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Experimental and numerical study of threaded steel fasteners under combined tension and shear at elevated loading rates

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A B S T R A C T

The behaviour of threaded steel fasteners subjected to combined tension and shear loading was investigated experimentally and numerically at elevated loading rates. Tests at low loading rates were performed in a servo-hydraulic testing machine, while tests at high loading rates were obtained using a split-Hopkinson tension bar. All tests were carried out using purpose-made fixtures to ensure uniform test conditions, this to control the load direction and the location of failure. In the experimental study, tests were performed with loading angle equal to 0°, 45° and 90°, where 0° corresponds to loading along the axis of the threaded steel fasteners. The numerical investigations were carried out using the finite element code LS-DYNA. A three-dimensional finite element model, adopting a thermoelastic-thermoviscoplastic constitutive model and a ductile fracture criterion, was used to predict the strength and behaviour characteristics of the threaded steel fasteners. In this numerical investigation, the load was applied at an angle varying between 0° and 90° with 15° intervals. The material parameters used in the finite element model were obtained from previously published work by the authors. The finite element model was capable of representing the ultimate load of the threaded steel fasteners with reasonable accuracy and was used to simulate tests with loading angles not covered in the experimental study.

1. Introduction

Structural metallic members are often connected with use of threaded steel fasteners, and the connections are generally classified according to how the fasteners are loaded. The typical loading conditions are tension, shear or combined tension and shear. Thus, the knowledge of the strength and behaviour characteristics of threaded steel fasteners is of major importance in design. For structures subjected to impact loads, the fasteners connecting the members may experience high deformation rates. Even so, the design of fasteners is often based on material properties that are obtained at low loading rates. This may lead to a structural behaviour which is not optimal with respect to energy absorption and load distribution. Hence, before a structure subjected to impact loads can be analysed, the behaviour of the involved components as well as the connections between them has to be known. Such analyses should be performed with numerical models that are able to represent the structural behaviour with sufficient accuracy and reliability.

Several studies have shown that there are many variables governing the behaviour of threaded steel fasteners subjected to tension, shear or combined tension and shear loading conditions. Chesson et al. [1] investigated the strength and behaviour characteristics of single, high-strength bolts subjected to various combinations of tension and shear at quasi-static load conditions. The effects of the bolt grip, bolt diameter, bolt types, location of the shear planes, and the material of the blocks gripped by the bolt were investigated. The conclusions from this work were that the bolt grip, bolt types and the location of the shear planes had an effect on the ultimate strength of bolts, while the effects of the bolt diameter and the material of the blocks gripped by the bolt were negligible. Shakir-Khalil and Ho [2] performed combined tension and shear tests on M20 black bolts with property class 4.6 to determine the ultimate strength at various ratios of tension and shear. These tests were performed at quasi-static load conditions,

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and the bolts were tested in pairs. In tests with failure in the threaded part of the bolts they observed that a slight increase in the shear component from pure tension caused a reduction in the load-carrying capacity of the bolts. Kulak et al. [3] reported results on different bolt–nut combinations that were exposed to tension, shear or torsion. These results were also obtained at quasi-static load conditions.

A literature survey concerning the behaviour of threaded steel fasteners subjected to combined tension and shear loads at elevated loading rates has been performed. A limited number of reports were found, and most of these reports discuss the tensile behaviour of bolts. Ansell [4,5] performed dynamical testing of rock bolts made of smooth, soft steel bars. The smooth section of these rock bolts was tested at low and high loading rate, while the influence of threads at the end of the rock bolts was not investigated. These rock bolt tests showed that the yield stress and probably the ultimate stress increased with increasing strain rate. Mouritz [6] examined the plastic deformation and the failure mode of mild steel M6 bolts with property class 4.6. He observed that the failure load of the threaded assembly decreased with increasing strain-rate. Fransplass et al. [7] investigated the tensile behaviour of M5 threaded rods with property class 4.6. They found that tests of the bolt material and the threaded assemblies gave approximately the same trend of an increased strength with increasing strain-rate, and that the thread engagement length, the grip length and the strain-rate had an influence on the failure mode of the threaded assemblies. A literature survey concerning numerical investigations of threaded steel fasteners subjected to combined tension and shear loads at elevated loading rates has also been carried out, but no published results were found.

Owing to the limited amount of available information concerning the behaviour of threaded steel fasteners subjected to combined tension and shear loads, an experimental programme was conducted with M5 threaded rods made of carbon steel with property class 4.6. The digits in the property class describe a strength rating system; e.g., property class 4.6 implies a minimum tensile strength of $4 \times 100\ \text{MPa} = 400\ \text{MPa}$ and a minimum yield strength of $0.6 \times 400\ \text{MPa} = 240\ \text{MPa}$, see Bickford and Nassar [8].

The same testing equipment as described by Fransplass et al. [7] was used to carry out these tests. Tests at low loading rates were performed in a servo-hydraulic testing machine, while tests at high loading rates were performed in a split-Hopkinson tension bar (SHTB). Different purpose-made fixtures were used to control the load direction and the location of failure. First, this new way of performing shear and combined tension and shear tests at high loading rates in an SHTB was evaluated, and the experimentally obtained ultimate load and behaviour characteristics of the threaded steel fasteners at low and high loading rates were compared. Second, a finite element (FE) model of the test set-up was established and shown to predict the ultimate load of the threaded steel fasteners with acceptable accuracy. This FE model was subsequently used in simulations of load combinations not covered by the experimental study.

2. Experimental programme

When threaded fasteners are loaded in tension, shear or combined tension and shear, several failure modes may occur. In tension, the fasteners may experience failure by thread stripping or fracture in the threaded portion of the fastener. In shear, the failure will occur in the shank or in the threaded area of the fastener, depending on the test set-up. In combined tension and shear, the failure mode will be a combination of the modes mentioned above. However, in order to control the loading direction and the location of failure in the present tests, purpose-made fixtures were used. This ensured that the location of shear fracture always occurred in the interface between the two fixture parts. These purpose-made fixtures were made of quenched Arne tool-steel, and had therefore a significantly higher yielding strength and ultimate strength than the threaded rod material. This large strength difference ensured that no plastic deformation or fracture took place in the purpose-made fixtures. It was expected that variations in the ultimate load and behaviour characteristics would occur if the failure location shifted from the shank to the threaded area in the test of a bolt. Thus, the specimens were here made of threaded rods.

The geometry of the test set-up with the different purpose-made fixtures used for tension, shear or combined tension and shear are shown in Fig. 1. The specimens were cut from an M5 threaded rod with property class 4.6 and length 1000 mm. The pitch of the threaded rod was 0.8 mm, and the major diameter was 4.71 ± 0.01 mm. These dimensions were measured with use of a micrometre screw. The cross-section area of the threaded rod was calculated according to ASMB B1.13M [9]. The chemical composition of the threaded rods was not available, but according to ISO 898-1 [10] the upper limits for the alloying elements were 0.55% C, 0.05% P, 0.06% S and 0.003% B. In a previous study published by the authors [7], material tests, Vickers hardness measurements and micromechanical investigations have been conducted. The conclusion from this work was that material taken at the centre region of the threaded rod would be representative for the behaviour of the threaded rod in general.

Three different purpose-made fixtures were applied to obtain tension, combined tension and shear, and shear, corresponding to loading angles of 0°, 45° and 90°. Here a loading angle of 0° corresponded to loading along the axis of the threaded steel fasteners. To avoid introducing any distortion of the propagating wave in the dynamic tests, the exterior diameter of the purpose-made fixtures was the same as the diameter of the bars in the SHTB set-up.

Fig. 1a) shows the geometry of the test set-up where the specimen is subjected to tension. The total length of the threaded rod was in the range of 21.4 ± 0.3 mm, and the thread engagement length was almost equal on both sides of the purpose-made fixtures. The large thread engagement length ensured that thread stripping was avoided. Fig. 1b) shows the geometry of the test set-up where the specimen is subjected to shear. The purpose-made fixtures were made such that the load was applied at an angle equal to 90° to the axis of the threaded steel fasteners. According to Shakir-Kalil and Ho [2], it is usually assumed that there is no friction between the adjacent surfaces and this assumption was also made here in the calculations of the load characteristics. Fig. 1c) shows the geometry of the test set-up for combined tension and shear. The loading angle is 45° with respect to the axis of the threaded steel fasteners. The installation of the threaded rods in the purpose-made fixture was performed without any pre-load of the fasteners that caused some lack of tightness between the internal and external threads. The adjacent surfaces were inspected visually before testing to check that there was no gap between them.

The experimental tests were carried out using two different testing machines depending on the loading rate. A total of 25 tests were performed at low and high loading rates. All tests were performed at room temperature.

Tests at low loading rates were performed in a servo-hydraulic testing machine. The loading rate in tension was approximately 7.0×10^{-4} mm/s, while in the other load cases the loading rate was approximately 6.0×10^{-3} mm/s. The elongation of the threaded assembly was measured with the use of a one-sided extensometer with gauge length 20.0 mm. The extensometer was attached to the purpose-made fixtures, which meant that the measured elongation included any elastic deformation of the fixture. After each test a visual inspection of the threaded rod and the purpose-made fixture