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Equivalent modelling strategy for a clinched joint using a simple calibration method

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ABSTRACT

Clinching is a mechanical joining technique that involves severe local plastic deformation of two or more metal sheet parts resulting in a permanent mechanical interlock. Today, it is a reliable joining technique used in heating, ventilation and air conditioning (HVAC), automotive and general steel constructions whilst still gaining interest. As it is not computationally feasible to include detailed sub models of these type of joints in FE simulations of clinched assemblies during the design stage, this paper proposes a simple methodology to represent these connections with simplified elements. The key point of the method is the use of uncoupled plastic behaviour to model the joint plastic properties. In order to calibrate the parameters governing the equivalent model, a simple shear lap and pull-out reference test of a single clinched joint was used. The presented methodology is validated using a modified Arcan test of a single joint, which enables to exert a combination of shear and pull-out loads. Finally, a peel test is conducted to study the influence of bending moments on the behaviour of the joint.

1. Introduction

From both economical and environmental point of view, lightweight constructions have gained more interest in recent years. The need to join dissimilar, coated or hard to weld lightweight materials have led to rapid development of mechanical joining techniques such as clinched joints [1–3], self piercing rivets (SPR), riveting, etc. 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.

Clinching has been used on an industrial scale for over more than 35 years and has been successfully applied to a wide variety of materials and material combinations. Although several materials can be joined by clinching such as steel [2,4], aluminium alloys [5,6], copper [7], magnesium [8], titanium [9], etc., an important advantage of the joining technique is the possibility of joining dissimilar materials. Several dissimilar materials have been successfully joined by clinching including combinations with high strength steels [10–12], thermoplastic polymers [13], composite materials [12,11] and wood [14]. Also, hybrid joints, in which the clinch technology is combined with adhesives, has gained interest in recent years [15,16]. Although the patent was granted in 1897, research and industrial interest started about 80 years later. The reason for this is the complexity of the process, the wide variety of materials, combinations and tools required to achieve the mechanical interlock. Additionally, the axial strength of a clinched joint is limited compared to alternative joining techniques [17]. The forming process, the influence of the tool geometry and the mechanical performance of a single clinched joint have been extensively investigated by finite element simulations [18,4,19–22]. The clinched region is a complex shaped zone where the material state varies from point to point. If a structure or assembly contains many joints, it is unrealistic because of the computational costs and means to build a numerical model containing a huge number of detailed sub-models. The goal of this paper is to propose a methodology to replace the complex full-scale clinch model in numerical simulations for quasi-static elastic-plastic loading (Fig. 1). The development of such an equivalent model might enhance the analysis of specific applications such as: clinched structures subjected to fatigue loads, design rules for clinched configurations and structural damage behaviour of clinched joints. Before focussing on such applications, however, the focus in this paper is on the reproduction of the global force displacement response up to maximum force to obtain a general equivalent modelling procedure for a single clinched joint. Later, the procedure can be extended, depending on the application at hand.

Simplified models were already successfully applied to other joining techniques. To calibrate and/or validate these models, an experimental test, which exposes the mechanical behaviour of the joint, is needed. For different joining techniques, a modified Arcan test set-up is there-

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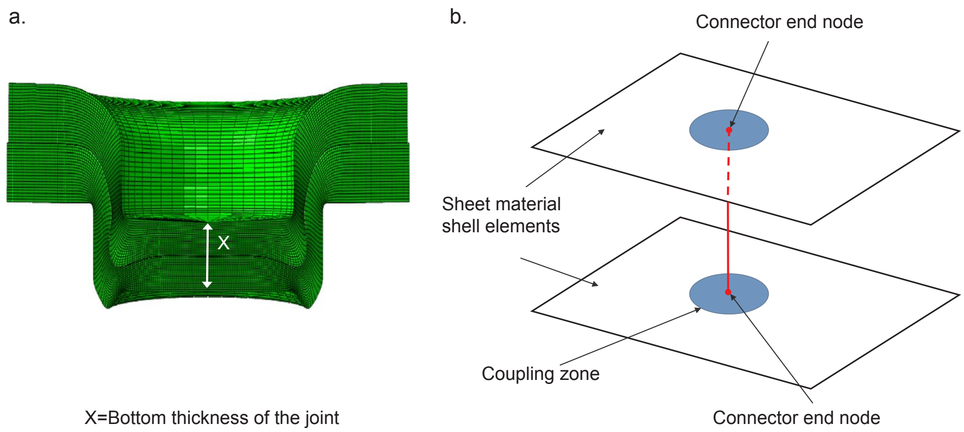

Fig. 1. Principle of equivalent modelling: a. full scale model b. equivalent model.

fore often applied [23–25]. The modified Arcan test set-up consists of two disk halves, which can be mounted in a uni-axial tensile machine under different angles, and was developed by Porcaro et al. [26] for riveted joints. Here, the modified Arcan fixture can apply a mixed-mode loading onto the joint. For use with clinched joints, a redesigned version of the modified Arcan set-up was developed by Coppieters et al. [21].

A first simplified model for riveted joints, using the modified Arcan test procedure, was proposed by Langrand et al. [23,27]. A non-linear spring formulation was used as an equivalent element and the parameters were calibrated using the experimental results of the modified Arcan test. For self-piercing rivets (SPR), Hanssen et al. [24] developed a point-connector model in an explicit FEM code to be used in large scale crash simulations. The paper describes the analytical definition of the model which entails 10 calibration parameters. These are determined from a peel test and the 0°, 45° and 90° modified Arcan test cases. Weyer et al. [25] suggested to use an equivalent SPR model for a crash analysis which reproduces the mechanical and damage behaviour of the joint. A simple fastener, provided in the ABAQUS code, is used and is calibrated using experimentally acquired data from the modified Arcan test and peel test. Grujicic et al. [28,29] extended this methodology and calibrated the equivalent model using a full scale numerical model of SPR test cases. For modelling assembly points in structures, Bérot et al. [30] proposed two universal equivalent elements, a connector based element and a virtual formulation. The calibration procedure is based on 6 test cases from which the calibration parameters are derived using an optimisation algorithm.

For spot welds, different methodologies are successfully applied depending on the application. Xu et al. [31] evaluated the performance of different simplified spot weld models against detailed three-dimensional models, under linear elastic load conditions. Five different load cases were evaluated (tension, out-of-plane torsion, out-of-plane bending, in-plane torsion and in-plane shear). Palmonella et al. [32] gives a brief overview of the simplified models used for spot welds in structural dynamics. The accuracy of six simplified spot weld models is updated using a finite element optimisation algorithm and two benchmark structures (double hat and single hat structure) for validation and updating. Khandoker et al. [33] applied six different simplified spot weld models, using an experimental U-shaped pull-out test as validation method. The possibilities in this field for clinched joints, however, have not yet been thoroughly investigated. In a first step, a shear lap and several pull-out tests are evaluated to be used as a reference case to characterize the mechanical behaviour of the joint. In a second step, an existing approach for SPR joints is adopted and evaluated for the use with clinched joints. As a final step, an modified methodology for a single clinched joint is proposed as proof of concept. This methodology is experimentally validated using a modified Arcan test and a peel test on both DC01 steel and EN-AW 5754 aluminium alloy.

2. Experimental tests and set-up

2.1. Material properties

DC01 steel sheet is used in this work because it has excellent deep drawing properties [34], is widely available as sheet metal and therefore ideal for clinch joining. In order to minimize the experimental work required for the proposed calibration method, the anisotropic properties of the base material are ignored and isotropic material behaviour of the DC01 steel sheet is assumed. As such, the elastic properties and strain hardening behaviour of DC01 sheet metal (thickness 1 mm) were obtained by means of a uni-axial tensile tests along the rolling direction of the specimen only. Six samples (Fig. 2b) were cut out of the sheet plate to ensure the reproducibility of the test. The tensile test was performed using a tensile machine with a maximum capacity of 10 kN and a speed of 1 mm/min. The elongation was measured using an extensometer with a gauge length of 80 mm. The stress-strain results can be found in Fig. 2a. An average Young's-modulus of 175544 N/mm^2 and hardening law were determined and used for the numerical simulation. The material was assumed to be elastically and plastically isotropic. The Swift law is of the following form:

$$\sigma_{eq} = 543.2(0.005549 + \varepsilon_{eq}^{pl})^{0.2249} \tag{1}$$

Were σ_{eq} is the equivalent stress and ε_{eq}^{pl} is the plastic equivalent strain. The material was joined with the Non Cutting Single Stroke (NCSS) clinch technology using an extensible die. Here, the die consists of two moving parts which enables the metal to flow in the radial direction during the clinch step, creating the mechanical interlock (Fig. 3). The details of the used tools can be found in Table 1. The average clinch diameter was 8 mm with a bottom thickness of X = 0.55 mm at the base of the joint. A section of the clinched joint can be seen in Fig. 4. In order to calibrate the numerical models, a reference test is necessary. Therefore a simple pull-out and shear lap experiment are performed on a clinched specimen. These experiments will be used to calibrate the equivalent numerical model of the clinched joint.

2.2. Pull-out test

During a pull-out test only axial loading is exerted onto the clinched joint. Three different type of pull-out tests have been investigated in order to identify the best reference test for calibrating the pull-out behaviour: Box test, cross tension test and H tension test [4,1,3]. A good pull-out calibration test for the equivalent model, exhibits a good ratio between sheet deformation in the zone surrounding the joint and intrinsic joint deformation. When a pull-out loading is exerted on a clinched joint, three failure modes can occur: neck fracture, failure by