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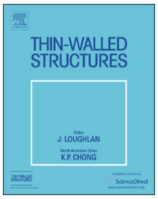

Full length article

Macroscopic modelling of flow-drill screw connections in thin-walled aluminium structures

Johan Kolstø Sønstabø [a,b,*], David Morin [a,b], Magnus Langseth [a,b]

[a] Centre for Advanced Structural Analysis (CASA), Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway
[b] Structural Impact Laboratory (SIMLab), Department of Structural Engineering, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway

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ABSTRACT

This paper presents an investigation on the modelling of flow-drill screw connections in thin-walled aluminium plates in large-scale finite element analyses using different macroscopic modelling techniques. Five models that were originally developed for adhesive bonds, spot welds and self-piercing rivet connections were examined. Two sets of experimental data were used, each with a different screw and material combination. Different trends were observed for the two sets, which challenged the flexibility of the models. The results indicated that a constraint-based model originally developed for self-piercing rivet connections was the best suited model. A two-step validation strategy was proposed and used for the present models.

1. Introduction

Joining with flow-drill screws (FDS) is a common technique for joining dissimilar materials in the load-bearing structure of cars. Under impact loadings, the behaviour and fracture of connections are important for the response of the thin-walled structure. In the automotive industry, large-scale finite element (FE) simulations with shell elements (for instance, crash simulations) are extensively used in the vehicle design process, and accurate modelling of connections plays an important role in obtaining reliable predictive results. Due to time step limitations, the physical geometry of connections and potential process effects cannot be modelled; rather, simplified models are necessary to represent the connections. These models should be capable of describing the macroscopic response while being computationally efficient.

Several different approaches have been used for different connection types, and various models have been designed for, e.g., spot welds, adhesives and self-piercing rivet connections. However, no models have been specifically developed for modelling FDS connections. Furthermore, no reports regarding the modelling of FDS connections have been found in the available literature. The aim of this study was to assess the ability of existing macroscopic connection models to represent FDS connections. Different strategies for connection modelling are presented in the following.

One of the simplest approaches is to assign a rigid link between two nodes on opposing shell surfaces (Fig. 1a). However, this approach requires the nodes to be aligned, which is an exhausting restriction for large-scale analyses, and with this approach, the local deformation behaviour of the connection cannot be taken into account. An easier approach is to use a beam element for the connection attached to the surfaces with tie constraints (Fig. 1b). Then, deformation behaviour may be accounted for, but this approach has been shown to be mesh dependent, as noted by Malcolm and Nutwell [11], who used a material model designed for spot welds in the beams. A drawback of this method is that the time step may be limited by the beam length. Another method is to use one or several hexahedral elements in an assembly to represent a connection (Figs. 1c and d), and this method has been shown to be mesh independent if eight or more elements are included in the assembly [11]. However, refining the connection mesh might decrease the time step. To predict accurate responses, different material models can be assigned to these clusters of elements. Such models are herein referred to as *element-based* models.

Element-based models are commonly used for modelling of structural bonds (e.g. [19]). In some part configurations structural bonding and discrete connections (such as FDS connections) are commonly combined. A way to model such hybrid joints is to use an element-based model for the adhesive bond, in combination

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* Corresponding author at: Centre for Advanced Structural Analysis (CASA), Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim Norway.

E-mail address: johan.k.sonstabo@ntnu.no (J.K. Sønstabø).

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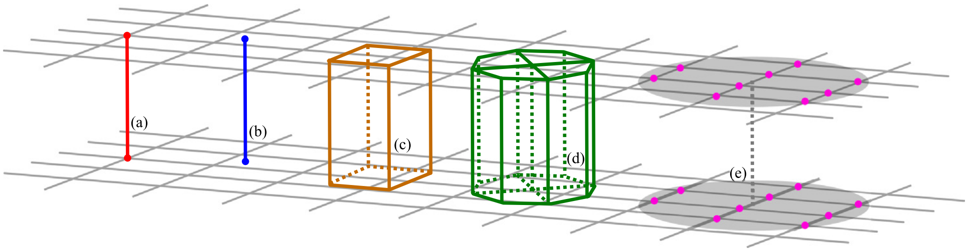

Fig. 1. Illustration of different connection modelling techniques. (a) rigid link. (b) beam element. (c) hexahedral element. (d) cluster of hexahedral elements. (e) constraint.

with a discrete model for the discrete connections (e.g. [5]).

A material model designed to predict spot weld failure was presented by Hallquist et al. [7], under the name *mat spotweld*. This model is an elastic-plastic model with isotropic linear hardening coupled with different failure models. Seeger et al. [15] showed that this model could realistically describe spot welds using either a single beam element, a single hexahedron element or four hexahedron elements to represent the connection (see Fig. 1b, c and d). These authors argued that using four hexahedron elements was too expensive because it limited the simulation time step. Bier et al. [4] evaluated the ability of the cohesive element model presented by Marzi et al. [12] to represent spot welds (this model is available in the FE software LS-DYNA under the name *mat cohesive mixed mode elastoplastic rate* [7]). It was compared to *mat spotweld*, and they found that the model of Marzi et al. [12] was beneficial for some load cases. They obtained better results with a cluster of four or eight elements rather than with a single element.

A model tailored for self-piercing rivet connections was reported by Hanssen et al. [8] (available in LS-DYNA as the model *constrained spr2* [7]). This is a *constraint-based* model, which means that the connection is represented by a constraint formulation rather than by an assembly of elements (Fig. 1e). Tensile and shear behaviours are uncoupled, and damage is taken into account. They defined a strong coupling between mode mixity and damage evolution based on experimental observations. It was shown that mesh dependency was limited and that the model was well suited for self-piercing rivet connections.

Another constraint-based model (named *constrained interpolation spotweld* (model 1 in LS – DYNA®) by Hallquist et al. [7]) was developed for spot welds. In this model, tensile and shear behaviours are coupled through a plasticity-like formulation.

Sommer and Maier [17] investigated the abilities of *mat spotweld*, the element-based model of Marzi et al. [12] , the constraint-based model of Hanssen et al. [8], and *constrained interpolation spotweld* to represent self-piercing rivet connections. They found that the model of Marzi et al. [12] was the most promising and that *mat spotweld* was the least promising. However, they noted that the model proposed by Marzi et al. [12] was insufficient under peeling loadings and that it had no flexibility to control the mixed-mode behaviour. The model *mat arup adhesive* is a cohesive zone model with linear elasticity and damage (no plasticity), which is too simple for FDS connections, and therefore, this model is not included in the present study.

Further modifications to *constrained interpolation spotweld* were presented by Bier and Sommer [3], and they showed that the ability to model self-piercing rivet connections was enhanced (this model is available in LS – DYNA® as *constrained interpolation spotweld* (model 2)).

When calibrating macroscopic models, it is important to have a proper strategy for validation. The model should be calibrated to tests under controlled loading paths and validated to tests with different and more complex loadings. Hoang et al. [9] used U-shaped specimens under controlled tensile, combined tensile and shear, and shear loadings for calibration and validated the model using a complex component test (T-component). Similarly, Bier and Sommer [3] used KSII tests for calibration and a complex component (T-joint) test for validation.

In this work, the ability of five common state-of-the-art connection models to represent FDS connections was studied. The examined models were the element-based *mat spotweld*, the element-based model by Marzi et al. [12], the constraint-based model by Hanssen et al. [8] and the two versions of the constraint-based model *constrained interpolation spotweld*. These models were calibrated to experimental data from two different connections with different screw and material combinations. A thorough two-step procedure for validation is presented and used.

2. Experiments

Here, the term *connection* is based on the definition of Sønstabø et al. [16], i.e., *a system that mechanically fastens two or more parts together*. Thus, a connection consists of a screw and surrounding plate material (see Fig. 2). In the first set of experiments, a short screw with a nominal length of 10 mm, a nominal shaft diameter of 4 mm and a nominal head diameter of 8 mm joined two aluminium sheets (alloy 6016 T4), while in the second set of experiments, a long screw with a nominal length of 30 mm, a nominal shaft diameter of 5 mm and a nominal head diameter of 14 mm joined an aluminium sheet (alloy 6016 T4) to an aluminium extrusion (alloy 6063 T6). The nominal thicknesses of the sheet and extrusion were 2 mm. A pre-hole was used in the top plate for both connections. The two connections are hereafter denoted as the *small screw connection* and the *large screw connection*, respectively. Each set of experiments consisted of cross tests in three loading directions (tension, shear and combined tension and shear), single lap joint and peeling tests, and T-component tests.

An extensive study of the behaviour of the small screw connection has previously been reported by Sønstabø et al. [16], which included cross, single lap joint and peeling tests. Using the same experimental set-up, corresponding tests were conducted in this work for the large screw connection. Drawings of the

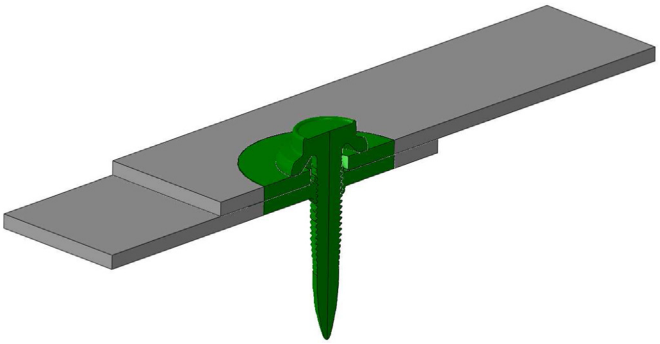

Fig. 2. Illustration of the definition of a *connection* (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)