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Testing and modelling of flow-drill screw connections under quasi-static loadings

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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

The behaviour of a flow-drill screw connection under different quasi-static loadings was simulated using finite element models with detailed solid element meshes. The numerical models were developed with a rate-independent isotropic hypoelastic-plastic material model. A process-effect analysis was conducted, including investigation of the microstructure as well as hardness tests. Based on the investigation, the process effects were considered negligible. A simple approach for building up the geometry of the connection was presented. An experimental programme consisting of five different single-connector tests was carried out to characterise the connection, and was presented in detail. Each test was simulated, allowing for one-to-one comparisons between tests and simulations. Satisfactory results were achieved.

1. Introduction

Flow-drill screws (FDS) are commonly used to join parts of dissimilar materials in the load-bearing structure of cars. Since connections play important roles for the crashworthiness of vehicles, knowledge about their physical behaviour under impact loadings is important for design decisions. Necessary knowledge and physical insight is usually gained through extensive experimental programmes, which typically involve loading specimens consisting of two or more plates joined with one or more connectors until failure (Sønstabø et al., 2015). Various loadings are achieved by changing the specimen design and loading directions.

A limited number of experimental studies on FDS connections can be found in the open literature. Szlosarek et al. (2013) presented a novel testing and analysis method. It was demonstrated for an FDS connection between plates of a carbon fibre reinforced polymer and aluminium. Skovron et al. (2014) studied the FDS process for a connection between sheets of aluminium alloy AA 5052-O. They explored feasible design space regions to determine how process parameters affect the geometry of the assembled connection. Mechanical tests were performed to validate the findings. Sønstabø et al. (2015) carried out a large experimental programme to characterize an FDS connection between sheets of AA 6016 T4. The results were compared to equivalent tests on self-piercing rivet connections. Skovron et al. (2015) studied the effect of thermally assisting the FDS process (i.e. pre-heating the plates with an external heat source), and performed mechanical tests on a connection between sheets of AA 6063 T5A. Sønstabø et al. (2016) presented experiments on connections between an AA 6016 T4 sheet and an AA 6063 T6 extrusion, which they used to evaluate state-of-the-art macroscopic large-scale finite element modelling techniques. A *macroscopic model* here means a simplified model used to represent connections in large-scale analyses where time step restrictions prohibit detailed modelling of the connections. On the other hand, a *mesoscopic model* is a detailed three-dimensional finite element model with a fine solid mesh, where the actual geometry of the connection is taken into account.

To the best of the authors' knowledge limited scientific literature exist on mesoscopic modelling of FDS connections. A literature survey revealed one paper by Grujicic et al. (2016), who made an attempt to simulate the FDS process. The results from the process simulation were mapped to finite element models of different coupon tests. The global force-displacement curves from the coupon simulation results were qualitatively compared to corresponding curves from the experiments of Sønstabø and Holmstrøm (2013) which have been presented in the journal article of Sønstabø et al. (2015). These experiments were with a different screw and different plate materials.

In addition to complement experiments with additional information not otherwise achievable, a validated mesoscopic model of the connection may be used to explore the design space as function of e.g. thicknesses, materials and screw geometries in an efficient way, or for example to investigate particular deformation or failure modes. Another incentive for building a validated mesoscopic model is to use it

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for virtual testing of the connections. Experiments are costly and time consuming, and from an industrial perspective it would be beneficial to replace experiments with validated simulations. The results can for instance be used to calibrate macroscopic connection models for large-scale simulations.

Although little information is available for FDS connections, detailed numerical studies using mesoscopic models have been carried out on other connection types, some examples of which are presented in the following. Bouchard et al. (2008) used three-dimensional numerical models to study the behaviour of self-piercing rivet (SPR) connections under quasi-static loading conditions. They included mechanical properties obtained with two-dimensional axisymmetric riveting process simulations, and were in most cases able to reproduce the correct behaviour of the connection with reasonable accuracy in terms of force-displacement response and deformation mode. Chen et al. (2014) conducted a numerical and experimental study of a riveted joint, including the riveting process and tension tests, to investigate the failure modes under tensile loads. Kong et al. (2008) predicted the plastic and failure behaviour of a single lap-joint test of a resistance spot-weld between two steel sheets. Constitutive models were calibrated for different weld zones and coupled with a failure model. The finite element model was used to study the effect of nugget size and sheet thickness. A similar study was carried out by Nielsen (2008), who used a modified Gurson material model to successively model plug failure for sufficiently large spot-weld diameter. Interface failure typically seen for smaller weld diameters was not well described. This was achieved later by Nielsen and Tvergaard (2010) by modifying an extension to the Gurson model. Sabuwala et al. (2005) used finite element analysis to study the behaviour of fully restrained steel connections subjected to blast loads. The results revealed that design criteria for steel connections subjected to blast loads were inadequate, and recommendations for modifications were presented. Liu et al. (2015) performed experimental tests to investigate the dynamic response of top-and-seat with web angle steel beam-column connections subjected to a sudden column removal. They employed three-dimensional finite element simulations to understand the deformation and failure mechanisms that were observed in the experimental tests.

Numerical simulations of the FDS process are difficult to set up. The process physics are complex, involving for instance friction, large plastic deformations and thermal softening. A coupled thermo-mechanical finite element model would be required, and accurate description of the different phenomena would be difficult. Moreover, the large deformations would cause numerical challenges, introducing the need for e.g. remeshing. In addition, one would need data of the process input parameters, e.g. rotational speed, torque and driving force. Besides, such a process simulation would be difficult to validate.

The present article explores the possibilities of modelling FDS connections between aluminium plates with a mesoscopic model, without taking the process into account. The developed numerical model was validated using experiments, both with respect to deformation modes and force-deformation characteristics. A simple approach for building up a sufficiently accurate model is presented. Five different finite element models were built up, each one resembling an experimental test, allowing for direct comparisons between simulations and experiments. The experimental programme consisted of cross tension, cross mixed, cross shear, single lap-joint and peeling tests. The novelty of this paper is related to the mesoscopic modelling of FDS connections, as well as the validation carried out using a new cross test set-up.

The experiments are explained and presented first, followed by a discussion about process effects. The finite element model is subsequently presented, and finally the simulation results are discussed.

2. Experiments

The term *connection* is in the present article defined as *a system that mechanically fastens two or more parts together* (Sønstabø et al., 2015,2016), implying that it consists of the screw itself plus some surrounding plate materials. The connection investigated in this work consisted of an M5 through-hardened steel screw connecting a 2 mm thick rolled sheet of AA 6016 in temper T4 to a 2 mm thick extrusion of AA 6063 in temper T6. A schematic drawing with nominal dimensions and a cross-section picture of the connection are presented in Fig. 1. This material combination was chosen since it is representative of a typical FDS connection in cars, with the top sheet having a yield stress of approximately 120 MPa and the bottom extrusion a yield stress of approximately 210 MPa. A pre-hole of 7 mm diameter was used in the top plate. Engineering stress-strain curves for the plate and screw materials are presented in Fig. 2. As seen, the extrusion (6063) had a higher yield stress, but the rolled sheet (6016) had stronger work-hardening and was significantly more ductile.

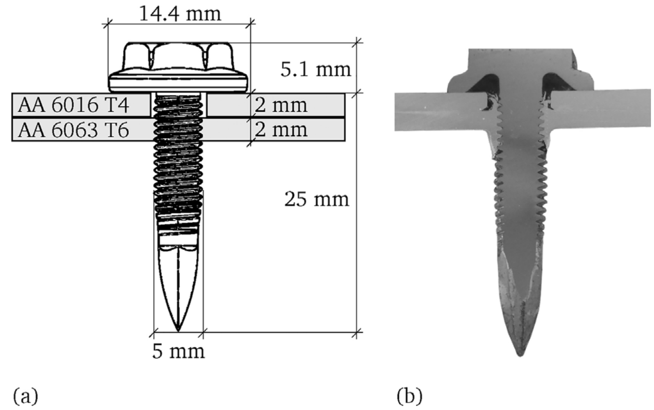

Fig. 1. FDS connection. (a) Schematic drawing. (b) Picture of the cross-section.

The connection was studied by means of cross tests in three loading directions (tension, shear, and combined tension and shear), and single lap-joint and peeling tests. Schematic drawings of the test specimens are presented in Fig. 3, where clamped areas are indicated with grey colour. The dark grey colour in Fig. 3a indicates where a smaller clamp was used in the cross mixed and shear tests. All tests were quasi-static. Three to five repetitions were carried out for each test. The global responses (force-displacement curves) are reported, together with detailed descriptions of the tests and post-mortem pictures of specimens. The global response in the single lap-joint and peeling tests has been briefly reported before (Sønstabø et al., 2016).

2.1. Cross tests

Fig. 4a illustrates the principle of the cross tests. The coloured areas in the figure were clamped in the tests. The red parts were fixed, while the blue parts were pulled in the directions of the arrows corresponding to tension-, mixed- and shear loading. To allow for relative sliding of the plates, only half of the area on one side of the bottom plate was clamped in the cross mixed and shear tests. This is indicated with a lighter red colour where the clamping was omitted. The bottom plate was fixed, while the top plate was pulled in the direction of the arrows in the figure.

Fig. 4b shows a principle drawing of the cross tension test set-up. The specimen was mounted on two steel fixtures, using screws and clamping blocks. A picture of the set-up is shown in Fig. 4c. The steel fixtures were placed in a regular Instron tensile testing machine, where they were pulled apart in the vertical direction. Pure tensile loading was ensured by hinging the fixture in each end. The pulling force was measured with a load cell mounted in series between the top fixture and the cross beam of the testing machine. A camera was used to take photographs during the tests to record the relative displacement of the steel fixtures with a digital image correlation (DIC) method (readers are referred to Fagerholt (2012) for details on DIC). Black and white