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The Thick Level Set method: Sliding deformations and damage initiation

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Highlights

- The Thick Level Set method (TLS) is applied to shear failure in a sandwich structure.
- Two difficulties of the TLS are encountered and solutions are proposed.
- An interphase material is introduced that allows for free-sliding deformations.
- A strength-related parameter is introduced to control the initiation stress level.

Abstract

The Thick Level Set method (TLS) is a new approach to the modeling of damage growth. In the TLS, damage is defined as a function of the distance to a moving front. The level set method with signed distance function is used to keep track of the front location and to evaluate the distance to the front throughout the domain. The update of damage is done indirectly by moving the damage front based on integration of the configurational force across the damaged band. In this paper, the TLS is applied to shear failure of a sandwich structure. Two problems with the TLS are encountered in this study and solutions are proposed. Firstly, it is found that sliding deformations across a crack lead to unrealistic activation of stiffness recovery that is included for modeling damage under compression. In order to allow for free sliding, a special interphase constitutive law is proposed that takes the direction of the material interface into account when it comes to stiffness recovery. Secondly, it is found that in the TLS the crack propagation stress is lower than the damage initiation stress, which is in many cases unrealistic. It is proposed to use two values instead of one for the material resistance against damage growth, one related to initiation and the other related to propagation. The resistance changes from the first to the second value as the damaged zone grows. With the two innovations presented in this paper, it is possible to simulate cusp formation in shear failure. It is emphasized that the robustness of the TLS is a significant advantage in the simulation of cusp formation which involves multiple merging cracks.

Keywords: Thick Level Set; Damage modeling; Fracture mechanics; Shear loading; Initiation

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1. Introduction

The Thick Level Set method (TLS) has been proposed by Moës et al. [1,2] as a new approach to the modeling of damage and fracture in solids. In the TLS, stiffness reduction is accounted for through a damage variable, bearing similarity to continuum damage methods which have been around for several decades [3,4]. However, in contrast to conventional continuum damage mechanics, the TLS damage variable is not a direct function of local strain. Instead, damage is a function of the distance to a moving front that separates the damaged material from the undamaged material. This results in a band of damage with predefined width. This band moves through the domain as a thick version of the moving front known from the level set method. The width of the band introduces an intrinsic length scale in the TLS. With this length scale, pathological mesh-size dependence that is known to appear in local damage methods with softening is avoided. In the context of damage mechanics, this problem can also be addressed. The most straightforward solution to the mesh-size dependence is the crack band method [5], but this does not remove the dependence of the solution on the orientation of the mesh. More advanced solutions exist in the non-local integral damage model [6] and the gradient-enhanced damage model [7], which both introduce a length scale. A more recent alternative regularized approach to damage modeling is the phase field approach [8].

The TLS offers a new theoretical framework for the analysis of damage and fracture. An advantage that has been mentioned by Moës et al. [1,2] with respect to other regularized damage models is that the additional computational effort related to the regularization is restricted to the actual damaged zone. This stands in contrast with the non-local integral damage model which requires non-local integration throughout the domain and with gradient damage and phase field models which involve the computation of an additional field over the entire domain. The additional system of equations that needs to be solved with the TLS to update the damage distribution is only related to the damaged subdomain. Another advantage of the TLS, with respect to other continuum damage mechanics methods as well as to discontinuous methods for fracture modeling, is its algorithmic robustness. In simulations of damage and fracture processes, convergence of the Newton–Raphson method is often problematic. Especially with multiple cracks, branching and merging, this can be a critical obstacle. The TLS has been proposed with a staggered solution scheme where displacements and damage are computed alternately rather than in a single iterative procedure. This means that the computation of displacements is free from the convergence-endangering negative tangents due to softening and from the even worse sign-changes in tangent due to loading/unloading behavior.

The background of this paper is given by a study into the micromechanics of mode II delamination. On the microlevel, mode II delamination is a complex process which includes the formation of cusps or hackles [9,10]. A complex crack pattern forms with multiple cracks that eventually join up in multiple merging events. The TLS is a promising method for analysis of this process for its superior robustness and for its easy handling of topological events as branching and merging. This paper presents a study into the suitability of the TLS for simulations of mode II delamination. Several innovations with respect to the TLS are proposed for reaching qualitative agreement with experimental observations of cusp formation. The method is primarily tested on a simplified shear problem for the micromechanics of mode II delamination, but proposed innovations are also applied to other cases.

In Section 2, the TLS is reviewed and relevant details from our implementation will be provided. Then, in the two subsequent sections, two limitations of the formulation from [2] are highlighted with numerical examples and changes to the method are proposed to overcome these limitations. Specifically, Section 3 is about free sliding deformations and Section 4 about stress-based initiation.

2. The Thick Level Set method

In this section, the main features of the TLS are outlined. A summary of the global algorithm is given in Fig. 1. The TLS allows for a staggered solution scheme in which displacements and damage are computed sequentially rather than iteratively. Every time step starts with a given damage distribution that is derived from a level set field (which could also consist of zero damage throughout the domain if nucleation is considered). With the given damage distribution, displacements, strains and stresses are computed in a standard finite element analysis. This analysis is performed with a unit load. It is a linear analysis, or slightly nonlinear if different behavior of the material under tension and compression is taken into account. More on the definition of damage will follow in Section 2.1.

Next, the displacement field is used to compute configurational forces. This is done with a weak form and involves the solution of another system of equations. This second system of equations is linear and much smaller than the first