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Test, modeling and design of bolted-angle connections subjected to column removal

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ABSTRACT

This paper reports an experimental test of two types of bolted-angle beam-to-column connections under a double-span condition. The first type used web angles only, and the second type used both flange and web angles. The test results included failure modes, load-carrying capacity, and deformation versus loads. A mathematical model is proposed for the test setup based on a component-based spring model for the bolted-angles. A new compressive force versus deformation curve is proposed for the angle springs in addition to an existing tensile force versus deformation curve. The numerical results of the mathematical models are compared with the test results to gain insights of the behaviors of the bolted-angle connections. Finally, two design examples are provided to illustrate the strategies for obtaining a good robustness of angle connections subjected to a column removal.

1. Introduction

Bolted-angle connections herein are referred to the steel angles whose two legs are connected to a beam and a column respectively through high-strength bolts. They are also called bolted-bolted or all-bolted angle connections to distinguish them from the welded-bolted or welded-welded connections whose one or both legs are welded to other structural members. Bolted-angle connections are widely used in simple and semi-rigid constructions.

The robustness of bolted-angle connections has received considerable attentions recently. Yang and Tan [1] reported a test of 12 bolted-angle connections with three different types under a double-span setup. They noticed that support restraints had a significant influence on the mobilization of a catenary action. Oosterhof and Driver [2] reported a test program of shear connections under simulated column-removal demands. Their test included 15 bolted single-angle and 6 double-angle specimens. The test setup used three actuators to apply a combination of tension, shear and rotational demand to the connections. They noticed that the tearing or rupture of the gross section near the angle heel was an unstable and sudden failure. Weigand and Berman [3] tested 15 bolted-angle and 2 welded-bolted connections subjected to a combined tension and rotation. They used the beam and column stubs whose sections were too weak to isolate angle behaviors.

Various researchers, such as Gong [4], Oosterhof and Drive [5], Yang and Tan [6], and Shen and Astaneh [7], have developed or adopted different mechanical spring models for bolted-angle connections. Stylianidis and Nethercot [8] provided an excellent review and description on the component-based connection models for progressive collapse analysis. In an earlier study on the analysis of shear connections under a middle-column removal scenario [9], this writer pointed out that it was primarily the ductility supply that distinguished the connection robustness design from the traditional shear connection design. The writer further suggested that the capacity design principle be adopted in the ductility design of connections.

This paper is a continued effort by the writer on the robustness design of shear connections. First, a test program on bolted-angle connections is described and the relevant test results are provided. Then, a mathematical model for the test setup, which uses a mechanical spring model for the bolted-angles, is used to explain the test results. Finally, based on the insights gained from the test and analysis, two examples are provided to show the approaches for designing the robustness of shear connections under a catenary action.

2. Test setup and connection specimens

The double-span test setup is schematically shown in Fig. 1, and a photo of the setup is given in Fig. 2. The column stub in the middle was connected to the two test beams through two identical bolted-angle connections. The setup was symmetric about the vertical centre-line of the middle column. The far end of each beam was pin-supported by a reaction column, which was fastened to the rigid floor by bolts (Fig. 2). The middle column and the beams were made of a same stocky H-shape section W310 × 202 (nominal properties as per [10]: linear mass 202 kg/m, depth 341 mm, flange thickness 31.8 mm, and web thickness 20.1 mm) of CSA G40.21 350W steel [11] (nominal yield

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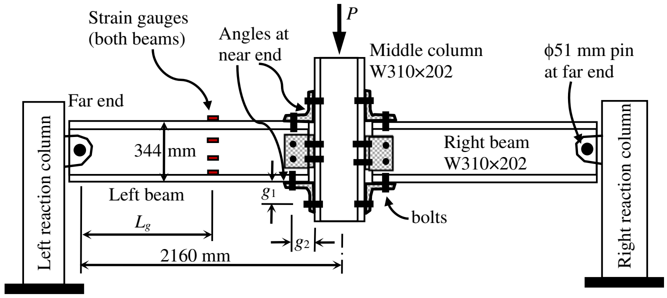


Fig. 1. Side view of test setup.

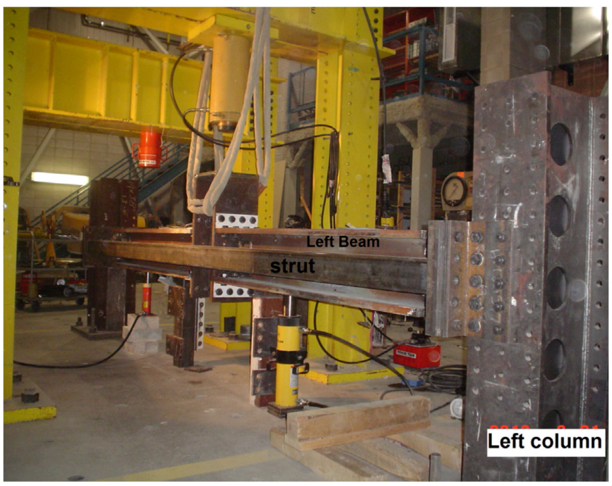


Fig. 2. Photo of test setup.

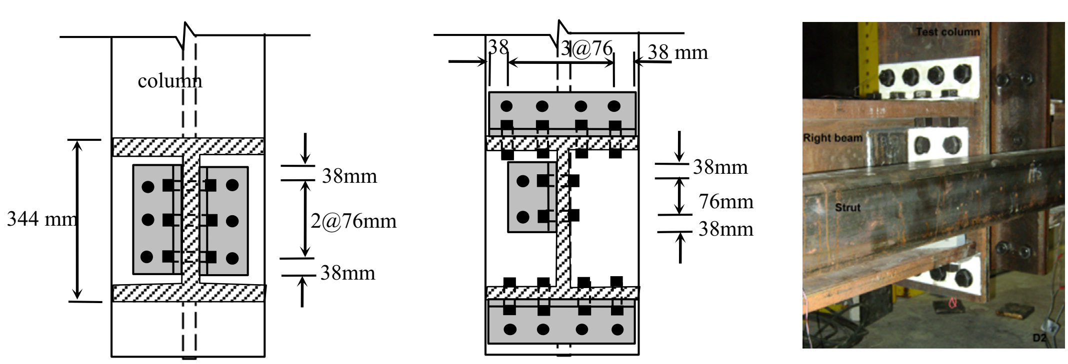
strength 350 MPa). The heavy section was chosen such that the members would remain elastic during tests, and thus could be re-used for several experimental studies. Also, since a longer beam span was impossible due to lab space limitation, the depth of the beam was chosen such that its span-to-depth ratio could be similar to common practice (the measured depth of the beams was d = 344 mm). A pair of struts, which is not shown in Fig. 1 but can be seen in Figs. 2 and 3c, made of hollow structural section HSS127 × 127 × 7.9 [10] of CSA G40.21 350W steel, was installed on the sides of the beams. The struts were used to balance the catenary action in addition to preventing the middle column from moving laterally (i.e., out of the plane of the beam web) during a loading. To avoid introducing bolt hole bearing deformation into the test parameters, the web at the near end of the beams was locally reinforced by a 6 mm thick parallel plate on each side (see Figs. 3c and 4b). The gap between the face of the middle column and the end of a beam was 26 mm.

The six specimens were divided into two groups based on the arrangement of angles (Table 1). Group C used double web angles with three bolts per leg (Fig. 3a). Group D had flange angles in addition to a single web angle (Fig. 3b and c). Each flange angle had four bolts while the web angle had two bolts. Among each group, three different angle thicknesses, i.e., 7.9 mm, 9.5 mm and 12.7 mm, were included. All angles were made of CSA G40.21 300W steel (nominal strength 300 MPa) [11], and their measured average strengths are given in Table 2. All specimens used ASTM A325 high-strength bolts of 22.2 mm diameter and standard bolt holes of 23.8 mm diameter. The bolt gauges g_1 and g_2 were 65 mm on both legs (Fig. 1). The high-strength bolts were snug-tightened. The tensile strength of a single-bolt was 302 kN based on the average of five single-bolt tests under a pure tension. Based on double-shear tests of single-bolt, the average strength per shear plane was 185 kN with the rupture at the threads and was 228 kN with the rupture at the shank. During the installation of the tensile bolts, it was purposely ensuring that the washer was on the side of the angle leg, which was considered to be helpful to prevent a bolt from pull-through failure, a failure mode was observed in [17]. The washer also enhanced the constraint of the bolts on the bending of the angle.

Two linear displacement sensors were placed under the middle column to measure its vertical deflection u. A load cell was used to measure the static load P that pushed down the middle column from above. For each test beam, at a section near to its half length, eight strain gauges were used to measure bending strains over the depth. The measured strains were used to calculate axial force F and bending moment M_b at that section. A dial gauge was used to monitor the horizontal displacement of each reaction column at the height of the beams.

The quasi-static test procedure was as follows:

1) The near end of the test beams and the middle column were lifted and temporarily supported in place. The angles were then installed in place preliminarily by loose bolts. Minor adjustments were then made to ensure that the test beams were levelled. All the bolts were then tightened.
2) The struts were installed, and the firm contact with the reaction columns should be ensured.
3) The temporary supports were removed to allow the middle column to sag slowly under the self-weight (which was 5.5 kN, including the weights of the column and one-half of each beam), while data acquisition system was recording the column deflection and the strain gauge readings.
4) A jack was then used to slowly push down the middle column from above (the loading rate was not greater than 20 mm/min) while the pushdown force, the column deflection and the strain gauge



(a) Group C (b) Group D (c) Specimen D2 prior to test

Fig. 3. Connection specimens.