSTRACT: Steel bracing has proven to be one of the most effective systems in resisting lateral loads. Although its use to upgrade the lateral load capacity of existing Reinforced Concrete (RC) frames has been the subject of numerous studies, guidelines for its use in newly constructed RC frames still need to be developed. In this paper, the efficiency of using braced RC frames is experimentally evaluated. A cyclic loading test was conducted on a braced frame. A rational design methodology was adopted to design the frame including connections between the brace members and the concrete frame. Test results showed that the braced frame provided adequate energy dissipation. The adopted methodology for designing the braced frame resulted in an acceptable seismic performance and thus represents the first step in the development of design guidelines for this type of frames.

1 INTRODUCTION

Braced steel frames are commonly used to resist lateral loads. Their design guidelines are readily available (AISC 2001, 2002). The use of bracing to upgrade the seismic capacity of existing RC frames has been the subject of several research investigations over the past three decades. Two bracing systems are typically considered, external bracing and internal bracing.

In external bracing, steel trusses are attached to the building exterior. Bush et al. (1991) conducted cyclic loading tests on scaled models of a number of structures retrofitted using external bracing. They reported the efficiency of such a method in retrofitting existing RC buildings. Badoux & Jirsa (1990) investigated numerically the behavior of RC frames retrofitted with external bracing. They recommended using cables instead of steel sections for the brace elements to avoid buckling of the brace members, and thus increase the ductility of frames.

In internal bracing, steel trusses or bracing members are inserted in the empty space enclosed by columns and beams of RC frames. A number of researchers (Rodriguez & Park 1990, Masri & Goel 1996) studied the effectiveness of using internal steel trusses to retrofit existing RC frames. They reported that such a method allows upgrading the seismic capacity of existing structures. Maheri & Sahebi (1997) recommended the use of internal brace members over internal steel trusses. Nateghi-Alahi (1995) successfully applied this technique to upgrade the seismic capacity of an existing eight-story building located in Iran.

Connections between the steel truss or bracing members and the RC frame are important to achieve the required lateral load capacity. A number of connections capable of transferring loads to the additional lateral load resisting elements were proposed by several researchers (Kawamata & Masaki 1980, Canales & Broseno de la Vega 1992). These connections relied on the use of adhesives, grout, or mechanical anchors. Maheri et al. (2003) proposed a connection that minimizes the eccentricity of the brace member force. This allowed transferring the brace force to the corner of the RC frame without producing local damage in concrete members. One of the benefits of using internal brace members instead of internal trusses is the reduction of the number of required connections and thus the construction cost.

Current seismic codes assume that the lateral loading system for newly constructed RC structures are either moment resisting frames, coupled walls, or shear walls. These systems can be designed to have low, moderate or high ductility. Steel bracing is generally not listed as one of the available lateral load resisting systems. Combined with the fact that previous studies were mainly conducted to evaluate the behavior of non-ductile RC structures retrofitted by attaching bracing elements, this limits the use of steel bracing for new construction. However, using steel bracing for new construction has many advantages over the use of shear walls including: reducing the weight of the structure, and thus reducing seismic loads and increasing the ductility of the structure.

In this study, the use of concentric internal steel bracing for new construction was investigated experimentally. The test specimen represented a braced RC frame and was designed according to a rational design methodology. The frame was constructed and experimentally tested using cyclic loads. The test results were allowed gaining an improved understanding of performance of braced frames and evaluating the proposed design methodology.

2 CHOICE OF TEST SPECIMEN

A four-storey building with dimensions of 12.0 m by 12.0 m was considered for the design process. It was assumed that the building is located in a highly seismic area. The lateral load resisting system (Fig. 1) was considered to be braced RC frames. A midspan panel measuring 4.0 m by 3.0 m was isolated from the third floor. The gravity and elastic earthquake forces acting on these panels were determined in accordance with IBC (2003).

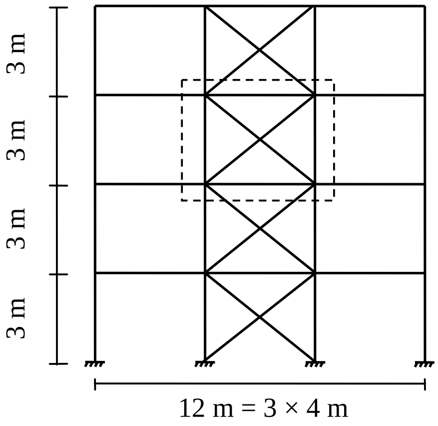

Fig. 1. Lateral load resisting system

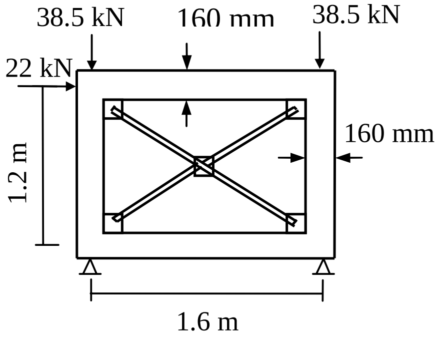

Fig. 2. Loads acting on the scaled model frame.

Modern seismic codes reduce the applied elastic seismic force by using a force reduction factor. This causes building deformations to exceed elastic limits. By using different reduction factors for each structural system and specifying guidelines for members and connections design, seismic codes assume that the ductility demand on each individual member or connection is lower than its capacity. This assumption comes from the relationship between the global structure ductility and the local member or connection ductility that is unique for each structural system. The elastic earthquake force was reduced using a seismic force reduction factor for moment frames with moderate ductility.

A scaled model frame measuring 1.6 m by 1.2 m was found to be satisfactory. To keep stresses in the scaled model similar to that in the full-scale panel, the forces acting on the panels were also scaled down. The boundary conditions for the tested specimen were chosen such that the distribution of the internal forces is similar to that in the full-scale frame. This was achieved by using two hinged supports at the ends of the bottom beam. Figure 2 shows the test specimen with the scaled design loads.

3 DESIGN AND CONSTRUCTION OF TEST SPECIMEN

The braced frame was composed of top and bottom beams, and left and right columns. The cross-section dimensions of the beams and columns were chosen to be 140 mm by 160 mm. The internal forces resulting from the scaled design forces were determined. These forces are then used to design the frame. The specimen was constructed using self-consolidating concrete. Its compressive strength at the time of testing was 55 MPa.

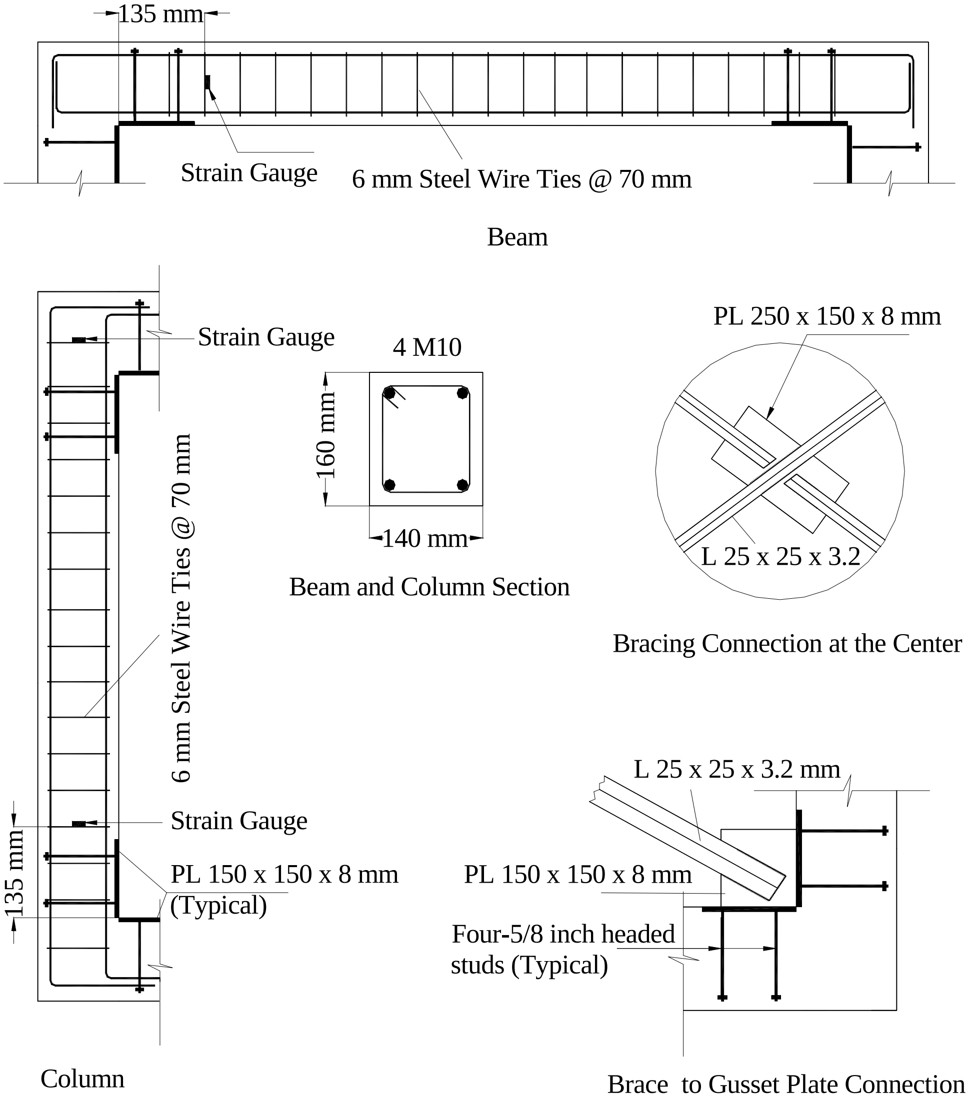

Figure 3. Detailing of the braced RC frame.

A rational design methodology is proposed and applied as explained below:

- RC beams, columns, and beam-column joints are to be designed according to standards for the design of RC elements. Detailing of steel reinforcement is to be done according to the general detailing requirements in these standards. Special seismic detailing of steel reinforcement is not required because of the expected reduced seismic demand. For the test specimen, it was chosen to use ACI 318 (2002) to design the RC beams, columns, and beam-column joints. The top and bottom reinforcement of the beam and column sections were 2M10. The transverse reinforcement of beams and columns consisted of 6 mm steel wires spaced at 700 mm. Details of this specimen are shown in Figure 3.

- The brace members and their connections are to be designed according to standards for the design of steel elements. Their design must satisfy the special seismic provisions in these standards. For the test specimen, AISC (2001) was used to design the brace members and their welded connections to the gusset plates. Their design was also checked using the AISC seismic provisions for steel structures (AISC 2002).
- The connection between the gusset plates and the RC frame can be achieved by welding the gusset plates to steel plates that are anchored to the concrete frame. The weld is to be designed according to standards for the design of steel elements. Its design must satisfy the special seismic provisions for steel structures. The anchors are to be designed according to standards for anchorage in concrete. For the present test specimen, a total of eight steel plates were positioned on the inner corners of the RC frame. Each plate had four-5/8 inch headed studs as shown in Figure 3. The studs were designed for the critical case of combined tension and shear according to Appendix D of ACI 318 (2002). The design ensured that concrete shear failure, bond failure, and connector shear failure are avoided.

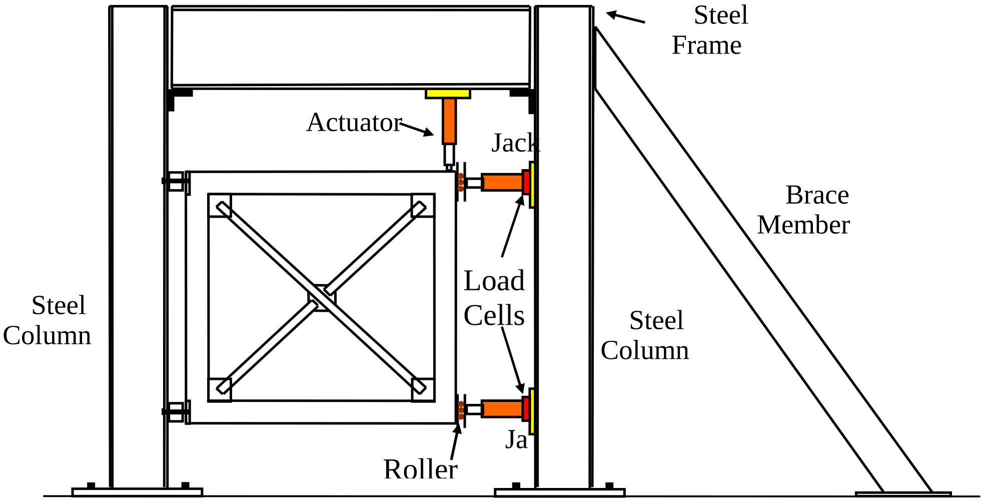

Figure 4. Schematic of the test setup.

4 TEST SETUP

The specimen was tested using the setup illustrated in Figure 4. The beams were oriented vertically and the columns horizontally. The specimen was pin jointed at the two ends of the bottom beam. It was subjected to constant gravity loads using two hydraulic jacks. Special rollers were manufactured to allow these jacks to slide on the concrete surface, and thus allow lateral deformation of the concrete specimen. An actuator was used to apply several cycles of loads using a displacement-controlled approach. In each cycle, the actuator was first pulled to a displacement d1 of 5 mm (drift of 0.417%) then pushed to the same displacement. The value of d1 was increased in the following cycles by increments of 5 mm. Strain gauges were used to monitor strains in the beam-column joint, the transverse reinforcement of the columns, and the longitudinal reinforcement of the beams. The locations of strain gauges on the test specimen are shown in Figure 3. The following sections summarize the results of the experimental tests.

5 SEQUENCE OF FAILURE

The observed cracking load for the braced frame was 90.0 kN. Cracks observed were minor (Fig. 5). At a load of 105.0 kN, yielding of the brace member initiated the plastic response. Failure resulted due to buckling of the compressive brace, which was directly followed by plastic hinging of the ends of the bottom and top beams. The failure load was 140 kN. It should be noted that the brace member connections, including welds and headed studs, behaved adequately.

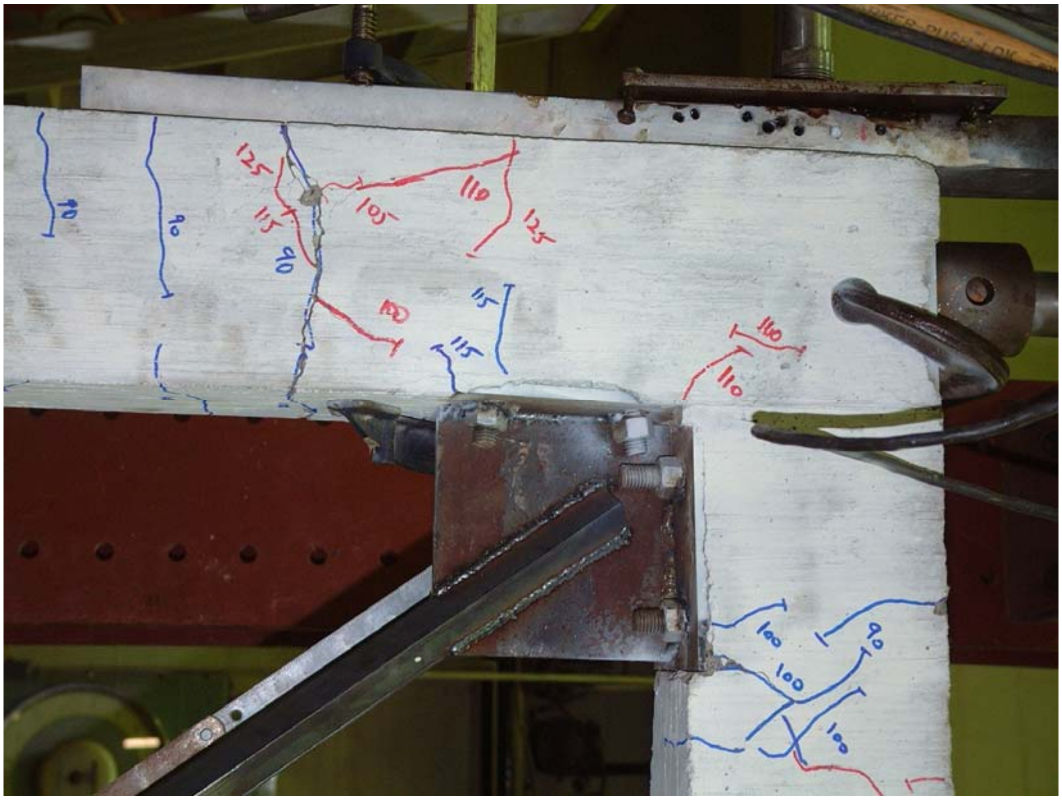

Figure 5. Close up of cracks observed in the braced frame at failure.

6 HYSTERETIC BEHAVIOR AND ENERGY DISSIPATION

The lateral load-drift curve is shown in Figure 6. The yield and failure drifts were 2.08% and 4.0%, respectively. This shows that the global ductility was 1.9. The reduction in the ductility was compensated by a considerable increase in the lateral load capacity, which was 140 kN. It is clear from the hysteretic behaviour that the pinching was not significant indicating an overall better seismic performance.

The ability of a structure to dissipate the ground motion energy is an accurate measure for its expected seismic performance. In this study, the energy dissipated by the tested specimen during reversed cyclic load testing was calculated as the area enclosed by each hysteretic loop. Figure 7 shows a plot of the energy dissipated during a load cycle versus the lateral drift. The energy dissipated by the braced frame is acceptable when compared to typical lateral load resisting systems.

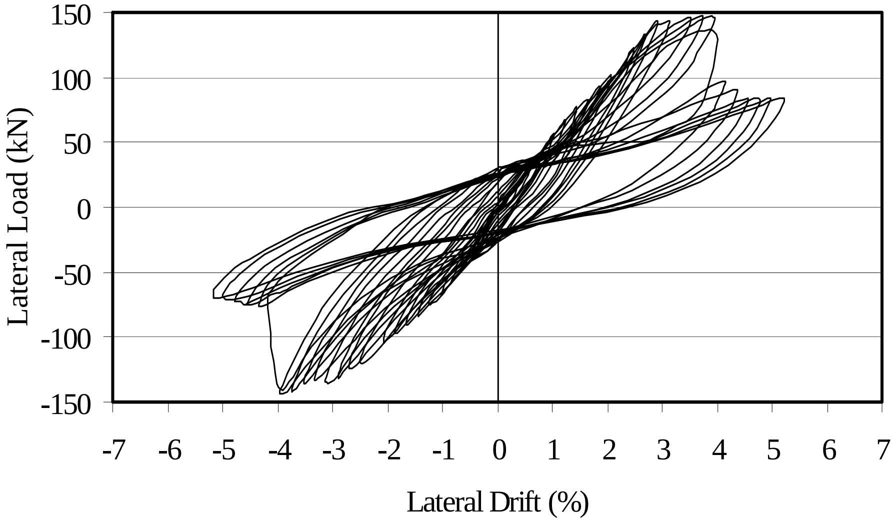

Figure 6. Lateral Load-drift curve of the braced RC frame.

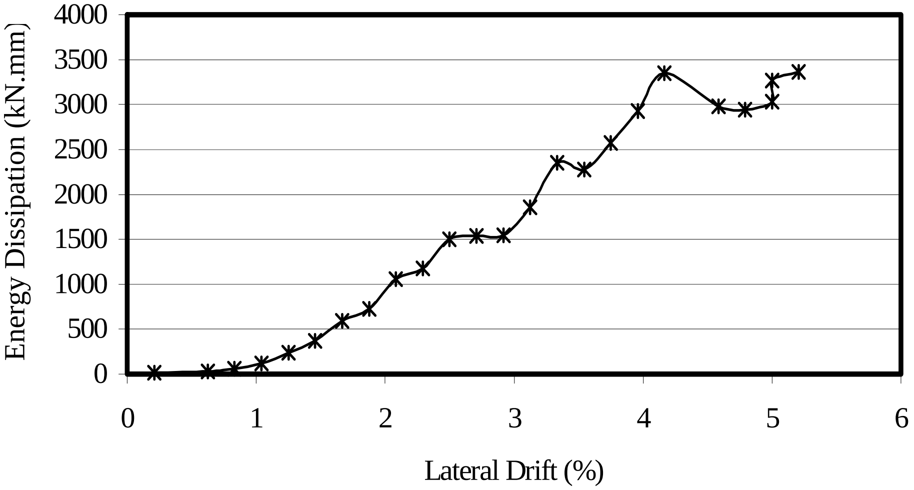

Figure 7. Variation of the energy dissipation with lateral drift.

7 DISCUSSION

The use of braced RC frames, as the main lateral load resistance system for RC structures is a promising technique. The lack of guidelines and provisions addressing the design of such frames is hindering their use. A comprehensive research program addressing design issues pertaining to braced RC frames is needed. Such a program is expected to result in seismic modification factors and design methodologies for connections, brace members, and concrete members.

The present study focused only on studying the behavior of a braced RC frame. A rational method was adopted to design the frame. Additional tests on braced RC frames are needed to identify suitable seismic modification factors for their design. The results of these tests can also be used to calibrate numerical models that can be used to conduct parametric studies for multi-storey braced RC frames.

8 CONCLUSIONS

In this paper, an experimental investigation was conducted to assess the behavior of braced RC frames. The following conclusions were drawn based on the results of the cyclic test.

- A braced RC frame designed using the same force reduction factor as that of a conventional RC moment frame with moderate ductility would behave adequately during an earthquake event.
- The design of RC sections in a braced RC frame can be carried out using conventional RC design methods. General reinforcement detailing requirements are adequate and there is no need to use special seismic detailing.
- The brace members and its connections can be designed using a similar procedure to that for braces in steel structures.
- The use of braced RC frames as the main lateral load resisting system is a promising design alternative. Significant experimental and computational research is needed in this area to develop adequate design guidelines and provisions along with best construction practice for such frames.

9 REFERENCES

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