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A numerical study of beam-to-column joints subjected to impact

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ABSTRACT

Limited documentation is concerned with the behaviour of steel joints subjected to severe impulsive loading originating from incidents such as explosions or impact. In this paper, finite element simulations are used to investigate the behaviour of beam-to-column joints with bolted end-plate connections subjected to impact loading. An elastic-thermoviscoplastic material model was employed in the simulations. Good agreement was obtained between the simulations and previously reported tests in terms of both global and local behaviour. In particular, the numerical model successfully reproduced the experienced failure mode of tensile bolt fracture combined with end-plate deformation. The validated model was employed in investigations of three cases, in which the main findings are as follows: (1) reducing the end-plate thickness significantly increased the energy dissipated by the joint; (2) axial forces in the beams only marginally affected the response; and (3) including the additional inertia introduced by the presence of floor slabs may change the failure mode to premature shear failure.

1. Introduction

In the past 15–20 years, particularly after the attack on the World Trade Center in 2001, there has been increased interest in the behaviour of joints subjected to extreme dynamic loads. The beam-to-column joints in a framed structure should preferably be able to transmit such loads to the surrounding members without failing. This requires that the joints have adequate properties such as energy dissipation capacity, which can be considered as a combined measure of the strength and ability to deform before failure. Similarly, design code UFC 3-340-02: *Structures to resist the effects of accidental explosions* [1] states that the main frame connections must be designed for strength, stiffness, and rotational capacity in the case of blast loading. Nevertheless, current design codes provide few guidelines on the design of beam-to-column joints for extreme impulsive loading conditions. In addition, there is only limited research on the topic.

Dynamic tests on full-scale joints can increase our knowledge of this topic, but such experiments are expensive and challenging to perform in a controlled manner. Compared to quasi-static tests, a well-defined application of the load is more difficult to achieve in the dynamic case, and more advanced instrumentation tools are required. The interaction between the joint and its surrounding structure is also challenging to consider in experiments; therefore, it is common to only perform tests on the joint itself and on a minor part of the adjacent beam and column members. An example of such an interaction is when large deformations of a framed structure induce considerable axial forces in the beams through catenary action. In addition, the interaction with structural components such as floor slabs is impractical to include in experiments. Considering floor slabs is particularly important under severe dynamic load conditions. This is because these members introduce considerable inertia, which may significantly alter the response compared to the quasi-static case. Moreover, it is difficult to accurately investigate parameters such as energy dissipation in the different components of the joints based on experimental data. Such challenges related to the testing of joints can be readily addressed with numerical simulations. A trustworthy numerical investigation requires that the model is validated. This means that the model is able to capture the experienced global as well as local response of the joint at hand, including the correct failure mode.

Few reports on numerical analyses of the transient dynamic response of beam-to-column joints can be found in the literature. Sabuwala et al. [2] studied the behaviour of beam-to-column joints subjected to blast loads. A pressure load was imposed on a finite element (FE) model of single-sided, beam-to-column joints with bolted fin-plate connections. The load represented the pressure originating from an internal explosion within a hypothetical room. It was observed that the recommendations from a design code (the precursor to UFC 3-340-02 [1]) were inadequate. A limitation of the study is that the FE model was only validated against physical experiments conducted under quasi-static load conditions.

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For some years, researchers at the Nanyang Technological University have performed experiments and FE simulations to investigate the behaviour of various steel connections during a so-called column-loss scenario; see, for instance, Yang and Tan [3]. Most relevant to the current study are the papers by Liu et al. [4–6] because they applied the load in a dynamic manner. They observed good agreement between the global displacement–time curves obtained from the experiments and simulations.

A comprehensive experimental programme commenced a few years ago at the University of Sheffield, where a purpose-built test rig has been used to study the behaviour of single-sided joints subjected to high loading rates; see Tyas et al. [7]. Rahbari et al. [8] simulated both quasi-static and dynamic tests on web-cleat connections performed with this test rig. They observed that their model captured the main aspects of the response, including the failure mode. A parametric study by Rahbari et al. revealed that the thickness of the web-cleat angles had only a minor effect on the moment resistance of the connection but that it strongly affected its rotational capacity.

Grimsmo et al. [9] tested double-sided, beam-to-column joint configurations both quasi-statically and dynamically. The test specimens consisted of two H-section beams connected with an H-section column using extended end-plates and high-strength bolts. The dynamic tests were conducted with a test rig designed for impact testing of structural components. Failure occurred by tensile bolt fracture combined with end-plate bending deformation in both the quasi-static and dynamic tests. However, it seemed that the ductility and energy dissipation of the test specimen increased with greater impact velocities.

The first objective of this paper is to present and validate a three-dimensional FE model of the impact tests reported by Grimsmo et al. [9]. Compared to most models presented in the relevant literature, the current study incorporates a material model where the strain-rate sensitivity and fracture parameters are calibrated using material test specimens machined from the members used in the beam-to-column joint assembly. The second objective is to demonstrate how a validated model can be employed to investigate aspects that are challenging to explore in physical impact tests. The following investigations were chosen for this paper:

(1) How the energy dissipated in the joint region is influenced by minor changes in the design of the joint. This study is limited to varying the end-plate thickness.
(2) How axial forces in the beams affect the behaviour of the joint configuration.
(3) How the response of the joint configuration is influenced by the inertia of floor slabs attached to the beams. The purpose of this investigation is to provide a qualitative assessment of the inertia effects.

Section 2 of this paper briefly summarizes the laboratory tests in terms of both full-scale component and material tests. Next, Section 3 presents the material model and discusses how the material parameters were identified. The FE model of the impact tests is introduced in Section 4 and subsequently validated in Section 5. The investigations of energy dissipation, axial force, and inertia are presented in Sections 6–8, respectively. Finally, concluding remarks are given in Section 9.

2. Laboratory tests

2.1. Test specimen and impact tests

The experimental programme, including impact tests in a pendulum accelerator, was thoroughly presented by Grimsmo et al. [9]. Only a brief survey of the experiments is provided here. A schematic illustration of the test specimen and experimental setup is shown in Fig. 1. The specimens consisted of: two HEA 180 sections that served as beams; an HEB 220 section representing the column; an "impact plate" spot welded to the end of the column; two 10 mm web stiffeners welded to the column; two 12 mm extended end-plates that were welded to the beams by fillet welds with throat thicknesses of 5 mm; and a total of twelve partially threaded M16 $\times$ 65 bolts of grade 8.8. The H-sections and end-plates were manufactured from grade S355 steel. Additional dimensions relevant to the modelling are provided in the Appendix A. The test specimen was designed so that several components of the joint experienced plastic deformation, and so that failure occurred by tensile bolt fracture combined with end-plate bending deformation. Thus, a numerical model of the tests may be considered reliable if it can capture this relatively complex deformation mode.

A key part of the pendulum accelerator is the trolley (727 kg) illustrated in Fig. 1, which rolled along two rails and impacted the test specimen with a given velocity. Four tests were performed on the specimen geometry in Fig. 1: two with an impact velocity of approximately 8 m/s and two with an impact velocity of nearly 12 m/s. The duration of a test, i.e., from impact to bolt failure, was between 5 and 10 ms, depending on the impact velocity of the trolley.

The beams were supported on steel cylinders placed 690 and 686 mm from each end-plate, as observed in Fig. 1. Thus, the joints were mainly loaded by bending moments and shear forces as the column displaced horizontally due to the impact. All tests included a high-speed camera that monitored the deformation and fracture process of the region around the upper end-plate in Fig. 1. Also, the slight difference in distance to the supports increased the likelihood of failure initiating at the part that was captured by the camera.

2.2. Material tests

Mechanical properties of the different components were determined by performing quasi-static and dynamic uniaxial tension tests. The specimens used in these tests are displayed in Fig. 2. Full-thickness specimens (Fig. 2a) were taken from the flanges of the sections and the end-plate, and specimens with reduced shank (Fig. 2b) were machined from the bolts. Quasi-static tests were conducted on the specimens in Fig. 2a and b in a standard

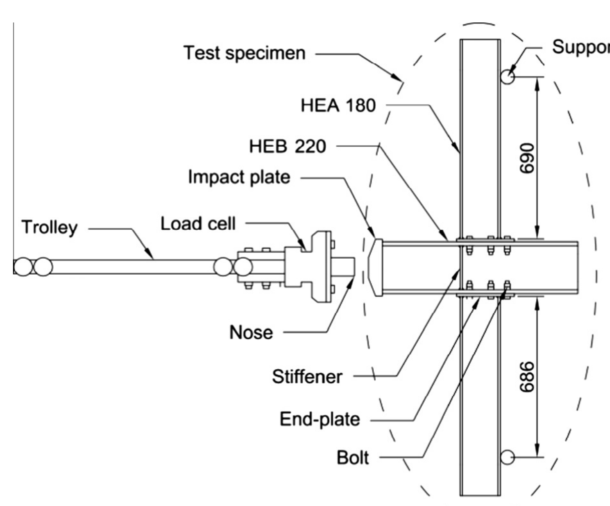

Fig. 1. Elevation view of the impact test setup.