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Predictive modeling of damage and failure in adhesively bonded metallic joints using cohesive interface elements

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ABSTRACT

A rate-dependent constitutive law for cohesive interface elements is introduced for the adhesive considering both, the rate dependency of the initiation stress and the rate dependency of the fracture toughness. The model is calibrated with experimental data available from the literature and validated against novel quasi-static and dynamic experimental results on an adhesively bonded T-joint made from high strength steel DP-K 30/50 and crash-optimized adhesive BETAMATE 1496V. The numerical predictions show an excellent correlation with the experimental results.

1. Introduction

In recent years, developments in the automotive industry have been driven by the need for a reduction of fuel consumption and CO_2 emissions by reduction of the vehicle weight. At the same time, the crash worthiness had to be maintained. This was achieved by introducing novel materials such as high strength steels and new joining techniques. Adhesive bonding is a joining technique with great potential for lightweight construction. Adhesive bonding is desirable as unlike joining methods using rivets or bolts, no initial damage or stress concentration is induced in the adherents [1]. Since there is no mechanical fastening, debonding becomes a major concern in adhesively bonded joints as this can result in catastrophic failure of the structure. Therefore, a good understanding of the behavior of adhesive joints is required in the design process. Geometric effects such as the thickness of the bond line, the type and thickness of the adherents or the presence and shape of fillets can influence the structural response of adhesive joints [2–8]. For the application of adhesives in automotive structures subjected to crash loading it is also important to consider rate dependent material behavior of both, the adherents and the adhesives. For metals it is well known that the yield and local strain at fracture in metals increases with increasing strain rate [9,10]. Similar behavior was also observed for the apparent yield stress in adhesives [2,11–13]. Another parameter that can be affected by the strain rate is the critical strain energy release rate of the adhesive. Here the trend is less clear than for the yield stress. There is experimental evidence for positive strain rate effects [14,15], negative strain rate effects [16] or no strain rate effect at all [17]. The reduction of fracture toughness with increasing loading rate observed by Blackman et al. [16] can be explained using thermodynamics. Once the crack exceeds a critical propagation speed the conditions at the crack tip change from isothermal to adiabatic. The poor properties of polymers at elevated temperatures then result in a reduction of measured fracture toughness. However, the adhesives characterized by Marzi et al. [14] (HENKEL TEROKAL 5077) and Marzi [15] (DOW BETAMATE 1496V) are optimized for crash loading. The different response compared to the data provided by Blackman is therefore thought to be caused by specific ingredients in the chemical composition of these adhesives.

Over the years, many material models have been developed for the simulation of adhesive joints (see recent reviews given by da Silva et al. [18] or He [19]). An interesting, computationally efficient approach to modeling damage and failure in adhesive joints or delamination in composite materials is the use of cohesive zone models. The concept of a cohesive zone model goes back to early work by Dugdale [20] who discovered a small zone of plasticity ahead of slits acting as crack starters in steel plates subjected to static tension load. Dugdale then postulated the assumption that stresses are constant within this area and equal to the yield strength of the material. Barenblatt [21] suggested that stress levels within this cohesive zone are variable. Inspired by the work of Barenblatt, Hillerborg et al. [22] used a cohesive zone formulation to correlate the traction at the crack tip to the crack opening displacement and used this in a Finite Element (FE) analysis of a concrete beam. Damage is initiated once the stress reaches the tensile strength. During the process of

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crack opening, energy is dissipated. The element fails once the energy dissipated during the crack opening, G, equals the fracture toughness of the material, G_c. The failure criterion can therefore be written as

$$G/G_C = 1 \tag{1}$$

since this early work the use of cohesive zone modeling has become a widely accepted technique for simulation of progressive crack growth under quasi-static [23–25] and, just recently, fatigue [26–28] loading conditions. Over the years several cohesive interface element formulations have been proposed addressing the issues of modeling dynamic loading such as crash and impact. Johnson et al. [29] used quasi-static material data for modeling impact on composite plates subjected to high-velocity impact. They showed that, despite neglecting the influence of the loading rate on the material properties, the model was able to correctly predict the damage sequence and delamination pattern in the composite plate. However, it was also shown that the predicted load-time response was not in agreement with the experimental evidence. Johnson highlighted that the predictions were very sensitive to the value chosen for the fracture toughness indicating that a model capturing the strain-rate dependency of the fracture toughness could have an improving effect on the result. Similarly Rahulkumar et al. [30] concluded that strain-rate insensitive models are not suitable for simulating T-peel tests of polymers and suggested the use of rate-dependent cohesive laws. There have been several attempts to addressing these issues by introducing rate dependent material properties. For example, Nossek and Marzi [13] and Matzenmiller et al. [31] introduced this rate sensitivity in form of a logarithmic law following Johnson and Cook [10]. Xu et al. [32,33] suggested a visco-plastic cohesive interface formulation for adhesives which suffered from the problem that the traction did not decrease to zero for high rates of loading, thus not allowing modeling of full failure. This model was improved by Giambanco and Fileccia Scimemi [34] by considering a decrease of viscosity with increasing damage, thus allowing the traction to decrease to zero for all strain rates. Zhou et al. [35] modeled dynamic crack growth in pre-strained PMMA plates using a cohesive interface model featuring a constant damage initiation stress and a direct correlation between the crack propagation speed and the fracture toughness. Samudrala et al. [36] and Marzi et al. [14,37] introduced concepts for describing both, the rate dependency of the damage initiation stress and the fracture toughness. The good correlation between numerical predictions shown by Marzi et al. [14] indicate that capturing the rate dependency of both, the damage initiation stress and fracture toughness of adhesives is critical to modeling adhesive joints under crash loading. Therefore, in this paper we intend to model damage in adhesively bonded metallic joints using rate dependent cohesive zone models capturing both rate dependencies.

2. Rate dependent cohesive zone model

Following the suggestions from the literature, a rate dependent cohesive zone model was developed incorporating both, the rate dependency of the initiation stress and the fracture toughness. The model is formulated in such way that combinations of bi-linear and tri-linear traction–displacement curves are allowed in order to satisfy the modeling requirements for different classes of materials. For example, for the application to adhesive joints, as discussed in this paper, it is useful to combine a bi-linear traction displacement curve for mode I loading with a tri-linear traction–displacement curve for mode II loading as for example used in the commercially available model for adhesives MAT_ARUP_ADHESIVE in LS-DYNA [38]. Haufe et al. [39] successfully applied this model for simulating static and dynamic failure of adhesive joints. For brittle composite materials on the other hand the application of bilinear traction–separation-laws for both, mode I and mode II loading is very common (see e.g., [24,29,40]). The transition between bi-linear and tri-linear traction displacement curves in pure fracture modes is realized by introducing a pseudo-plasticity parameter Γ defining the ratio of the area underneath the plateau and the total area underneath the traction–separation curve. If the pseudo-plasticity parameter is equal to zero, then the traction–displacement curve becomes bi-linear as shown in Fig. 1.

The traction displacement curve for a single mode is defined by three points: the onset of damage (δ^0,σ^0), the end of the plateau (δ^{pl},σ^0) and complete cohesive failure (δ^f,0).

The displacement at damage initiation, δ^0, is given as

$$\delta^0 = \frac{\sigma^0}{K}, \tag{2}$$

where σ^0 is the stress at initiation, and K is the element stiffness.

The displacement at the end of the plastic plateau, δ^{pl}, is defined as follows:

$$\delta^{pl} = \delta^0 + \Gamma \frac{G_C}{\sigma^0}, \tag{3}$$

where Γ is the pseudo-plasticity parameter defined above, and G_C is the fracture toughness.

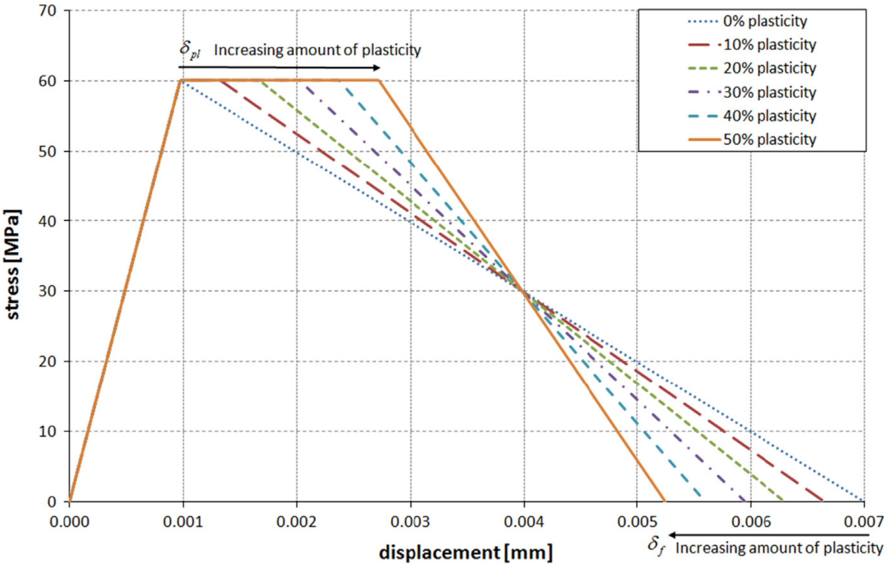

Fig. 1. Effect of pseudo-plasticity parameter Γ on traction–separation law.