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Macroscopic modeling of thin-walled aluminum-steel connections by flow drill screws

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ABSTRACT

The modeling procedure of a flow drill screw connection between thin-walled aluminum and steel plates is presented. The discretization is oriented towards application for large-scale FE-models, in which the connection is modeled by hexahedron and the plates by shell elements. Material model phases for connection and substrates are examined on the basis of single-lap shear. The final material model originally developed for describing spot welds is then validated in cross tension. This paper shows the effort required to obtain a desired level of accuracy and provides an application-oriented approach for determining parameters for a numerical connection model.

1. Introduction

1.1. State of the art

In the course of multi-material lightweight design for high-volume production vehicles the variety of available mechanical joining techniques increases, e.g. flow drill screwing, self-piercing riveting and tack setting [1–5]. Consequently, the number of connections – containing joining technologies and material combinations – with different mechanical properties rises and has to be modeled in numerical simulations. Due to the numerical stability of explicit time integration using the finite element method, it is necessary that connections, for instance in crash simulations, are modeled as macroscopic models. These should predict the mechanical behavior of the connections under complex loading conditions to obtain a reliable prediction of the structures deformation. In order to ensure this, a considerable experimental effort must be undertaken. With respect to the shortening development periods of these structures, the motivation to reduce this experimental effort rises.

Joining with flow drill screws is one of the key technologies in joining dissimilar materials [2,6]. Nevertheless, there has been no modeling technique developed specifically for this joining technology. Thus, different modeling philosophies have evolved to model the connection using existing macroscopic models for other joining techniques. The suitable macroscopic models can be basically divided into two groups. The models of the first group are based on the use of kinematic relationships between nodes. As in [7], they are called *constraint-based* models. The other group contains the *element-based* models (also as in [7]). Here, the discretization is carried out with elements with assigned diverse and specific material models.

Sønstabø et al. [7] compares several approaches to describe the macroscopic behavior of flow drill connections in thin-walled aluminum structures. Table 1 shows the models studied in [7], supplemented by the modeling according to Seeger et al. [8] and Sønstabø et al. [9,10]. In [7] it is shown that the *constraint-based* modeling by Hanssen et al. [11], which was developed for describing self-piercing rivets, is the most accurate to model the macroscopic behavior. He also points out that the *element-based* models are too inflexible to describe the characteristics of the screw joint in mixed-mode loading conditions. Due to this inflexibility the investigations into the *element-based* model using hexahedral elements and the material model *mat spotweld* presented by Hallquist et al. [12] were terminated before validation. Sommer and Meier [13] used the material model according to Marzi et al. [14] to describe a self-piercing-riveted joint and also noted this inflexibility. This is why Sønstabø et al. [9,10] presented new material models based on the material model according to Marzi et al. [14] with added flexibility to control the mixed-mode behavior and a *constraint-based* modeling in a cohesive element framework.

The material model *mat spotweld (Daimler)* used in this paper is a bilinear elastoplastic material law according to von Mises with isotropic hardening [12]. This makes it possible to describe the pre-failure behavior with a few parameters, which promotes an effective description of the modeling. Seeger et al. [8] shows that this modeling technique is useful for modeling welding points in vehicle crash simulations. With a failure criterion based on equivalent stresses for normal, shear and bending, good results can be obtained. The description of the joining

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Table 1
Modeling approaches for macroscopic modeling of a flow drill connection, based on Sønstabø et al. [7].

Modeling technique	Source	Type	Original purpose
constrained spr2	Hanssen et al. [11]	Constraint-based	Self-piercing rivets
constrained interpolation spotweld	Hallquist et al. [12]	Constraint-based	Spotwelds
constrained interpolation spotweld (modified)	Bier, Sommer [15]	Constraint-based	Self-piercing rivets
mat spotweld with hexahedron-cluster (16 units)	Hallquist et al. [12]	Element-based	Spotwelds
mat spotweld Daimler with hexahedron-cluster	Seeger et al. [8]	Element-based	Spotwelds
mat cohesive mixed mode elastoplastic rate with hexahedron-cluster (4 units)	Marzi et al. [14]	Element-based	Adhesive bonding
mat cohesive mixed mode elastoplastic rate (modified) with hexahedron-cluster	Sønstabø et al. [9,10]	Element-based	Flow drill connections
constrained spr2 in a cohesive element framework	Sønstabø et al. [9]	Element-based	Flow drill connections

technique using *mat spotweld Daimler* has been further improved with the implementation of a fracture energy based criterion to control post-failure behavior [16]. It might be mentioned that it is considered advantageous for future research activities, with regard to the material mix of an overall structure, that selected parameters in the material card can be defined as a function of the substrate material properties [12].

Previous publications on the simulation of joining technology are characterized by the aim to build an exact model of the macroscopic behavior by a comprehensive experimental program. In order to determine reliable parameters for the investigations in [7], the results of 7 experimental configurations presented in [17] were used. Here, cross specimens under tension, shear and combined loading are used to calibrate the connection and are followed by single-lap shear tests and peeling tests as so-called benchmark tests. Then, tests at a component level are conducted to validate the connection. Other strategies are based on the use of a U-shaped specimen, such as N.-H. Hoang et al. [18] uses them or so-called KS2-specimens, developed by the LWF (Laboratorium für Werkstoff- und Fügetechnik / Laboratory for materials and joining technology) in Paderborn in Germany.

1.2. Modeling strategy

In this paper an attempt is made to estimate a macroscopic behavior of the connection, which is adequate for engineering development practice. Due to its key role in automotive development processes complex crash simulations lead to the focus on energy absorption. A minimal effort in testing and simple numerical models using LS-DYNA are desired. The screw connection is modeled by an element-based approach with one hexahedron element. Starting from elastic material behavior, the complexity of the model is gradually increased to improve the accuracy of the simulation. The models are calibrated by the single-lap shear joint presented in Section 2.1. In order to obtain a reliable model for further loading conditions the material *mat spotweld Daimler* [8] available in LS-DYNA is used. In contrast to [7], a stress-based failure criterion is implemented here. In order to determine the necessary parameters, a parameter optimization is carried out using specific parameter trends from available literature. The created numerical model of the connection is validated with a cross tension test presented in Section 2.2.

Fig. 1 shows the plastic deformation of the specimens under the chosen loading conditions – single-lap shear and cross tension. In Fig. 1(a) it can be seen that the largest deformation occurs in the connection element by shearing, whereas in cross tension the deformation in the substrate material is dominant. A significant plastic deformation does not take place in the joining element in cross tension. Therefore, it is appropriate to calibrate the joining element parameters on the basis of the single-lap shear joint because here the influence of the substrate material is low [19]. The influence of the material in the immediate vicinity of a connecting element on the behavior of the connection in the simulation was also described by Bier et al. [20].

2. Experiments

The samples were joined with a flow drilling joining system (RSF with control unit WSG 100) from Weber. For the joining process, in Fig. 2(a) the relevant quantities of the shear test specimens are presented over time. Until the characteristic point 1 (phase one) the screw has no contact to the sheet. Between point 1 and 2 (phase two) the specimen is penetrated. Beyond point 2 (phase three), the screw is screwed in at controlled torque of 5.5 Nm until tightening torque is reached. In the different phases the rotational speed is set as shown in Fig. 2(a). The tightening torque for the single-lap shear joint specimens is 12 Nm and for the cross tension specimens it is 14 Nm. The higher tightening torque of the cross tension specimens is required to close the gap between the plates during the joining process.

The connection element is a flow drill screw made of case-hardened steel manufactured by EJOT. It has an M5 thread with a length of 17 mm and a head diameter of 11.8 mm. A representive cross section of a joined shear test specimen with nominal dimensions of the screw is shown in Fig. 2(b).

2.1. Static single-lap shear test of a flow drill screwed aluminum-steel connection

The basis of this investigation is a single-lap shear joint test in accordance with DIN EN ISO 14273. For this purpose, the specimen geometry is shown with the nominal dimensions in Fig. 3(a). The joining materials are an aluminum wrought alloy EN-AW-5083 H111 (AlMg4.5Mn) and a micro-alloyed steel HC340LA (ZStE340). For the experiments the aluminum plate is joined with the steel plate at the center of the overlap without using a pre-hole.

The joint is clamped as shown in Fig. 3(b) at the gray-shaded areas in Fig. 3(a). During the loading of the screw, the force and the local displacement were measured. In Fig. 3(a) the measuring locations are indicated by black dots in the initial position of the two-arm mechanical extensometer, which is also displayed in Fig. 3(b). The tensile load is position-controlled with a test speed of 5 mm/min. In Fig. 3(c) the results are shown as force-displacement curves.

It can be seen from the fractures in Fig. 3(d) that the specimens fail via bending up of the plate edge with failure of the head of the screw in combination with a tear out of the aluminum sheet. This complex fracture is characterized by highly nonlinear effects, which is to be contained in the proposed macroscopic model. In comparison, for the aluminum-aluminum connection from [17], a different failure mode was observed for the shear tests (cross shear and single-lap shear). In [17], rotation of the screw due to the shear force led to a one-sided thread engagement and a through thickness shear fracture of the bottom sheet material. In contrast to the experiments carried out here, the screw remains in the top plate. The different failure mode is caused by the lower strength of the aluminum sheet compared to the steel sheet.