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Cohesive zone model for high-cycle fatigue of adhesively bonded joints under mode I loading

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ABSTRACT

A cohesive zone model adequate for simulating the behaviour of adhesively bonded joints subjected to high-cycle fatigue and pure mode I loading is presented. The bilinear cohesive zone law with linear softening relationship was considered. The main advantage of the proposed formulation is the use of a unique damage parameter accounting for cumulative damage resulting from static and fatigue loading. The method was implemented in a user subroutine of the commercial finite element software Abaqus®. Two-dimensional numerical simulations of the double cantilever beam test using different representative combinations of the modified Paris law coefficients were performed. It was verified that the results of the model simulate with excellent agreement the several Paris laws used as input, thus demonstrating the good performance of the method as a predictive tool.

1. Introduction

Adhesively bonded joints are nowadays widely used in several industries such as automotive and aerospace. They have been increasingly adopted in structural applications due to their many advantages over classical mechanically fastened joints. Some of those advantages are lower weight, more uniform distribution of load, and better fatigue performance.

The increase use of adhesively bonded joints in structural applications has been accompanied by an increase interest in the development of models that can predict the behaviour of those joints under different types of loading. A very attractive way of modelling these joints is to use the finite element method in combination with the cohesive zone model (CZM). The proponents of the CZM were Dugdale (1960) and Barenblatt (1962) and its combination with the finite element method was introduced by Hillerborg et al. (1976). Since those ideas were proposed, a significant number of studies have been published where the CZM and interface elements have been used to study the initiation and propagation of damage in several types of structures and materials subjected to monotonic loads. Examples are studies of delamination in laminated composite materials (Schellekens and de Borst, 1993; Reddy et al., 1997; Mi et al., 1999; de Moura et al. 2000) and studies of crack initiation and growth in adhesively bonded joints (Yang et al., 1999; Sørensen, 2002; Gonçalves et al., 2003; de Moura et al., 2012). Contrary to fracture mechanics based methods, the CZM provides the capability to simulate the initiation and propagation of damage without requiring the definition of an initial crack. This type of model is based on a relationship between stresses and relative displacements at points where damage can occur. Usually, the CZM is embedded in interface finite elements and these are used to model the regions of the structure where initiation and propagation of damage is likely. In bonded joints, the interface finite elements are usually used to model the thin adhesive layer where adhesive or cohesive failure occurs (de Moura et al., 2012).

Fatigue is an important type of loading for many structures that contain adhesively bonded joints. Therefore, it is important to accurately predict the fatigue strength of these joints and several methods have been developed for that purpose (Wahab, 2012). Recently, the framework for modelling adhesively bonded joints described above has been adapted in several studies to the modelling of fatigue initiation and propagation in bonded joints and in laminated composite materials. In general, those studies combine the CZM and interface elements with a fatigue damage evolution law to simulate fatigue degradation. In some of those studies (see for example Nguyen et al., 2001; Roe and Siegmund, 2003) the fatigue damage accumulation is computed cycle-by-cycle. This strategy has a very high computational cost and it is impractical for the study of high-cycle fatigue. To overcome this limitation, a strategy where it is assumed that several fatigue cycles occur between each update of the accumulated damage has been proposed and it is used in all the studies described below. Robinson et al. (2005) modified an interface finite element previously developed, and previously applied to predict delamination growth due to monotonic loading in laminated composites, to incorporate the effects

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of cyclic loading. The constitutive law implemented in the original interface element was extended by incorporating a modified version of a continuum fatigue damage model. Numerical results showed that the model replicates the behaviour of the modified Paris law observed in experimental testing. Muñoz et al. (2006) tested the computational robustness of the formulation described in Robinson et al. (2005) with respect to the number of cycles per increment and the element size. Their numerical results showed some limitations in the values that those parameters can take and, in particular, they showed that large interface elements can cause oscillations in the crack growth rate. Muñoz et al. (2006) also extended the formulation of Robinson et al. (2005) to include cyclic loads where the minimum value is non-zero. Turon et al. (2007) developed a CZM for modelling delamination in laminated composite materials subjected to high-cycle fatigue loading. The CZM uses a single damage variable and defines its evolution in terms of the crack growth rate. The damage state depends on the number of cycles but also takes into account the loading conditions. The model was tested for modes I, II and mixed-mode I/II loading conditions and the results showed a higher level of accuracy for mode I compared with the other modes of loading. Pirondi and Moroni (2010) introduced a procedure to predict fatigue crack growth in bonded joints that also uses a CZM with a single damage variable as presented in Turon et al. (2007). Their work includes an automated procedure to compute the applied strain energy release rate, which is not part of the model in Turon et al. (2007), and was developed for loading modes I and II. In Moroni and Pirondi (2011), the same authors extended their model to mixed mode I/II loading. In both studies, the results from the models were compared with experimental results from the literature and good agreements were obtained. Harper and Hallett (2010) developed a CZM based on a detailed study of the numerical cohesive zone and its use in the computation of the strain energy release rate. Their model was implemented in three-dimensional interface elements within the explicit finite element software LS-Dyna. They applied it to fatigue fracture toughness tests of composite materials and studied mode I, mode II, and mixed-mode I/II loading. Their numerical results showed good agreement when compared with experimental results from the literature and with theoretical solutions. May and Hallett (2010) introduced a phenomenological damage variable for fatigue damage initiation into the model previously developed in Harper and Hallett (2010). Their objective was to better model fatigue initiation in the region where the modified Paris law is invalid. Their conclusion was that their model showed potential to model fatigue initiation for cases in which damage would not occur in models based on the modified Paris law. However, they identified some limitations in their new model which was not able to provide accurate predictions in some of the tests conducted. Kawashita and Hallett (2012) proposed a crack tip tracking algorithm which is used in conjunction with a CZM implemented in three-dimensional interface elements and implemented as a user-defined subroutine in LS-Dyna. Their formulation is completely independent of the cohesive zone length and it is relatively insensitive to mesh size. They applied their method to the study of delamination propagation in composite laminates under cyclic loading. The predicted delamination rates were found to be weakly dependent on mesh size. Khoramishad et al. (2010a) used a CZM integrated with a strain-based fatigue damage model to simulate fatigue damage in adhesively bonded joints. The numerical fatigue model was calibrated against experimental results obtained for single lap joints and that same model was then used to accurately predict the fatigue behaviour of laminated doublers in bending. This model was later extended by the same authors (Katnam et al., 2010; Khoramishad et al., 2010b) to take into account the effect of load ratio on the fatigue behaviour of adhesively bonded joints.

The objective of this work is to develop and numerically validate a cohesive zone model adequate to simulate high-cycle fatigue behaviour of adhesively bonded joints under pure mode I. The method is implemented in the finite element software Abaqus® by means of a user subroutine. The proposed methodology is based on the modified Paris law, which establishes a relation between crack growth rate and energy release rate. Material stiffness deterioration as a function of the number of cycles is simulated by means of a damage parameter that includes static and fatigue degradation. A data reduction scheme based on the crack equivalent concept is also proposed in order to simplify the process of monitoring the energy release rate in the course of the DCB fatigue test. Two-dimensional numerical simulations were performed in order to analyse the influence of the Paris law coefficients on the fatigue behaviour and it was verified that the model is able to properly capture that influence.

2. Cohesive zone model

2.1. Monotonic loading

Cohesive zone models have been used with success in the simulation of damage initiation and propagation at interfaces (Mi et al., 1999; Yang et al., 1999). The basis of a CZM is a constitutive relationship between tractions (σ) and relative displacements (w). The relative displacements at interfaces are obtained from the displacements of the homologous points belonging to both sides of the interface (Gonçalves et al., 2000). The most used CZM is the bilinear (Fig. 1), which includes a linear softening relationship when the local strength (σ_u) is attained. The softening region aims to reproduce several damaging phenomena at the crack tip in a non-negligible fracture process zone, thus falling under the domain of non-linear fracture mechanics. The area circumscribed by the cohesive law represents the critical strain energy release rate G_{Ic}. Thus, from Fig. 1 the following relationship can be written

$$G_{Ic} = \frac{\sigma_u w_u}{2} \tag{1}$$

where σ_u is the local strength and w_u the ultimate relative displacement leading to complete failure at the integration point. This means that G_{Ic} and σ_u are material parameters that should be known a priori to define the cohesive law. The bilinear CZM is characterised by two different relations. Before damage starts to grow,

$$\sigma = kw \tag{2}$$

being k the interfacial stiffness. After damage onset ($w > w_o$ in Fig. 1), the simulation of progressive damage in the softening region of the CZM is achieved by

$$\sigma = (1 - e_s)kw \tag{3}$$

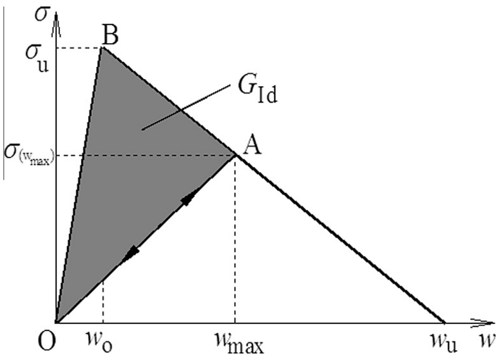

Fig. 1. Schematic representation of the cohesive law.