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Fillet welds subjected to impact loading – an experimental study

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A R T I C L E I N F O

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A B S T R A C T

Virtually no studies in the open literature are concerned with the behaviour of fillet welds under impulsive loading, which may occur due to actions such as explosions and impact. We therefore developed a novel test setup allowing for measurements of the force and the deformation of fillet welds subjected to impact load conditions. The test specimens had either longitudinally or transversely oriented fillet welds, and they consisted of structural steel. Furthermore, the test specimens were designed so that plastic deformation and failure predominantly occurred in the fillet welds. In addition to the impact tests, corresponding quasi-static tests were performed for comparison. The results showed that the resistance was practically unaffected by the applied displacement rate for both types of specimens. Thus, existing formulas for estimating the resistance of fillet welds that are based on quasi-static behaviour may also be employed for severe impulsive load cases. The deformation capacity of the transverse specimens appeared unaffected by the displacement rate as well. However, the deformation capacity of the longitudinal specimens was significantly reduced for the impact load case. Images of fractured welds recorded with microscopes displayed that the welds experienced stronger localization of deformation for this load case than during quasi-static loading. This enhanced localization was probably induced by self-heating and corresponding thermal softening of the weld material.

1. Introduction

The static behaviour of welds has been studied extensively ever since welded joints became popular in the early 20th century. In the 1930s, transverse and longitudinal fillet welds were recognized to define the upper and lower bounds, respectively, of the resistance of fillet welds; see for instance Freeman [1]. Butler and Kulak [2] noted that also the deformation capacity of the fillet welds depended on the load direction. From tests on fillet welded lap joints, they showed that the deformations of the welds at ultimate load were significantly reduced for transverse welds compared to longitudinal welds. However, Miazga and Kennedy [3] observed from similar tests that the deformation of fillet welds at failure divided by the gauge length were fairly unaffected by the load direction.

In recent years, there has been an increased interest in the behaviour of joints in steel structures subjected to extreme impulsive loading. Structural joints often include several fillet welds. These welds are normally designed to have greater static resistance than the other components of the joints because the welds are typically less ductile. Thus, possible plastic deformations is ensured to occur predominantly in the more ductile components of the joints. The dynamic resistance of fillet welds, however, might be affected by possible strain-rate hardening effects as well as softening due to plastic work and self-heating. It is currently unknown how severe impulsive loading affects the response of fillet welds because no literature on this topic is seemingly available.

There are papers, typically concerned with crashworthiness of automotive structures, which study other types of welds subjected to severe impulsive loading. For instance, Langrand and Markiewicz [4] subjected spot-welded mild steel plates to transient dynamic load conditions. They observed that the yielding, hardening, and failure displacement of the test specimens were deformation-rate dependent. The majority of plastic deformation and fracture was reported to occur in the base material near the spot weld. There are also some papers that study the behaviour of weld material subjected to high strain rates. Wang and Lu [5] employed a split-Hopkinson pressure bar to impose strain rates of nearly $10^3\,s^{-1}$ to test specimens machined from base and weld materials of steel of similar strengths. According to their test results, the strength of the base material was somewhat more strain-rate dependent than that of the weld material. In a similar study, Xu and Li [6] tested a welded stainless steel material at strain rates ranging from 200 to $3800\,s^{-1}$, and at ambient

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temperatures ranging from 20 to 600 °C. They noted that the weld material exhibited less temperature dependence than the base material. In terms of strain-rate dependence, the two materials showed approximately the same behaviour.

The objective of this paper is to study the response of fillet welds of steel subjected to impact loading, particularly in terms of the resistance and deformation capacity of the welds. This was achieved by developing a test method that enabled impact and quasi-static testing of purpose-made test specimens consisting of structural steel components that were joined by fillet welds. In addition to testing these specimens, we conducted material tests on both the base and weld material, and fractography on the failed fillet welds to further investigate the observed differences between the dynamic and quasi-static response.

In Section 2, we introduce the geometry and manufacturing process of the component test specimens. Section 3 provides the mechanical properties of the weld and base materials in terms of strength, strain-rate sensitivity, ductility, and hardness. The test setup for both the impact and quasi-static component tests is presented in Section 4. Subsequently, Section 5.1 provides and discusses results from the impact tests. In Section 5.2, we compare the response obtained from the impact and quasi-static tests in terms of resistance and deformation capacity, whereas in Section 5.3 we study fractured welds originating from both load cases. Finally, the results are summarized and conclusions are drawn in Section 6. Additionally, Appendix A provides a short discussion regarding force measurement, and in Appendix B a particular imperfection in the test setup is evaluated.

2. Geometry and manufacturing of test specimens

We designed the test specimens with the following requirements in mind:

- Plastic deformation and failure should predominantly occur in the welds. Therefore, the weld throat thickness was designed small compared to the thickness of the steel parts surrounding the welds, and the length of the welds were designed short.
- The specimens should be suitable for the available impact-testing rig.
- The specimens should facilitate video monitoring of the weld deformation, which means that there should be free sight to the welds from outside the test rig.
- The force acting on the welds in the impact tests should be measurable. This requirement is a challenge because inertia forces are typically prominent for impact load conditions. With the aid of FE simulations, we designed test specimens where the contribution from inertia forces to the measured force is relatively low. This is discussed in detail in Appendix A.

Based on the requirements above, we designed the two types of component test specimens depicted in Fig. 1. Both specimens consist of two 15 mm steel plates that were fillet welded to a brick of steel with measures $60 \times 60 \times 30\ \text{mm}^3$. All these parts were made of steel grade S355. The so-called longitudinal specimen shown in Fig. 1a has four fillet welds with the longitudinal axis parallel to the direction of the applied load. Each of the four welds have a specified throat thickness of 4 mm and a length of 30 mm; see Fig. 1a. Fig. 1b shows the transverse specimen, which has two fillet welds with the longitudinal axis oriented transversely to the direction of the applied load. The specified throat thickness of the welds is 4 mm for this specimen type as well, whereas the length of each weld is 60 mm; see Fig. 1b. Eleven specimens of each type, i.e., longitudinal and transverse, were manufactured. One of each specimen type was used for extraction of material test specimens, as discussed in Section 3.1.

The plates and bricks were manufactured by laser cutting, and subsequently assembled by means of shielded metal arc welding. Basic-coated electrodes of the type Elga P 47 were used for the welding. The chemical composition of the electrode is listed in Table 1. This electrode type is suitable for general welding applications, and is classified E 46 4 B 12 H5 according to EN ISO 2560-A [7] and E7060-1 according to AWS A5.1 [8]. A certified welder assembled the specimens with a welding procedure approved by the international certification body DNV GL. Only a single pass was necessary for each weld. Run-on and run-off tabs were employed to facilitate relatively uniform welds along the entire length designated for welding. These tabs were removed after welding, and the welds were subsequently grinded to create a practically triangular shape of the weld bead, as shown in Fig. 2.

Weld inspection performed by a certified inspector revealed that all welds were within acceptance level B according to ISO 5817 [9] (visual inspection), and within acceptance level 2X according to ISO 23278 [10] (magnetic particle testing).

A coordinate-measuring machine was used to determine the throat thickness of the welds. In the machine, a mechanical probe measured the spatial coordinates along appropriate faces of the plates, brick, and welds. From these readings, the throat thickness could be calculated. Several of these measurements of the throat thickness were made along the length of each weld. For the majority of the welds, the throat thickness varied 0.3 mm or less within the length of each weld. The mean and the standard deviation of the throat thickness obtained from the longitudinal specimens were 4.0 and 0.2 mm, respectively. The transverse specimens tended to have somewhat larger welds; the mean and the standard deviation of the throat thickness for these specimens were 4.3 and 0.3 mm, respectively.

3. Mechanical properties

3.1. Uniaxial tension tests

The minimum yield stress of the weld material is 460 MPa according to its classification [7], whereas the plates and bricks (i.e., the base material) are made of S355 steel, which is a structural steel with a specified minimum yield strength of 355 MPa. In order to determine the actual mechanical properties of the weld and base material, a series of uniaxial tension tests were conducted at different strain rates. Two types of tension test specimens were employed; see Fig. 3. The comparatively small dimensions of the tension specimen in Fig. 3a enabled extracting specimens from the fillet welds of the component specimens, as illustrated in Fig. 4a. This was an elaborate and economically expensive procedure. Therefore, only four specimens of the type in Fig. 3a were manufactured; two from each type of component specimen, i.e., longitudinal and transverse.

The V-butt weld assembly seen in Fig. 4b was made to simplify the manufacturing of tension specimens from the weld material. This assembly includes two 16 mm plates that were distanced 14 mm apart and a 10 mm backing plate spot-welded to the two other plates. The 16 mm plates were bevelled so that a V-shaped groove between the plates was obtained. Finally, the groove was filled using the same electrode type and weld procedure as employed for the component test specimens. Several weld passes were necessary to fill the groove. Specimens of the type in Fig. 3b were machined from the butt weld, as illustrated in Fig. 4b. Several specimens of this type were also machined from the plates and bricks of the component test specimens.

We subjected the tension test specimens to strain rates of approximately 10^{-3} and $10^{-1}\ \text{s}^{-1}$ using an Instron screw-driven test machine. The load cell in the test machine measured the forces acting on the specimens. Further, a high-resolution digital camera