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An experimental study of static and dynamic behaviour of bolted end-plate joints of steel

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ABSTRACT

Many actions, such as accidental or malicious explosions, may impose high loading rates to structural frames. To enhance the knowledge of the behaviour of joints subjected to severe impulsive loading, a double-sided beam-to-column joint configuration was tested at quasi-static and dynamic loading rates. The test specimens consisted of H-section beams and columns, extended end-plates, and high-strength bolts. In both the quasi-static and dynamic tests, the fracture modes were bolt failure in combination with plastic deformation of the end-plates. However, it was observed that the joints absorbed considerably more energy before failure in the dynamic tests than in the quasi-static tests, partly due to changes in the deformation modes. Also, the ductility of the joints seemed to increase for higher loading rates. These results suggest that the tested joints behave in a preferable manner under extreme impulsive loads.

1. Introduction

The behaviour of steel joints under static loading conditions has been studied extensively in the open literature, and several design codes provide guidelines for calculation of the resistance. On the other hand, the behaviour of steel joints subjected to severe impulsive loading is less documented. In the past decade, after the attack on the World Trade Center in New York in 2001, there has been increased interest in the behaviour of steel structures under extreme loading conditions [1–5]. The design code Unified Facilities Criteria [6] states that joints subjected to blast loads should have adequate strength, stiffness, and rotation capacity. Even though a joint has satisfactory properties for static load conditions, it does not necessarily behave in a favourable manner under impulsive load conditions. It is therefore important to acquire knowledge about the behaviour of joints subjected to severe dynamic loading.

Several publications present experimental studies on the scenario where the loss of a column in a framed structure cause an abnormal load situation for the adjacent joints, e.g. Refs. [2,5,7,8]. In most of these mentioned studies, the load is applied quasi-statically. The exception is the paper by Liu et al. [2], which presents experiments where a test specimen consisting of two beams joined with a central column was subjected to a sudden vertical movement. The reported failure mode was fracture in the web angles, and it was similar in both the dynamic and quasi-static tests.

Sabuwala et al. [3] and Tyas et al. [4] express that there is lack of experimental data published on the behaviour of steel connections subjected to extreme, non-cyclical loading. Karns et al. [9] report the results from tests where double-sided beam-to-column joint configurations were subjected to an explosion blast and subsequent progressive collapse load conditions. Joints with various connections were tested and it was found that the joints can behave in a very ductile manner, even when subjected to high strain-rates. Recently a research group in England started an extensive test program of dynamic tests on bolted steel joints, where single-sided beam-to-column joints loaded at very high strain rates are studied [4,10,11]. They report that dynamic effects increased the stiffness and decreased the ductility of joints with the flexible end-plate connections [4].

The test specimens in the current study represent a typical joint configuration within a framed steel structure; two short beams were connected to a short column by end-plate connections. A test series comprising of four quasi-static tests was performed, where the test specimens were gradually loaded until failure by a hydraulic actuator. Further, eight dynamic tests were

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carried out in a test rig designed for impact testing, where the impact velocity was varied. The purpose of the experimental programme was to study and compare the quasi-static and dynamic response of the joints. More specifically, the deformation modes, evolution of force-displacement response, and energy absorption have been studied. The test set-up and boundary conditions were designed to provide mainly moment and shear in the joints, and the effect of axial forces in the beams was thus not considered. Moreover, the tests were performed with the intention of producing results that can validate numerical models in future studies, and a simple test arrangement was therefore chosen. The test results demonstrate that the behaviour under quasi-static and dynamic load conditions were similar in some aspects. For instance, failure of the joints occurred by tensile bolt fracture for both load conditions. However, the dynamic tests produced different deformation modes, which induced for example more shear deformation of the bolts. Furthermore, the energy absorption and ductility of the joints seemed to increase in the dynamic tests compared with the quasi-static tests.

2. Experimental programme

2.1. Test specimens

Fig. 1a and b display the two types of test specimens studied in the experimental programme. The beams and column of the test specimens were short lengths of rolled steel sections of type HEA 180 and HEB 220, respectively. The weight of the beam lengths was 34.5 ± 0.3 kg each, while the column was 60.3 ± 0.3 kg. End-plates with 12 mm thickness were welded to the beams with a continuous fillet weld with a throat thickness of 5 mm. Fig. 1c depicts the cross-section of the beam and the dimensions of the end-plate. All sections and end-plates were of steel grade S355. Six partially threaded M16 bolts of grade 8.8 were used to connect each end-plate to the respective column flange.

Fig. 1a and b also indicate the loading and boundary conditions of the specimens. A force was applied to the column, while the end of the beams was fixed in the direction of the force. The load configuration in Fig. 1a induces two rows of bolts in tension, and is referred to as the *Design Load Direction* (DLD), because the joints at hand are in practical applications loaded in this direction. Stiffener plates of 10 mm thickness were welded to the column in the compression region, parallel to the beam flanges. This was done to avoid potential buckling of the column web, which would inhibit a controlled deformation to failure. The specimen in Fig. 1b is identical to the specimen in Fig. 1a, except that it is rotated 180° in the plane and the stiffeners are here moved parallel to the opposite beam flanges. This provides a load configuration where only one bolt row is in tension. The latter load case is denoted the *Reverse Load Direction* (RLD), and is related to for instance the load conditions in a column-loss scenario. For later reference, the specimens in Fig. 1a and b have a double-sided joint configuration that consists of left and right joints (indicated in Fig. 1a). This terminology is similar to the definitions in Fig. 1 in NS-EN 1993-1-8, Eurocode 3: Design of steel structures - Part 1–8: Design of joints [12] (hereafter denoted Eurocode 3).

Firm contact between the end-plates and column flanges was achieved by applying a tightening moment of 80 Nm to the bolt and nut assemblies. Two nuts were used on each bolt to prevent thread failure. The reason for this choice is discussed in Section 3.1. Washers were not used.

The dimensions of the test specimens were chosen with regard to the available space in the dynamic test rig. Details of this test rig are presented in Section 2.4. Another deciding factor for the dimensions of the test specimens was that ductile fracture of the joints was preferred. Ductile fracture means that relatively large plastic deformations would appear before ultimate failure in the test specimen. The joints were therefore designed such that the failure mode that gave the lowest resistance was tensile bolt fracture, partially due to prying effects induced by local bending deformation of the end-plate, according to the calculation procedure in Eurocode 3 [12].

2.2. Mechanical properties

The test specimens described in the previous section were made of sections, end-plates and bolts coming from the same production batch, respectively. A material test series consisting of quasi-static and dynamic uniaxial tension tests was performed to determine relevant mechanical properties of the materials.

Fig. 2 displays representative engineering stress–strain curves acquired from the different materials, where the strain rate was approximately 10^{-4} s^{-1}, which is in the order of magnitude of the strain rate expected in the quasi-static component tests. The curves show data up to the onset of diffuse necking. All the tests in Fig. 2 were repeated twice and an excellent agreement between the replicate tests was achieved.

It is reasonable to assume that the strain-rate sensitivity is approximately the same for the S355 steel in the sections and end-plates. Thus, a strain-rate sensitivity investigation performed only on the end-plate and bolt material was assumed sufficient. Tests at low and medium speeds were carried out using a standard servo hydraulic test machine, while high-speed tests were executed with a split-Hopkinson tension bar, applying the methods described by Vilamosa et al. [13]. Fig. 3a provides the obtained true stress at certain values of strain as a function of strain rate. Both the end-plate and bolt material exhibited strain-rate dependence with respect to the stress.

The fracture strain of the end-plate and bolt material was determined from optical measurements of the fracture surface area of the ruptured tensile specimens used in the strain-rate sensitivity investigation. By the assumption of conservation of volume during plastic deformation, the logarithmic fracture strain was calculated as $\varepsilon_f = \ln(A_0/A_f)$, where A_0 and A_f are respectively the areas of the initial cross-section and fracture surfaces of the specimen. Fig. 3b displays the acquired fracture strain versus strain rate. The fracture strain of the plate material is slightly reduced at the highest strain rate, whereas no clear dependency is obtained for the bolt material. Dey et al. [14] also observed that steels with a low strength tended to lose ductility as the strain rate increased, while steels with a high strength exhibited no noticeable effect. As all measured fracture strains in the strain rate investigation were around 1 or larger, both materials may be considered ductile at the range of strain rates covered in the component tests.

2.3. Set-up for quasi-static component tests

The test set-up for the quasi-static tests of the joint configuration is displayed in Fig. 4a. A bolted grip connection at the upper end of the column of the test specimen transferred a vertical force P to the test specimen. The force was recorded by a load cell connected in series with a hydraulic actuator (not shown in Fig. 4a). A hinge between the load cell and test specimen ensured that no bending moments were transferred to the load cell. One portal frame at each side served as supports for the beams, and thus restricted vertical displacement of the tip of the beams as the actuator pulled the column. Pulling the test specimen upwards rather than pushing it downwards was done because the former choice is geometrically more stable.