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Numerical study of fillet welds subjected to quasi-static and impact loading

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ABSTRACT

Fillet welding is widely used in connections in civil engineering and marine structures. Thus, understanding the behavior of fillet welds under various types of loading is important, and numerical simulations can provide increased insight into this topic. This paper concerns finite element simulations of previous quasi-static and dynamic (impact) tests on fillet welds. The test specimens employed were structural steel components joined by either longitudinally or transversely oriented fillet welds. In the simulations, the material of the fillet welds was modeled using a shear-modified Gurson model, which accounts for material softening in both low and high stress triaxiality regimes. Additionally, strain rate and temperature dependencies were incorporated in the material model with a modified Johnson–Cook constitutive relation for the matrix material. Several types of material tests were conducted to identify the parameters entering the material model. For the quasi-static component tests and simulations, a good agreement was observed in terms of both force–deformation curves and failure mechanisms. The simulations of the dynamic tests predicted appreciably higher force levels and weld deformations at failure than those obtained in the corresponding experiments. A parameter study showed that these discrepancies may partly be due to inaccurate values used for the material parameters related to strain-rate hardening and thermal softening. Finally, a comparison was made between simulations with the shear-modified Gurson model and a simpler material model that does not account for void-induced softening. The simpler model employed the Cockcroft–Latham failure criterion, uncoupled from the constitutive relations. This model was unable to capture the response of the fillet welds to the same extent as the shear-modified Gurson model.

1. Introduction

Fillet welds are common connection elements in structural joints such as beam-to-column joints. A vast amount of experimental data concerning fillet welds under quasi-static load conditions can be found in the literature, as the literature review by Miazga and Kennedy [1] shows. However, hardly any studies are concerned with the behavior of fillet welds under severe impulsive loading. Grimsmo et al. [2] therefore performed experiments where fillet welds of steel were subjected to quasi-static and impact loading. The test specimens had fillet welds oriented either longitudinally or transversely to the load direction. It was experienced that the resistances of the welds were practically unaffected by the deformation rate. The deformation capacity, i.e., deformation before fracture, of the transverse welds was also independent of the deformation rate. On the other hand, the longitudinal welds experienced a significant reduction in the deformation capacity as the deformation rate was increased. The principal purpose of the present work is to investigate whether the behavior observed in these quasi-static and dynamic tests can be captured with finite element (FE) simulations. Moreover, the simulations are employed to study strain rate and thermal effects in the dynamic tests. The simulations of the quasi-static and dynamic tests are hereafter denoted the quasi-static and dynamic simulations, respectively.

In the past decades, efforts have been made to model fillet welds subjected to quasi-static loading by means of FE simulations. One major advantage of simulations compared to experiments is the low economical cost. Thus, parametric and sensitivity studies are cheap to perform. Furthermore, the inevitable scatter of results obtained from physical tests of welds is avoided with FE simulations, which makes it simpler to isolate and investigate the effects of varying parameters. Numerical simulations also conveniently allow for studying local mechanisms such as the evolution of plastic strain and damage in the deforming welds. Many of the FE models of fillet welds in the literature, where the geometry of the welds is explicitly modeled, are two-dimensional (2D) and employ

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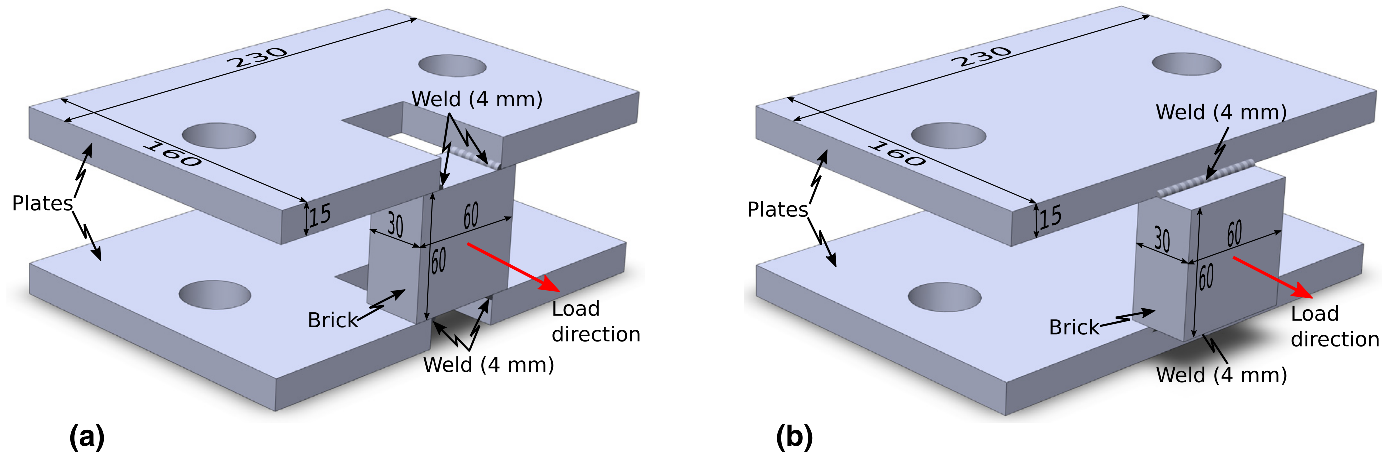

Fig. 1. Illustrations of the component test specimens (dimensions in mm). (a) The longitudinal specimen, which has four fillet welds, (b) The transverse specimen, which has two fillet welds.

plain strain elements; see for instance [3–5]. As the number of elements is significantly lower for 2D models than for comparative 3D models, finer element meshes can be used. However, 2D models cannot account for out-of-plane deformations, which restricts the analyses to simulate fillet welds loaded transversely to the length axis of the weld. To accommodate more general loading conditions, we employed 3D models in the present work.

An adequate material model is a necessary prerequisite for capturing the behavior observed in the tests. This implies that the material model should incorporate yielding, work hardening, strain-rate hardening, thermal softening, and damage softening. Kanvinde et al. [3] employed a micromechanical model called the Stress Modified Critical Strain (SMCS) model to predict fracture in FE simulations of fillet welds under quasi-static loading. By comparing the simulations with corresponding tests, as well as simulations with a traditional fracture model based on the *J*-integral, they observed that the SMSC model was better suited to predict fracture than the *J*-integral model. Nielsen and Tvergaard [6] applied a shear-modified Gurson model similar to the one proposed by Nahshon and Hutchinson [7] to simulate failure of spot welds of steel. However, Nielsen and Tvergaard [6] argued that the damage contribution from the shear modification is possibly too large for moderate and high stress triaxiality states where effects of the third deviatoric stress invariant are less significant. They therefore modified the shear contribution to be a function of stress triaxiality so that it vanishes at high stress triaxialities. From their simulations of shear and plug failure of spot welds, they observed that this modification allowed the shear-modified Gurson model to be used for both low and high stress triaxiality regimes.

In the present work, we employ a shear-modified Gurson model similar to the one used by Nielsen and Tvergaard [6]. However, two modifications are incorporated. First, the yield function of the matrix material is described by the general isotropic yield criterion proposed by Hershey [8] rather than the von Mises yield criterion. Thus, effects of the third deviatoric stress invariant are incorporated in the yield criterion. Second, the shear damage contribution is governed by a slightly different function of triaxiality. Strain-rate and temperature sensitivity are introduced in the material model by assuming that the flow stress of the matrix material follows a modified Johnson–Cook constitutive relation similar to the one proposed by Børvik et al. [9].

We have performed a comprehensive set of material tests to determine several of the parameters employed in the material model. These experiments included tensile tests with smooth specimens conducted at different strain rates, tensile tests with notched specimens, and shear tests with in-plane shear specimens. The material test programme incorporated both the fillet weld material and the base material around the welds, but the main focus was on the weld material. Note that welding-induced residual stresses are not considered in the present work.

The paper is organized as follows. Section 2 presents both the component tests and the material tests. The material model and the calibration of material parameters from the material tests are discussed in Section 3. Section 4 presents the FE model of the components tests, and the corresponding simulation results are provided in Section 5. Finally, some concluding remarks are presented in Section 6.

2. Laboratory tests

2.1. Component tests

Grimsmo et al. [2] provide a detailed description of the component test specimens and setup, and only a summary is therefore presented herein.

Fig. 1 depicts the two types of component test specimens employed; one with four fillet welds oriented longitudinally with respect to the load direction and one with two fillet welds oriented transversely with respect to the load direction. The specimens are denoted longitudinal and transverse specimen, respectively. Both specimen types comprise two plates with dimensions $230 \times 160 \times 15\,\text{mm}^3$ that were fillet welded to a brick with dimensions $60 \times 60 \times 30\,\text{mm}^3$. These parts were made of S355 steel, whereas the specified minimum yield stress was 460 MPa for the basic-coated stick electrodes used to assemble the specimens. The specified throat thickness of the fillet welds was 4 mm, and the lengths of the welds were 30 and 60 mm for the longitudinal and transverse specimens, respectively. This design of the specimens ensured that plastic deformations and failure predominantly occurred in the fillet welds, and not in the adjacent base material. Thus, the strength and ductility of the welds can be determined, which is essential knowledge in design of welded components and structures.

The specimens were mounted in a fixture, as shown in Fig. 2. The fixture consisted of two supporting blocks that were welded to a supporting plate and bolted to the stationary part of the test machines. Two M30 bolts of grade 12.9, which were finger-tightened, fixed the specimens to the supporting blocks. The so-called nose in Fig. 2 was welded to a circular plate that was attached to the moving part of the test machines. During a test, the nose displaced along its longitudinal axis and between the supporting blocks. As the nose attained contact with the brick of the test specimens, the fillet welds became loaded. Since the plates of the specimens were practically fixed, the fillet welds were deformed and eventually failed. The strain gauges attached to the nose (see Fig. 2) enabled determining the axial force developing in the nose.

The quasi-static tests were carried out with a standard servo-hydraulic test machine, and the applied displacement rate was approxi-