SEISMIC BEHAVIOR OF BEAM-TO-COLUMN MOMENT CONNECTIONS USING HIGH-STRENGTH STEEL

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Abstract

Cyclic behaviors of moment connections using the high-strength steel are explored in this study. Two large-scale specimens were fabricated and tested. The specimens represented a subassemblage including a one-story high column between mid-height of the two adjacent stories and a half span beam. One specimen (RBS-QCA) had reduced beam section with quarter circular weld access hole. The beam web was bolted to a shear tab which welded to the column flange. The other specimen (WUF-W) was designed without trimming the beam section but with weld access hole details as specified in AWS. The beam web of this specimen was welded to the column flange via a completely join penetration weld. The test results of the specimen RBS-QCA demonstrated that this specimen achieved 5% rad story drift angle with plasticity concentrated on the reduced beam section. Although minor cracks occurred at the tip of the beam flange near the penetration groove weld and the root of the weld access hole, the cracks did not propagate. Local buckling of the beam flange at the reduced section was occurred and led to minor strength deterioration. The specimen WUF-W reached 5% rad story drift angle also. Plasticity of the beam occurred near the beam-to-column interface. Minor cracks were observed at the tip of the beam flange near the penetration groove weld. With the AWS weld access hole details, no cracks occurred in the region of the weld access hole. Using either the reduced beam section or AWS weld access hole, the specimens exhibit significant, reliable strength and ductility.

Keywords: high-strength steel; beam-to-column connection; reduced beam section; ductility; weld access hole.

1. Introduction

Special moment frames are effective for resisting lateral forces generated by seismic excitation. Within the frames, moment connections are usually designed to join the beam and the column. Based on the design philosophy of the strong column – weak beam, plastic hinges are expected to form on the beam section and to dissipate energy exerted by seismic force. However, many moment connections were severely damaged during the 1994 Northridge and 1995 Kobe earthquakes [1-3]. The moment connections suffered a brittle failure mode with very little ductile behavior. The brittle failures were in the forms of the cracking, fracturing and buckling and occurred on the column flange, beam flange, beam web, and shear tab. After the earthquakes, many efforts have been made to improve the cyclic behavior of the moment connections. The improvement can be generally classified to two categories: strengthening and weakening strategies. The strengthening strategy is to reinforce the beam-to-column connection by adding cover plate, rib plate, widened plate, or side plate [4-7]. The weakening strategy is to reduce the beam section near the column by trimming the beam flange [8-10]. The effectiveness of both strategies has been demonstrated by many tests and the details of the improvements have also been documented in the literature [11-13].

Recently, high-strength steel has been intensively used in bridges and high-rise buildings [14-18]. The high-strength steel characterizes high yielding and tensile strengths. However, the high yield and tensile strengths associate with a high yield ratio which is defined as the ratio of the yield strength to the tensile strength. A high yield ratio may result in a less ductile behavior. Therefore, the cyclic behavior of moment connections using high-strength steel were experimentally explored in this study. One of the moment connections was the reduced beam section while the other one was improved at the weld access hole.

2. Experimental investigation

2.1 Design of test specimens

Two large-scale specimens were designed and fabricated. The specimens represent a subassemblage of an exterior joint. The subassemblage includes a column between two inflection points and a beam with a length of a half span, representing a portion of a frame subjected to a lateral force. Table 1 tabulates the details of the specimens. Specimen RBS-QCA was designed to have the reduced beam section (RBS) and the weld access hole in the shape of a quarter circular arc. The quarter circular arc has a radius of 35 mm but with a small radius of 10 mm at the joint with beam flange. Specimen WUF-W did not trim the beam flange and used the weld access hole suggested by AWS [19]. Fig. 1 illustrates the details of weld access hole.

Table 1 – Specimen details

Specimen	**Beam and column**	**Details of weld access hole**	**Details of beam flange**
RBS-QCA	Beam H550×250×13×21 Column H600×420×21×30	A quarter circular arc	RBS a=195 mm b=400 mm c=48 mm
WUF-W	Beam H550×250×13×21 Column H600×420×21×30	AWS details	Without RBS

As shown in Table 1, the specimens has the column of H600×420×21×30 and the beam of H550×250×13×21, both confirm to SM570 steel. Due to the availability of the steel plate, the steel plates of the beam web and column flange are SM570MB while those of the beam flange and column web are SM570.

Fig. 2 depicts the connection details of the two specimens. Specimen RBS-QCA has the traditional connection details that the beam flanges are welded to the column flange via completely joint penetration weld and the beam web are bolted to the shear plate which is welded to the column flange. Specimen WUF-W was designed according to the prequalified connection details [13] that both the beam flange and web are welded to the column flange. Specimen WUF-W was the moment connection in the form of welded unreinforced flange – welded web. Fig. 3 shows the completely joint penetration weld between the beam flange and column flange that the welding was conducted to be consistent with the welding in the field. Electrode of E81 flux-coated wire was used to match the strength of the high-strength steel.

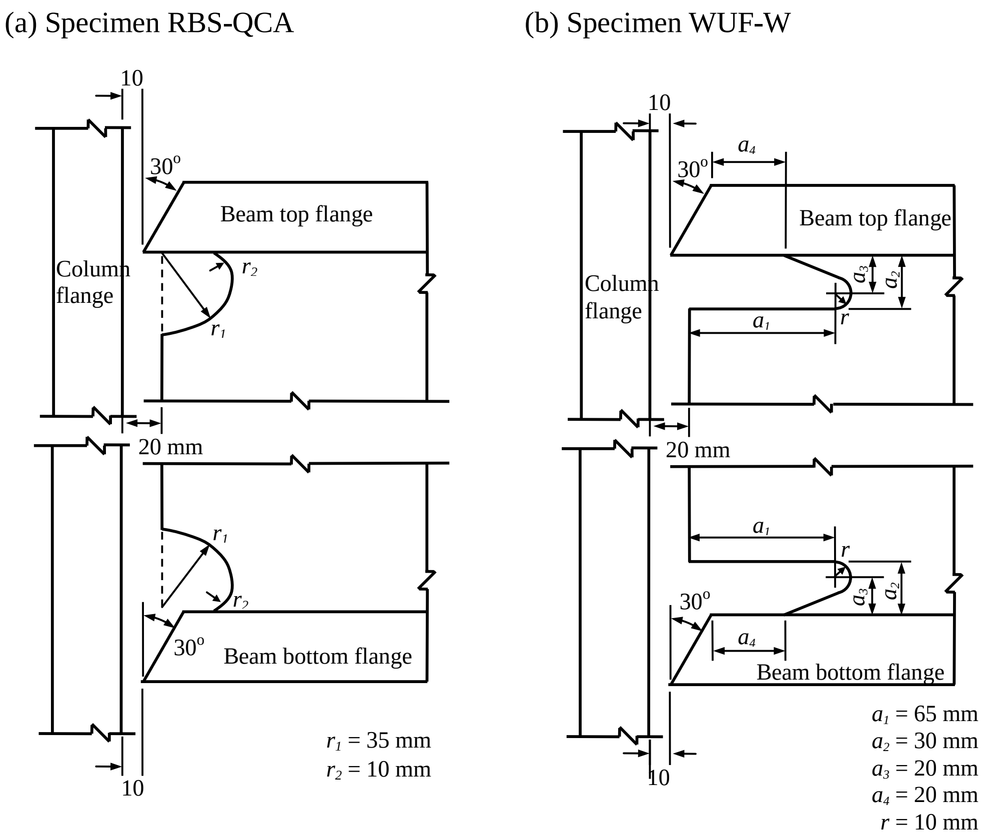


Fig. 1 – Details of weld access holes

2.2 Test setup, loading history and instrumentations

The test setup for the beam-to-column connection is displayed in Fig. 4. The column was placed horizontally while the beam was set upright. The column was axially restrained and two hinged supports were provided at the inflection points. A horizontal hydraulic actuator applied a lateral force to the beam tip which represented an inflection point. Lateral brace was installed to prevent out of plane deformation of the specimens.

Cyclic loading was applied to the beam tip by a predetermined cyclic displacement history. The cyclic displacement protocol was in accordance with the recommendation in the AISC seismic provisions [20]. Fig. 5 shows the story drift angle sequence. Six successive cycles at the story drift angles of 0.375, 0.5 and 0.75% rad were applied first. Four cycles of 1% rad were followed. Afterward, two cycles of 1.5, 2, 3, 4 and 5% rad were succeeded until the specimens failed. The story drift angle of 1% rad corresponds to a 33 mm displacement at the beam tip.

In addition to the displacement measurement at the beam tip, four displacement measurements were recorded at the panel zone (Fig. 6) to measure the rotation at the joint and the shear deformation at the panel zone. Strain gauges were also installed on the beam flange and web to record the local strains.

(a) Specimen RBS-QCA (b) Specimen WUF-W

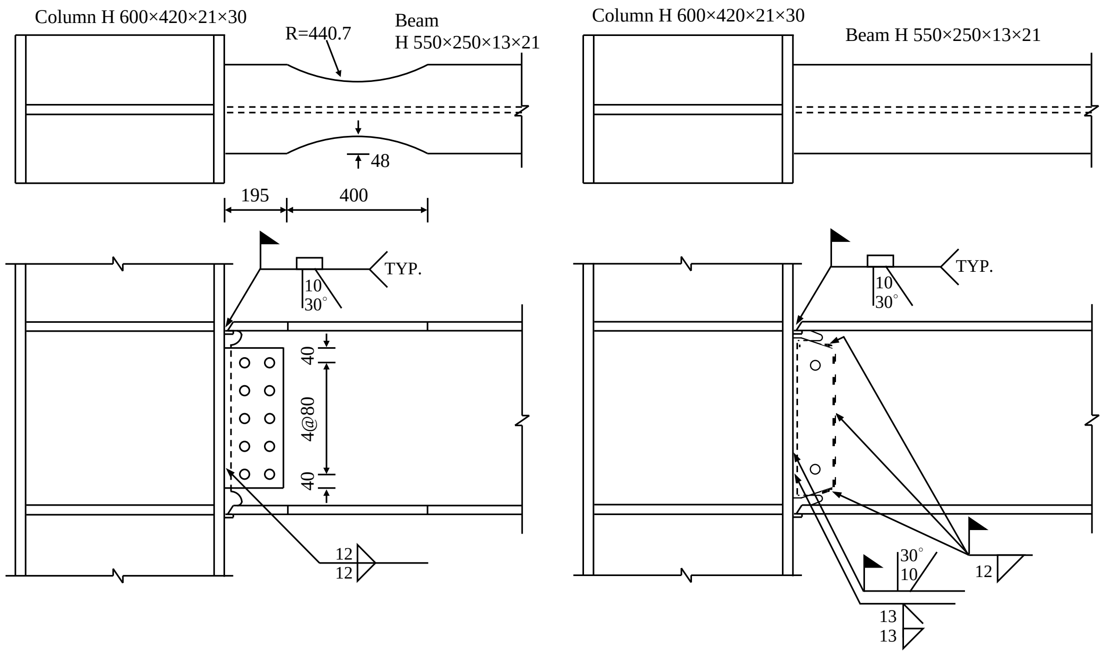


Fig. 2 – Connection details

Fig. 3 – Completely joint penetration weld

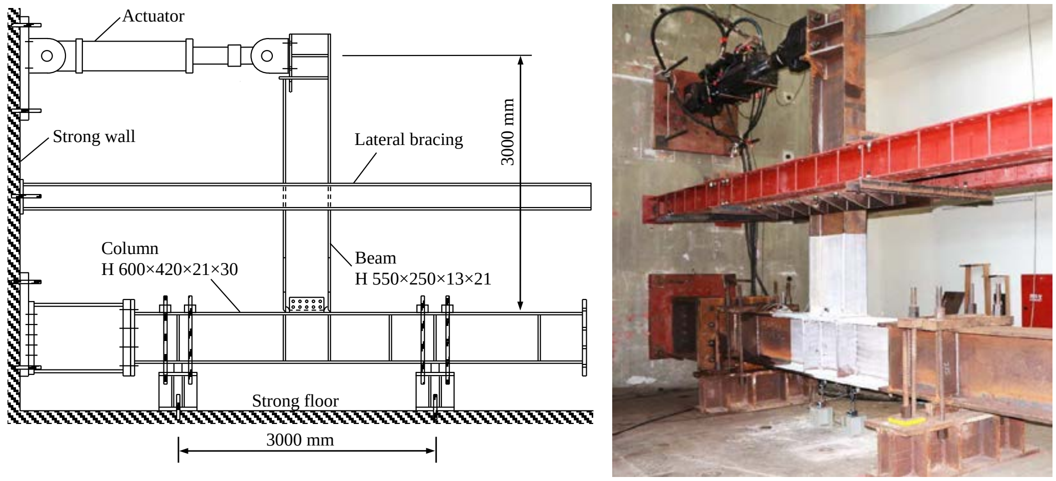


Fig. 4 – Test setup

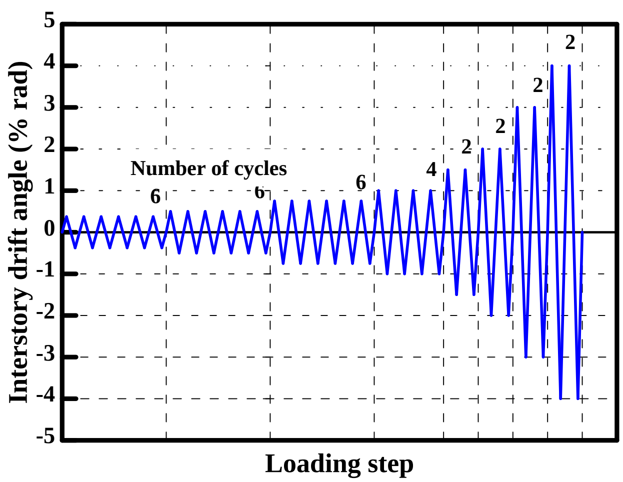


Fig. 5 – Story drift angle sequence

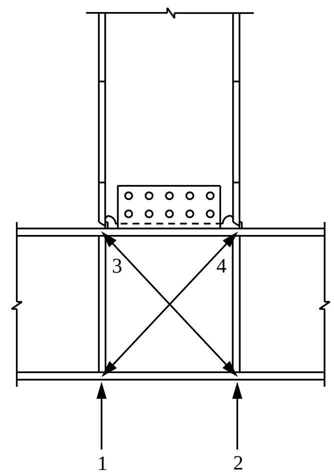


Fig. 6 – Measurements at panel zone

3. Experimental results and discussion

3.1 Material mechanical properties

The mechanical properties of the steel plate are listed in Table 2. Coupon tests of the high-strength steel plates indicated that the yield strengths are ranged from 486 to 520 MPa and the tensile strengths reached 572 to 638 MPa. The yield ratios of these high-strength steel plates are in the range of 0.81 to 0.86. The yield ratio of 0.86 is greater than 0.85 that exceeds the requirements of the code specification. Notably, the 21 mm steel plate with yield ratio of 0.86 is used in the beam flange.

Table 2 – Material properties of the steel plates

Steel plate (thickness in mm)	**Material**	**Yield strength (MPa)**	**Ultimate strength (MPa)**	**Yield ratio**
13	SM570MB	486	581	0.84
21	SM570	491	572	0.86
30	SM570MB	520	638	0.81

3.2 Observed behavior

Specimen RBS-QCA demonstrated linearly elastic behavior before the cycles of 1.5% rad story drift angle (SDA). Flaking of the whitewash occurred on the beam flange at reduced section at 2% rad SDA. Minor crack was observed at the edges of the beam bottom flange at 4% rad SDA. Although the crack width was enlarged during the subsequent cycles, the crack did not propagate. In the cycles of 5% rad SDA, a crack occurred on the beam bottom flange at the root of the weld access hole as shown in Fig. 7. Moreover, the beam flange and web at the reduced section buckled locally and caused the gradual deterioration in the strength.

Specimen WUF-W behaved linearly before 1.5% rad SDA. A crack occurred at the edges between the completely joint penetration weld and the beam bottom flange at 2% rad SDA, and this crack enlarged at the successive cycles. The flaking of the whitewash happened on the beam flange and web close to the column at 3% rad SDA, and the beam flange began to buckle locally at 4% rad SDA. At 5% rad SDA, additional crack was observed on the beam bottom flange at the root of the weld access hole, and severe local buckling of the beam flange was observed as shown in Fig. 8.

Fig. 7 – Local buckling and cracking at weld access hole of specimen RBS-QCA

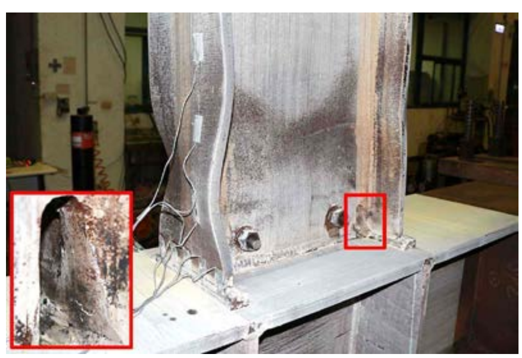


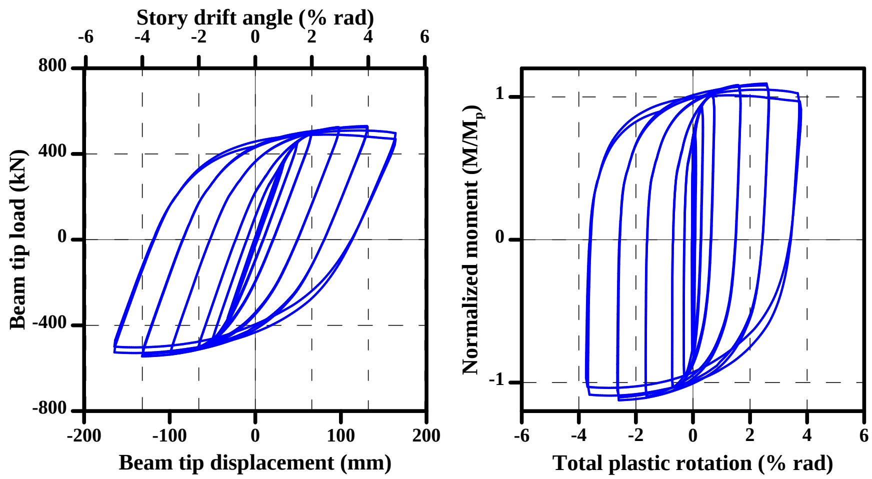
Fig. 8 – Local buckling and cracking at weld access hole of specimen WUF-W

3.3 Hysteretic response

Fig. 9 shows the specimens' hysteretic loops in the relations between the load and displacement at the beam tip, and relations between the moment and total plastic rotation. The moments of the beam were calculated to the column face, and were normalized to the plastic flexural strength of the beam. Both specimens demonstrated stable hysteresis by developing a plastic hinge at the beam. Specimens reached their maximum flexural strengths at cycles of 4% rad SDA. Then, the flexural strength decreased owing to the local buckling of the beam flanges and web. However, the strength decrease at 5% rad SDA is very minor for both specimens as indicated in the hysteretic loops. The tests of both specimens were terminated at 5% rad SDA because of the excursion limitation of the actuator.

Table 3 tabulates the test results that indicate the plastic rotation developed by the specimens and modes of failure. Both specimens reached 5% rad story drift angle and greater than 3% rad plastic rotation that are satisfactory the code requirement for the moment connection [20]. In addition to the local buckling of the beam flanges and web, specimens cracked on the beam flange at the root of the weld access hole, confirming the analysis results conducted for the effects of the weld access hole.

(a) Specimen RBS-QCA



(b) Specimen WUF-W

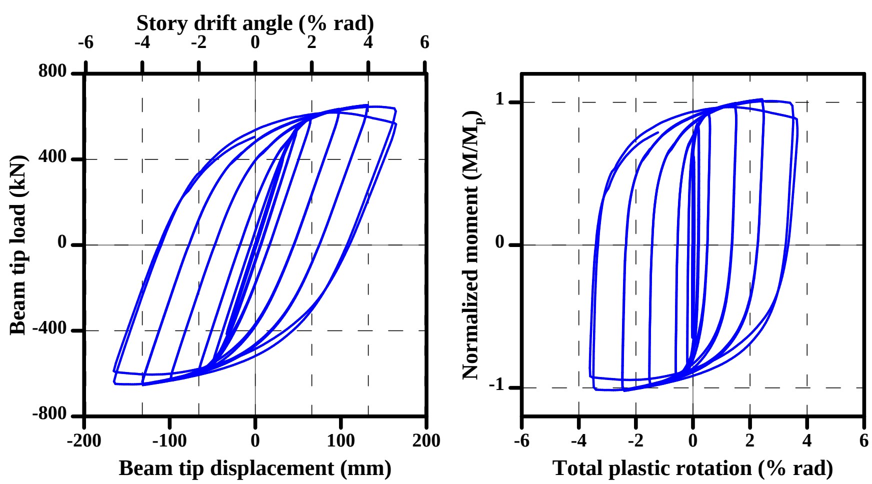


Fig. 9 – Hysteretic curves of specimens

Table 3 – Test results

Specimen	Total story drift rotation* (% rad)	Total plastic rotation (% rad)	Description of failure
RBS-QCA	+5.0	+3.8	Local buckling of beam flanges and web, minor cracking at the root of the weld access hole
	−5.0	−3.7	
WUF-W	+5.0	+3.7	Local buckling of beam flanges and web, minor cracking at the root of the weld access hole
	−5.0	−3.6	

*Test was stopped due to the stroke limitation of the actuator.

4. Conclusions

This study explores the seismic performance of the moment connections using high-strength steel. Based on the experimental results, the following conclusions are made. Specimen RBS-QCA had the weld access hole of quarter circular arc which resulted in cracks on the beam flange at the root of the weld access hole. Undoubtedly, plastic hinge formed at the reduced beam section away from the column, associated with local buckling of the beam flange and web. With AWS weld access hole details, specimen WUF-W could develop significant yielding and plastification on the beam section close to the column, although cracking was observed at the root of the weld access hole and edges of the beam flange at the column face. Using the high-strength steel and designed to have either reduced beam section with a quarter circular arc weld access hole or welded unreinforced flange – welded web, the specimens can achieve 5% rad story drift angle and greater than 3% rad plastic rotation.

5. Acknowledgements

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