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Assessment of experimental methods for calibrating rate-dependent cohesive zone models for predicting failure in adhesively bonded metallic structures

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ABSTRACT

Calibration of rate-dependent cohesive zone models for predicting damage and failure in adhesively bonded structures requires several parameters including rate dependent strength values in mode I and shear loading. This paper presents a total of six different combinations of parameter sets for mode I and shear strength which can all be derived from available experimental data. A finite element model of a T-joint subjected to six different loading configurations is calibrated with the six different parameter sets. Based on the available experimental data, recommendations are given for the type of test to choose for calibration of rate dependent strength parameters. It is recommended to use data from thick walled tube specimens for the mode I strength and a combination of torsion tests on thin-walled tubes and compressive double lap shear tests for the calibration of rate-dependent shear strength.

1. Introduction

Over the last two decades, the use of structural adhesives has significantly increased in automotive [1,2] and aerospace [3,4] industry. The application of this technology reduces the number of stress raisers in a structure such as holes required for bolts and rivets [5] and therefore offers substantial potential for reducing the weight and associated cost of structural parts made from metals, composites or composite/metal hybrids. It is crucial to consider the aspects of crashworthiness in the design process in order to insure passenger safety. Therefore, the application of finite element crash simulations plays an important role in state-of-the-art design process [6]. The increasing amount of structural adhesives used in safety relevant load bearing structures calls for predictive models for describing the response of adhesively bonded structures subjected to high rates of loading. Historically, the concept of cohesive zone modeling dates back to early work by Dugdale [7] and Barenblatt [8] who discovered a small damage process zone, referred to as cohesive zone, ahead of a crack tip in metals. For adhesively bonded joints this process zone is confined to the adhesive layer which is thin compared to the global structure. Consequently, when applied to an adhesive joint the response of the adhesive can be described by a traction-separation based on the displacement jump between the adherends. Cohesive zone models have since proven to be a powerful tool for describing the behavior of adhesively bonded structures [9–11]. In these models damage initiation is commonly described using strength based criteria, final failure is described using energy based criteria. Recently efforts were made to extend the

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applicability of these originally quasi-static formulations by accounting for fatigue damage [12–14] or rate-dependent material properties [15–17]. Whilst the numerical concepts have been verified and validated several times, open questions remain about the calibration procedure for cohesive zone models, especially if rate-dependent material properties are considered. Whilst the Double Cantilever Beam (DCB) test [18,19] and the End Notched Flexure (ENF) [20,21] test and their derivatives such as the Tapered Double Cantilever Beam (TDCB) test [22,23] and the Tapered End Notched Flexure (TENF) [24,25] test seem to be set for determining the critical strain energy release rates for structural adhesives, things are not as clear for the choice of test for determining the rate-dependent strength parameters – especially in shear loading. There are a significant number of test methods which have been proposed for determining the shear strength of adhesives and adhesive joints; however each of these tests has some drawbacks. Comprehensive reviews about adhesive strength testing methods are given by Kinloch [26] and the Adhesives Design Toolkit Project Website [27]. Gustafson and Waas [28] assessed the influence of cohesive constitutive parameters in cohesive zone models using a kriging analysis allowing determining relationships between different parameters. As a result they found that different parameters are interacting making it difficult to reliably quantify them from independent tests. Over the last decade our research group in Germany has worked in order to enhance understanding of structural adhesives and to develop numerical models for predicting damage and failure of adhesive joints. During this time a vast amount of experimental data, including rate dependent material properties obtained from different types of tests, was collected for the structural adhesive Dow Betamate 1496 and its replacement Betamate 1496 V. Section 2 of this paper summarized the relevant strength data measured in different types of tests. It is shown that different types of test produce different results and therefore different input for the cohesive zone model. In Section 3, a recently published rate-dependent cohesive zone model for structural adhesives [29] is presented. A total of six different parameter sets are derived from the available experimental data. These data sets are then used to modeling the response of an adhesively bonded metallic T-joint subjected to different types of loading. The predictions are compared to available experimental data [30]. Based on this "best-fit" approach, recommendations are given for determining cohesive zone parameters for rate-dependent cohesive zone models.

2. Experimental database

Dow Betamate 1496 V is a one component, epoxy based structural adhesive designed to bond to automotive steels. As stated before, this adhesive has been the subject of many previous studies dealing with the characterization of rate-dependent material properties and the derivation of material laws for the numerical simulation of adhesively bonded metallic structures. The different test campaigns used different types of tests for determining the mode I and shear strengths of the adhesive. Three different types of tensile butt joints were used for determining the mode I properties. In [31], two thin-walled tubes of length 120 mm, outer diameter 60 mm and inner diameter 50 mm were bonded and subsequently tested under constant strain rate of $\dot{\varepsilon} = 1 \cdot 10^{-3}\ \text{s}^{-1}$. In [32] compact butt joint tests were manufactured using metallic cylinders of diameter 15 mm. Rate dependent properties were measured in a range from $\dot{\varepsilon} = 1 \cdot 10^{-4}\ \text{s}^{-1}$ to $\dot{\varepsilon} = 1 \cdot 10^{3}\ \text{s}^{-1}$. Böhme et al. [33] used tubes of length 25, outer diameter 20 mm and inner diameter 13.5 mm to investigate the rate dependent behavior of Betamate 1496 V for strain rates in the range of $\dot{\varepsilon} = 1 \cdot 10^{-3}\ \text{s}^{-1}$ to $\dot{\varepsilon} = 1 \cdot 10^{4}\ \text{s}^{-1}$. Fig. 1 shows sketches of the three different specimens.

Fig. 2 compares the results obtained during these three studies. The black diamond indicated the quasi-static data obtained from the thin-walled tube tests; the black crosses mark the data obtained from butt joint tests on metallic cylinders; the black circles mark the data obtained from compact butt joint tests.

It can be seen that both rate dependent data sets show an approximately linear increase of strength on a semi-logarithmic plot. However, quasi-static and medium rate strength values obtained from butt joint tests on full cylinders [32] are somewhat higher than strength values obtained from thick-walled tube specimens [33]. For a rate of approximately 1000 s^{-1} the strength values are about the same. This means that both, the slope and the quasi-static reference value of the strength evolution with strain rate are different if different types of test are used for model calibration.

Similar observations were made for evaluations of shear strength. In [31], two thin-walled tubes of length 120 mm, outer diameter 60 mm and inner diameter 50 mm were bonded together and subsequently tested under constant shear rate of $\dot{\gamma} = 2 \cdot 10^{-3}\ \text{s}^{-1}$. Böhme et al. [33] used single lap joints to investigate the rate dependent shear behavior for shear rates in the range of $\dot{\gamma} = 1 \cdot 10^{-3}\ \text{s}^{-1}$ to $\dot{\gamma} = 1 \cdot 10^{3}\ \text{s}^{-1}$. May et al. [29] used the compressive double lap shear test originally proposed by Challita et al. [34] for measuring the rate dependent shear behavior for shear rates in the range of $\dot{\gamma} = 5 \cdot 10^{-2}\ \text{s}^{-1}$ to $\dot{\gamma} = 5 \cdot 10^{4}\ \text{s}^{-1}$. The three different specimen types are sketched in Fig. 3.

Fig. 4 compares the results obtained during these three studies. The diamond indicates quasi-static data obtained from torsion tests on thin-walled tube specimens [31]. Rate-dependent data taken from compressive double lap shear tests [29] are indicated by triangles. Rate-dependent data taken from single lap shear tests [33] are marked as circles.

Differences between the different types of tests are evident. The quasi-static shear strength obtained from single lap shear tests is lower than the (extrapolated) quasi-static shear strength obtained from compressive lap shear tests. Both tests suffer from the fact that the stress state in the failure zone is not pure shear. In both cases, the stress state is a combination of shear stress and out-of-plane stress caused by rotation and bending of the specimen during loading. However, due to the variation in overlap length and loading direction, the shear stress distribution and magnitude of out-of-plane stresses are different for both types of specimens [32]. Consequently, both strengths are lower than the strength obtained by torsion testing of