SIMULATION OF CUSP FORMATION IN MODE II DELAMINATION

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Abstract
On the microlevel, cusps are formed during delamination crack growth under mode II loading conditions. In this work, two different approaches to simulate this process are presented. Firstly a cohesive zone method where cohesive segments are introduced between a pair of neighbouring elements when the traction between those elements exceeds the strength. And secondly the thick level set method, which allows for a staggered solution scheme. Both methods successfully predict the inclined cracks that form initially if constitutive laws are chosen carefully, but both have difficulties to simulate final failure.

1. Introduction

The interfacial fracture toughness is a key parameter for delamination analysis. This toughness is not a material constant but displays a significant variability under changing load conditions, which is due to the micromechanical fracture process in the interface. In current modeling practice, the variability of the fracture toughness is characterized with aid of fracture mechanics concepts. However, fracture mechanics has limited validity for this characterization as the fracture process zone is not negligibly small with respect to the structural dimensions (most notably the ply thickness). Computational models that can predict the delamination process on the microscale may lead to better understanding of the mechanisms behind the variability in fracture toughness. Eventually, a virtual testing approach can be helpful in the development of a more reliable characterization of delamination.

This contribution deals with one of the primary challenges that comes with an effort to perform micromechanical simulations of delamination: namely the simulation of cusp (or hackle) formation under mode II loading conditions. Two modeling approaches are evaluated with respect to their ability to predict cusp formation until final failure. Reaching final failure is of particular importance if one is interested in predicting fracture energy, because the fracture energy will only be known when the fracture process is complete.
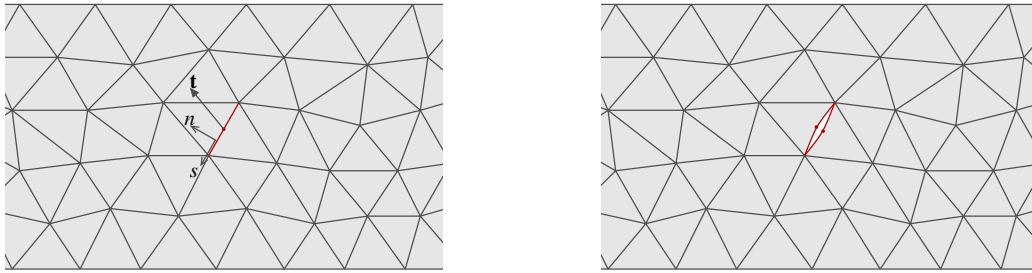
Figure 1. Introduction of a crack segment based on traction **t**.

2. Cohesive zone method

Cohesive zone methods are a powerful class of methods for the modeling of cracking in materials. The central idea is that the failure process is collapsed onto a plane. A crack is modeled as a discontinuity in the displacement field, which is initially closed by cohesive tractions but gradually opens as softening occurs. Different numerical approaches exist in which cohesive zone methods can be used such as interface elements, where the crack path must be discretized in advance, or the extended finite element method (XFEM), where the crack can run through the finite elements. Another approach is to place cohesive elements between neighboring finite element during the simulation, wherever the stress exceeds a critical value. This approach was successfully applied to explicit dynamics simulations by Ortiz and coworkers [1, 2].

An advantage of this approach over the use of interface elements is that no a priori information is needed about where cracking takes place: cracks can initiate and grow along any element edge. The only way to achieve such flexibility with interface elements is to put them between every pair of elements in advance, which would lead to a significant increase in number of degrees of freedom and difficulties with the initial undamaged stiffness in the interface elements. An advantage of this approach over XFEM, on the other hand, is that it can deal with branching and merging of cracks very easily. Moreover, a very high number of cracks can be modeled without implementational challenges in decisions on where to initiate new cracks and where not.

For the current purpose, where many cracks are to be expected and their location and orientation is not known in advance, the approach with cohesive segments inserted on the fly is therefore an interesting option.

2.1. Method

In our implementation, 6-node triangular elements are used. A new cohesive crack segment is placed between two elements if the following criterion is violated [1]:

$$t_n + \beta |t_s| > f_t \tag{1}$$

where t_n and t_s are the normal and shear traction with respect to the element edge (see Figure 1), f_t is the tensile strength and β is an interaction parameter. Assuming that fracture occurs locally in mode I, i.e. in the direction of maximum principal stress, this parameter is needed to account for the misalignment of the element edges with respect to the principal stress directions. The influence of β will be assessed in the results section.
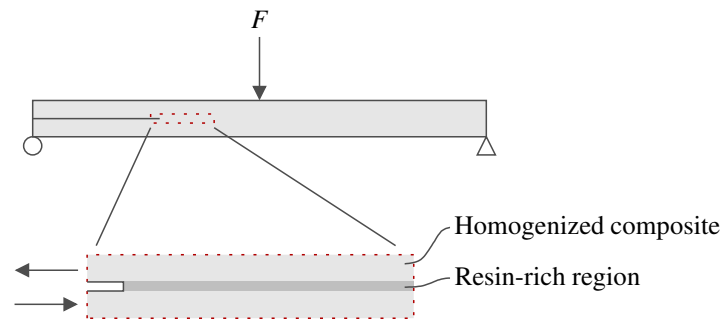
Figure 2. Simplified micromechanical test problem for mode II fracture.

A mixed-mode cohesive law is applied on the crack surface. As a starting point, a general purpose cohesive law is used, which has zero traction at zero opening and a finite but high initial stiffness. A shift is then applied to the formulation to mimic initially rigid behavior without introducing a singularity at zero opening (cf. [3, 4]). The shift is applied such that the nodal force on the mid-node from the cohesive traction at zero opening exactly match the nodal force on the mid-node from the connecting solid element when criterion (1) is exactly satisfied.

In initial simulations, convergence difficulties were regularly encountered at the moment of crack merging. The described technique with the shifted cohesive law served to reduce sudden changes in the internal force upon insertion of a crack segments. In case of merging, however, the strategy may not be sufficient for that purpose. Therefore, additional corrective forces are added on top of the forces due to the cohesive tractions on all three node pairs of a crack segment that merges earlier cracks. These forces diminish along with the cohesive tractions through the development of cohesive damage. Additional energy dissipation due to these forces remains limited because they are only applied on a minority of all crack segments.

2.2. Results

As a numerical test case, the setup illustrated in Figure 2 is considered. Two pieces of stiff material (homogenized composite) are held together by a weaker core (pure matrix material or an adhesive) inside which failure may occur. The interface is loaded in shear by applying opposing axial forces on the stiff arms. As long as cracking does not reach the unloaded side of the specimen, the stress state is very similar to that around the crack tip in an end-notched flexure test.

In Figure 3, the influence of the interaction parameter β on the results is shown. For high β, the response is very smooth. However, in this case, the simulations do not show any cusp formation. Instead, a single crack appears along the interface between the stiff and weak material. With high β, the directional preference of cracks to grow perpendicular to the maximum principal stress direction is removed from the model.

For low β, however, the response becomes very brittle. Cohesive cracks appear along all edges that are aligned more or less perpendicular to the maximum principal stress direction. However, crack segments hardly join up and many crack bridges appear. When the bridges are finally cut, a sharp snapback occurs which is very hard to track. With $\beta = 0.1$ the simulation could not be continued until final failure.
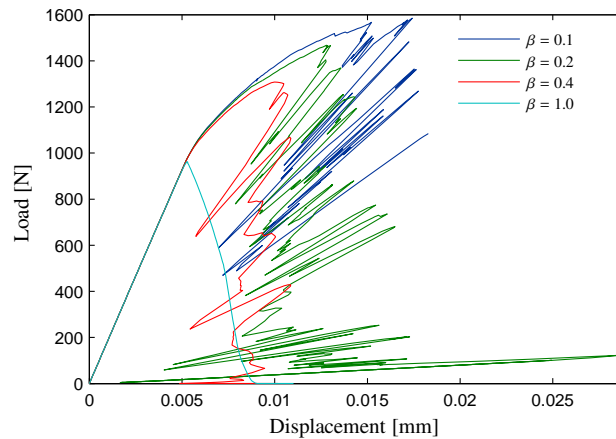
Figure 3. Load-displacement relation and influence of β from cohesive simulation of interface failure.
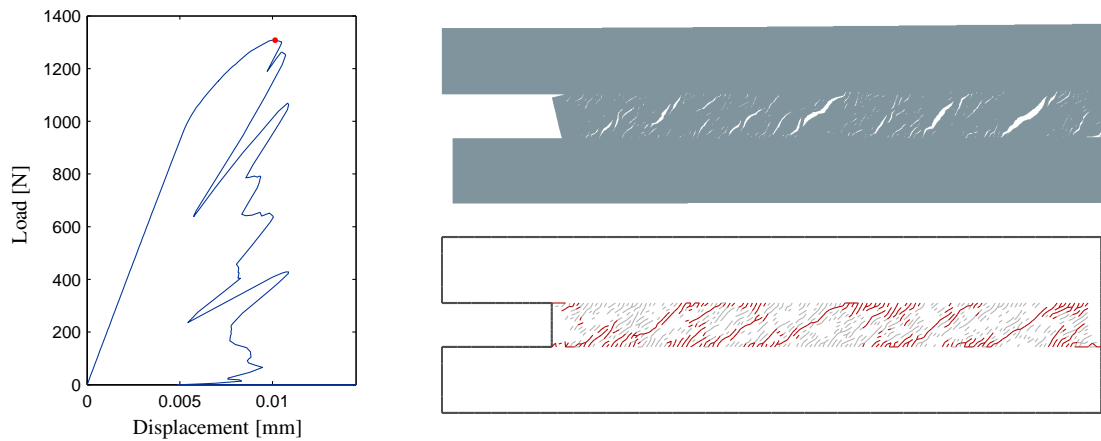

Figure 4. Peak load response in cohesive zone model with $\beta = 0.4$: load displacement relation (left), deformation with cusp formation (right top), and overview of active and passive cracks (right bottom).

For intermediate β, the simulation is more robust, and still cusp formation is observed. More detailed results are presented in Figure 4 for $\beta = 0.4$. The tendency to form cusps can be observed from the illustration of the deformed mesh with magnified deformations. Oblique cracks have formed through the thickness of the core and a number of them are opening. In the lower right image, all crack segments are shown, with those in which damage is still increasing at the peak load in dark red and others in light grey.

Although these results show the versatility of the cohesive zone approach, convergence difficulties persist. Highly unstable behaviour occurs when crack bridges break and obtaining convergence in even with a very carefully crafted algorithm not always within reach. With a longer specimen, final failure is out of reach. Therefore, an alternative approach has been explored which allows for the use of a robust staggered solution scheme: the thick level set method.

3. Thick level set method

In the thick level set method, originally proposed by Moës et al. [5, 6], a level set field is used to define the location and evolution of damage. Damage is applied in the continuum stress-strain law as in continuum damage methods. However, in contrast with continuum damage methods, the update of the damage is not strain-based, but rather based on the evolution of a level set
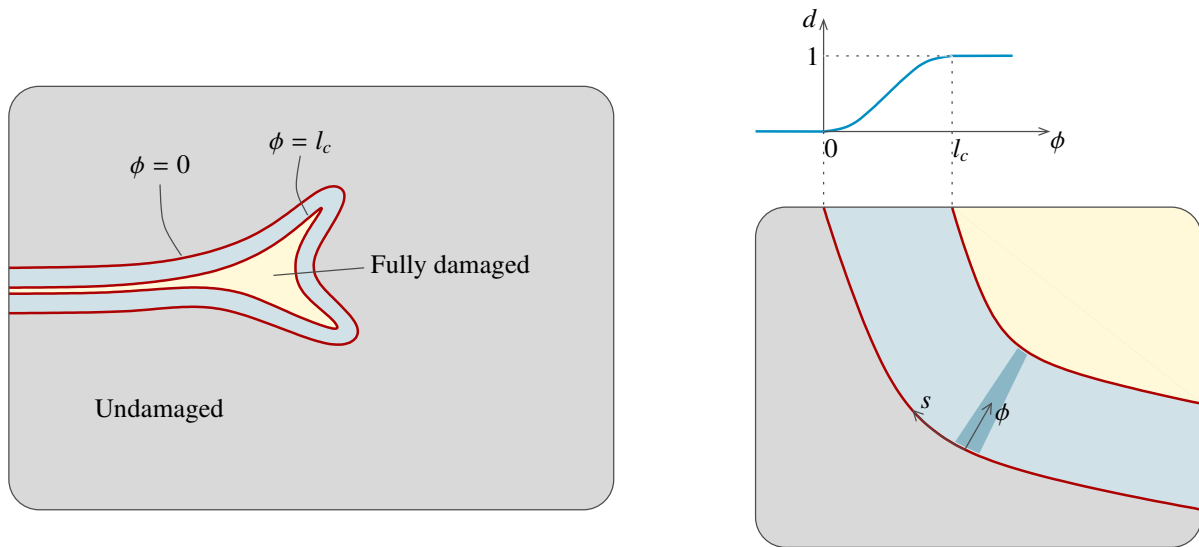
Figure 5. The thick level set method, defining damage d as a function of the distance to a front of which the location is defined as the level set $\phi = 0$.

field.

3.1. Method

In the thick level set method, a predefined function is used in which damage varies from 0 to 1 over a distance l_c behind the damage front (see Fig. 5). The crack growth simulation is performed with a staggered solution scheme which consists of the following sequence of computations in every time step:

1. The mechanics problem is solved with fixed damage distribution.

2. The energy release Y upon front movement is computed along the front.

3. The energy release is related to front velocities through a constitutive relation.

4. Initiation of new damage nuclei is checked for.

5. The level set field (and hence the damage distribution) is updated from the front velocities.

The first step is the most time-consuming. Nevertheless, it is much easier to solve than a time step in a full nonlinear finite element simulation, as the problem is nearly linear[1]. The second step also involves the solution of a system of equations. This system is much smaller than the system of equations of the mechanics problem, because it is only defined in the elements that span the band width $0 < \phi < l_c$. Steps 3–5 are computationally very cheap. The method is robust and efficient. Moreover, the method is regularized due to the presence of the characteristic length l_c.

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[1]To be precise, the only nonlinearity is due to the fact that the damaged material behaves differently under compression and tension. However, softening does not occur within this step.
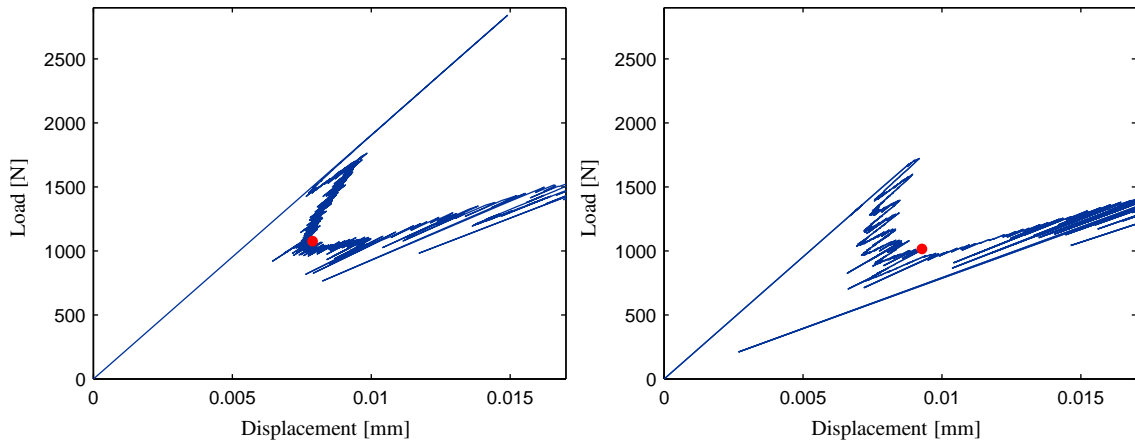
Figure 6. Load-displacement results from thick level set method with Y_c as only parameter (left) and with additional parameter Y_0 (right); markers correspond to time steps used for Fig. 7

A change with respect to the most recent version of the thick level set method [6] is that an additional material parameter is added to the model. Moës et al. [5, 6] use a single fracture resistance parameter Y_c which is related to the fracture toughness G_c through the characteristic length l_c as:

$$G_c = 2Y_c \int_0^{l_c} d \, \mathrm{d}\phi \tag{2}$$

where the integral depends on the predefined function that relates damage to ϕ. For a typical symmetric damage profile, the integral evaluates to $l_c/2$, resulting in $G_c = Y_c l_c$.

In [5, 6], it is suggested that the same value of Y_c can be used for both crack growth and damage initiation. The idea for initiation is that a new damage nucleus is inserted where the local stress and strain lead to a configurational force Y that is higher than Y_c. Supposing that l_c follows from geometric considerations and Y_c from the material fracture toughness G_c through Eq. (2), this approach does not leave an option to specify the material strength. However, the stress level at which damage is initiated in a material is generally not related to the fracture toughness. Therefore, in this work, Y_0 is introduced as an input parameter for damage nucleation independent from Y_c. The resistance then varies from Y_0 to Y_c as the damaged zone grows from a very small nucleus to a crack. In order to compute the size of the damaged zone, a third system of equations is solved that is similar to the one for Y as proposed by Bernard et al. [6]. This additional computation is performed at the beginning of the time step, i.e. before step 1 in the scheme described above.

3.2. Results

The example from the previous section has also been analyzed with the thick level set method. Both strategies described above, with single parameter Y_c and parameter pair Y_0 and Y_c, are compared (see Figs 6 and 7). In both cases, an initial damage nucleus is predefined at the mid-height of the core. It has been found that, with a single parameter, the damage nucleus starts to grow with a sharp load drop and after that no secondary damage zones initiates (Figure 7 – top). The peak load level depends strongly on the size of the initial damage. For the results here, a circular initial damaged zone with radius 0.4 mm is chosen. With smaller initial damage, the peak load would be much higher.

Figure 7. Damage profiles from thick level set method with Y_c as only parameter (top) and with additional parameter Y_0 (bottom).

In other words, the stress level at which a damage nucleus grows depends strongly on the its size. This is also the reason that no secondary damage is initiated: the critical stress level for a small nucleus is never reached after the initial damage zone starts growing.

With two parameters, the peak load is preceded by damage growth and by initiation of secondary nuclei. The size of the initial crack nucleus is therefore of no influence on the results. After the peak load, cracks grow one after another from the center of the core to the edges. In the load-displacement relation, this results in a series of snapbacks.

In both simulations, the load did not decrease to zero. After the damage distributions in Figure 7 are obtained, the load keeps increasing. This unrealistic response is due to the fact that large shearing deformations in the damaged zone lead to locking with the current formulation. The problem is caused by the constitutive law from [6], which was designed to give stiffness recovery under compression. The differentiation between compressive and tensile behaviour that this constitutive law offers is crucial for the initial stage of the presented simulations. The question how to prevent the locking in the later stage while maintaining correct behaviour in the early stages remains for the time being unanswered.

4. Conclusions

Two different methods are presented to model cusp formation under mode II delamination: a cohesive zone approach with crack segments inserted on the fly and the thick level set method. Both methods predict inclined cracks if the right constitutive relations are used. For the cohesive approach, this condition boils down to the need for a low influence of shear traction on the crack initiation criterion. For the thick level set method, it is important that the constitutive law distinguishes between tension and compression.

Both methods have difficulties simulating the complete failure process. Robustness is a big issue with the cohesive zone method. This will hold in general for approaches where microcracks are modeled in an implicit quasi-static framework. The thick level set method does not suffer from

this, but in this approach spurious stresses appear before the failure mechanism has developed fully.

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