The effect of sheet metal anisotropy on the calibration of an equivalent model for clinched connections

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Abstract. Clinching is a mechanical joining technique that involves severe local plastic deformation of two or more sheet metal parts using a punch and die. The local deformation results in a permanent mechanical interlock. It is widely applied as a reliable joining technique in automotive, heating, ventilation, air conditioning (HVAC) and general steel constructions and is still gaining interest. In FEA models of structures containing a large number of clinched joints, it is not computationally feasible to use detailed sub models of the joint. Therefore an equivalent model was proposed by Breda et al. to predict the force-displacement behaviour. This equivalent model was calibrated using a simple shear-lap and pull-out test. During the calibration step, some local effects due to the material properties are captured in the calibration parameters. This paper investigates the impact of the plastic material properties on this calibration method. The effect of strain hardening due to the bending process prior to pull-out testing, potential plastic anisotropy of the base material and their relation to the calibration parameters are investigated. This research has been validated with experimental results on mild deep drawing steel.

1. Introduction
For both economical and environmental point of view, lightweight constructions have gained more interest in recent years [1, 2]. The need to join dissimilar [3], coated or hard to weld lightweight materials [4], led to rapid development of mechanical joining techniques such as clinched joints. To predict the mechanical behaviour of structures containing multiple clinched joints it is computationally infeasible to included detailed sub models of this type of joint [5]. Therefore it is important to investigate the possibility of an equivalent model for clinched joints. An equivalent model for clinched joints was proposed by Breda et al. [6]. Although this model provided good results on DC01 (low carbon steel sheet), more research was needed to examine the potential of the methodology. Some factors which need to be considered are the effect of sheet metal anisotropy and residual stresses on the calibration step of the equivalent model. In order to fully understand the goal of this paper the key points of the method [6] are summarized briefly. The proposed equivalent model consists of a connector element with 6 degrees of freedom and a kinematic coupling which connects the connector element with the shell elements of the sheet material. The elastic-plastic properties of the connector element were calibrated using a simple...
Figure 1. Schematic overview equivalent model

experimental shear lap and pull-out test (H-tension test) [7] by comparing the experimental results with the response of a numerical model using a rigid connector as initial guess. The elastic-plastic properties of the connector element were softened, using following formulas:

**Elastic properties:**

\[ F_i = D_{ii} \cdot u_i \]  \hspace{1cm} (1)

**Plastic properties:**

For the normal direction:

\[ F_N = f_3 \]  \hspace{1cm} (2)
\[ u_{pl}^N = u_{3}^{pl} \cdot K_{u,N} \]  \hspace{1cm} (3)

For the shear direction:

\[ F_S = f_1 = f_2 \]  \hspace{1cm} (4)
\[ u_{pl}^S = u_{1}^{pl} \cdot K_{u,S} \]  \hspace{1cm} (5)

This process results in a matching set of parameters. The visualisation of the process can be seen in figure 2.

During this calibration step some local effects due to the local plastic deformation of the base material were captured in the calibration parameters. As a consequence, it is important to understand the effect of the material properties on the calibration parameters. To investigate this, an equivalent model for a clinched sheet material was calibrated using different material properties in the numerical simulation process. Both the numerical models of the shear lap and pull-out test were considered.
Figure 2. Connector calibration step (shear behaviour) using the shear lap test experimental results (equal steps for the normal behaviour): a. Elastic calibration step b. Plastic calibration step
Table 1. Base material properties: Thickness, Young’s modulus, Lankford ratio’s, Fitted Swift parameters

| t (mm) | Young’s modulus (Mpa) | r₀ | r₉₀ | r₄₅ | K (Mpa) | ε₀ | n   |
|-------|-----------------------|----|-----|-----|--------|----|-----|
| 1.2   | 232857                | 1.928 | 2.51 | 2.03 | 540.2  | 0.004622 | 0.2684 |

Table 2. Calibration parameters shear lap test

| Model | Radius (mm) | Material model | D₁₂ (N/mm) | Fᵢᵤ,Ŝ₁,₂ (N) | Kᵤ,S |
|-------|-------------|----------------|-----------|-------------|------|
| S-1   | 4           | von Mises      | 50000     | 830         | 0.5  |
| S-2   | 4           | Hill’48        | 50000     | 830         | 0.5  |

2. Material and joint properties
The material used for this study was steel sheet with a thickness of 1.2 mm. From the experimental tests on the sheet material, it could be concluded that plastic anisotropic behaviour was inherent to the material. The pull-out and shear lap specimens with a width of 50 mm were joined using the non-cutting single stroke clinch (NCSS) technique with a closed die. The bottom thickness of the joint was 0.55 mm. The diameter of the punch was 5 mm and the diameter of the die was 8 mm. The material properties can be seen in table 1. A Swift hardening law was characterized to describe the hardening behaviour of the material:

\[ \sigma_{eq} = K(\varepsilon_0 + \varepsilon_{eq}^{pl})^n \]  

Where \( \sigma_{eq} \) is the equivalent stress and \( \varepsilon_{eq}^{pl} \) is the plastic equivalent strain.

The experimental shear lap and pull-out test, which were used to calibrate the connector shear and normal behaviour, respectively, were executed using a standard tensile testing machine with a capacity of 10 kN. A quasi static speed of 1 mm/min was used. The experimental set-ups can be seen in figure 4.

3. Numerical calibration
In all numerical models linear S4R shell elements were used with a size of 1 mm. For the equivalent representation, a kinematic coupling with a radius of 4 mm was used to couple the end nodes of a connector element to the sheet material elements. The shear lap calibration step test was executed using two material parameter sets using the von Mises (S-1) and Hill’48 yield criterion (S-2) [8], respectively. The pull-out calibration process, which calibrates the normal properties of the connector, was carried out using four different material models PU-1, PU-2, PU-3 and PU-4. Von Mises (PU-1 and PU-3) and Hill’48 (PU-2 and PU-4) yield criterion were both implemented to simulate the yield behaviour of the material during the pull-out test. The residual stresses and strains due to the bending process prior to the testing of the specimen were included in model PU-3 and PU-4. The bending process, which included the elastic spring back of the test specimen, was simulated prior to the calibration step (figure 3). Model PU-1 and PU-2 neglect the bending process during the calibration step, and, consequently assume a virgin material state. An overview of the parameter sets can be found in tables 2 and 3.

4. Results and discussion
The results of the calibration process of the shear lap test and pull-out test can be found in tables 2 and 3, respectively. It can be concluded that the incorporation of an anisotropic yield function in the model does not affect the shear calibration parameters of the equivalent model. This is due
Figure 3. Pull-out process overview: a. Fold 1 b. Fold 2 c. Applying clinch/equivalent model d. Tensile testing

Table 3. Calibration parameters pull-out test

| Model | Radius (mm) | Material model | Residual bending | $D_{U3}$ (N/mm) | $F_{3}^{y}$ (N) | $K_{u,N}$ |
|-------|-------------|----------------|------------------|-----------------|----------------|-----------|
| PU-1  | 4           | von Mises      | no               | 2500            | /              | /         |
| PU-2  | 4           | Hill’48        | no               | 2500            | 668            | 0.24      |
| PU-3  | 4           | von Mises      | yes              | 2500            | 788            | 0.34      |
| PU-4  | 4           | Hill’48        | yes              | 2500            | 250            | 0.4       |

to the fact that the plastic deformation of the sheet material surrounding the clinch zone is very limited compared to the pull-out test. Therefore, for applications only exerting shear loads onto the joint, and were the deformation of the sheet material is limited to elastic deformation, it is not necessary to include the anisotropic properties of the base material in order to obtain a good response of the equivalent clinch model. However, for the pull-out calibration process, it can be concluded that the anisotropic yield criterion highly influences the calibration parameters in the normal direction of the joint. The reason for this is the biaxial tension state, which occurs around the joint zone during normal loads. Therefore, the plastic anisotropy needs to be considered during the calibration process in the normal direction. For a material which exhibits a significant level of plastic anisotropy, such as the material under investigation, it was not
even possible to obtain (plastic) calibration parameters assuming plastic isotropy. The response after elastic calibration was already too soft in order to obtain matching calibration parameters. Residual stresses due to the bending process also affect the calibration parameters in the normal direction. To avoid residual stresses, an alternative specimen such as a cross tension specimen [9] could be used or a correction factor could be included. The consequence for a design engineer ignoring plastic anisotropy and residual stresses during the calibration procedure, could lead to an overestimation of the sheet deformation when applying the equivalent model for structural analysis. Future work will aim at providing an upper bound for the degree of plastic anisotropy guaranteeing a reliable calibration of the equivalent model.

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Figure 4. a. Shear lap specimen and experimental set-up b. Pull-out specimen and experimental set-up