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An explicit cohesive element combining cohesive failure of the adhesive and delamination failure in composite bonded joints

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ABSTRACT

Delaminations can change the mechanical behaviour of bonded joints significantly in crash simulations. A cohesive element is presented that enables the simulation of delamination failure in bonded joints on a full scale structural level. The principle of the approach is to compute the through thickness stresses of the adherends analytically within the cohesive element representing the cohesive behaviour of the complete adhesive. Via a stress based interaction criterion it becomes possible to detect delamination in the adherends. The delamination failure is implemented by an adaptation of the cohesive law.

The new cohesive element is validated numerically by a single lap joint geometry. The results show good correlation with a conventional cohesive zone modelling when cohesive failure of the adhesive occurs. It can well predict the delamination initiation and approximates the joint strength conservatively. The convergence behaviour of the model is improved. The numerical efficiency is high and enables a representation of both cohesive failure of the adhesive and delamination failure on a structural level.

1. Introduction

Fibre reinforced materials are increasingly used in modern lightweight structures. The reason lies in their low density, high stiffness and high strength. Usually, several layers are stacked in the thickness direction. A delamination of the layers can occur in critical cases e.g. in load introduction areas like bonded joints, where peel and shear stresses from an adhesive act on the surface of the layered adherends, and promote a delamination failure. In this case, the joint's bearable force as well as the energy absorbed can reduce drastically.

In the automotive industry, the crash scenario serves as a verification of the car design. To reduce experimental costs, numerical simulations of car crash scenarios are done with explicit finite element solvers. Since the delamination failure process in bonded joints takes place between the single plies of the laminated adherend, a high resolution of the model is necessary which makes the simulation of a complete car structure difficult to solve in adequate time.

The prediction of delamination failure in bonded joints has been addressed by several works using numerical approaches. There have been 2D and 3D continuum models to study the stress distributions, stress intensity factors and energy release rates in pre-cracked bonded joints [1–3]. The models are very useful to study the locations of crack initiation in bonded joints, the criticality of existing cracks and crack sizes and the influence of joint design parameters. However, a high resolution of the mesh has been necessary and dynamic crack propagation has not been simulated in the studies. The models are, therefore, not suitable for crash simulations.

Cohesive zone modelling has turned out to be a computational efficient technique to model the dynamic crack propagation along a predefined interface [4–6]. It has been applied to the simulation of delamination crack growth [7,8] and to the modelling of cohesive failure in adhesive layers [9,10]. An explicit formulation has been presented for the simulation of adhesive bondlines in crash structures with high numerical efficiency [11].

Delamination failure in bonded joints can occur by a kinking of an existing crack from the adhesive into the adherends or the delamination crack can develop directly in the adherends. Li et al. [12] studied the kinking of a crack into an adherend with random-oriented fibres. The adherends were modelled by continuum elements and the adhesive by one layer of cohesive elements over the complete bondline thickness. A cohesive zone perpendicular to the bondline was introduced in the adherends to model the kinking of the crack. The cohesive zone in the adherend was modelled 10 mm long to keep the size of the simulation model small. When the adherend crack reached the end of the cohesive zone the model was re-meshed.

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Campilho et al. [13] studied the damage growth in single and double lap joints using cohesive zones in the adherend for delamination failure, in the adherend/adhesive interface, within the adhesive and at the adhesive/patch interface of a repaired structure. The cohesive zones were placed in a 2D plane strain continuum model. An additional cohesive zone was introduced perpendicular to the bondline and the first delamination interface to account for a dynamic intra-ply failure of the first ply next to the adhesive. Modifying the strength properties of the cohesive laws, the location of failure was observed at different locations, while the fracture energies of adhesive and delamination were found to have a minor influence. In the case of delamination failure, the outer ply of the laminate adherend which is attached to the adhesive delaminated.

Neto et al. [14] set up a 2D model of a single lap joint with laminated adherends. The adhesive bondline was modelled by one cohesive zone over the complete bondline thickness. The dynamic crack growth in the delamination interface was modelled with a second cohesive zone parallel and close to the adhesive bondline. For all cohesive zones a triangular mixed mode cohesive law was used. The simulation model was compared for a ductile and brittle adhesive and for various overlap length with analytical solutions and experiments. The failure mode of the numerical model correlated well with the experimental findings. For the brittle adhesive, delamination failure occurred for long overlap length which was non-conservatively approximated by the numerical model. For the ductile adhesive, cohesive failure of the adhesive occurred which was underestimated by the numerical model due to the simplified shape of the cohesive law.

The studies mentioned [12–14] use continuum elements for the adherends with cohesive zones introduced for possible crack interfaces. This type of modelling still leads to high computational costs and modelling effort, if at all feasible on a full scale structure. In order to reduce the model size, the laminated adherends can be modelled by shell structures. Dávila et al. [15] introduced the concept of cohesive zones for shell elements. This concept was applied to bonded composite joints by Rauh [16]. In the later work, the cohesive behaviour of the adhesive in a bonded tube specimen and in a double hat structure was modelled via one cohesive zone over the complete bondline thickness. The laminate was split into two sub-laminates represented by shell elements and connected via a cohesive zone representing the dynamic crack growth in the delamination interface. Using this modelling approach, the model size was significantly reduced. A further reduction to one shell element for the complete adherend and only one cohesive zone for the complete adhesive bondline was, however, desired.

In this case, the delamination failure can be integrated either in the shell formulation of the adherend or into the cohesive zone. Since conventional shell elements do not provide degrees of freedom in the thickness direction, the cohesive zone is chosen. Then, the delamination failure can be integrated in two ways into the cohesive zone. The cohesive law can be calibrated empirically by experiments failing by delamination. In [16], single lap shear experiments showing a mixture of delamination and cohesive failure of the adhesive have been used to inversely calibrate the cohesive law. The problem using this method is that an appropriate calibration for different joint geometries, loading conditions and loading rates is difficult to find and a high experimental effort can arouse.

The objective of this article is to develop a formulation for a cohesive element that models the cohesive behaviour of the adhesive and integrates the delamination failure. This is a new approach compared to state-of-the-art simulation with conventional cohesive zones that only model the cohesive behaviour of the adhesive. With the new formulation, the adherends can be modelled via conventional shell elements. The simulation model can be significantly reduced. This is illustrated in Fig. 1.

In the next section the formulation for the element is presented. Then a numerical study of a single lap joint is carried out comparing it with a continuum model including cohesive zones for delamination failure in the adherends. The accuracy of the new element as well as its computational performance is investigated.

2. Element formulation

The momentum equation of the dynamic structural boundary value problem in local form is [17]

$$\sigma_{ji,j} + b_i = \rho \ddot{u}_i \qquad in \qquad \Omega \tag{1}$$

where σ_{ij} denotes the Cauchy stress tensor, b_i the body forces, ρ the mass density and $\ddot{u}_i$ the acceleration of a local point in an arbitrary body Ω. A stress boundary condition $\sigma_{ji}n_j = \hat{t}_i$ on a surface Γ_σ and a displacement boundary condition $u_i = \hat{u}_i$ on a surface Γ_u are applied in the general case. A potential crack surface Γ_c shall be introduced additionally within the body Ω according to Fig. 2 where a traction equilibrium has to be fulfilled [18].

$$t_i^+ = \sigma_{ji}n_j = -t_i^- \qquad on \qquad \Gamma_c \tag{2}$$

The crack Γ_c divides the body Ω in two parts $\Omega^\pm$. For each body, the momentum equation according to Eq. (1) is still valid. Using the principal of weighted residuals, the structural boundary value problem can be formulated in a weak form. Using the virtual displacements δu_i as weights, the weak form for each body can be written as [18]

$$\int_{\Omega^\pm} \delta u_i \rho \ddot{u}_i d\Omega^\pm + \int_{\Omega^\pm} \delta\epsilon_{ij}\sigma_{ij} d\Omega^\pm = \int_{\Omega^\pm} \delta u_i b_i d\Omega^\pm + \int_{\Gamma_\sigma^\pm} \delta u_i \hat{t}_i d\Gamma_\sigma^\pm + \int_{\Gamma_c^\pm} \delta u_i^\pm t_i^\pm d\Gamma_c^\pm \tag{3}$$

where $\delta\epsilon_{ij}$ is the virtual strain tensor. Summarizing over both parts of the body and using Eq. (2) gives

$$\int_{\Omega} \delta u_i \rho \ddot{u}_i d\Omega + \int_{\Omega} \delta\epsilon_{ij}\sigma_{ij} d\Omega = \int_{\Omega} \delta u_i \rho b_i d\Omega + \int_{\Gamma_\sigma} \delta u_i \hat{t}_i d\Gamma_\sigma + \int_{\Gamma_c} \delta [\![u_i]\!] t_i d\Gamma_c. \tag{4}$$

This is the weak form of the complete body Ω which includes a crack Γ_c. The crack is kinematically described by a global displacement jump $[\![u_i]\!]$.

$$[\![u_i]\!] = u_i^+ - u_i^- \tag{5}$$

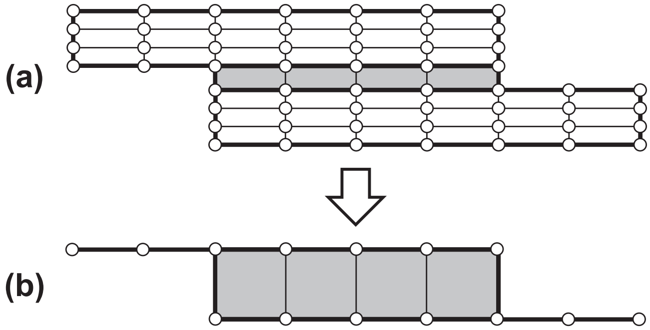

Fig. 1. (a) Conventional cohesive zone model: The adherend is modelled by continuum elements with optional delamination interfaces for the simulation of dynamic crack growth in the adherend; (b) Model reduction with one cohesive zone over the complete adhesive thickness including delamination failure.