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SIMULATION OF CUSP FORMATION IN COMPOSITE MATERIALS USING THE THICK LEVEL SET METHOD

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Abstract

On the microlevel, cusps are formed during delamination crack growth under mode II loading conditions. In this work, the Thick Level Set (TLS) approach is used to simulate the cusp formation process. A plasticity model for polymers is implemented in the TLS method and a new loading scheme is devised to deal with permanent strain. A numerical test case is analysed under shear loading to mimic the fracture process which has been observed in mode II delamination growth in fiber reinforced polymer. By varying the cross-section geometry, different load-displacement behaviours and fracture morphologies are produced. The cross-section geometries considered includes variation in size and shape of longitudinal sides (grooves). The approach presented predicts the cusp formation, which begins with the initiation of a series of inclined cracks distributed along the length of the specimen, and can reach final failure.

1. Introduction

It is a widely observed fact that the fracture energy for delamination depends on the loading mode. However, much less is known on how different dissipative processes contribute to this fracture energy. The most mentioned cause for the difference in fracture energy between normal (mode I) and shear (mode II) loading is that, on the microlevel, in mode II delamination growth cusps or hackles are being formed. This process begins with initiation of an array of inclined cracks which are perpendicular to the direction of maximum principal stress. Propagation of theses cracks leads to S-shaped ligands which eventually debond from the upper or lower boundary of the resin regions in the inter-fiber spacing [1–3]. Computational models that can predict the delamination process on the microscale may lead to better understanding of the mechanism behind the variability in fracture toughness.

This works seeks to analyse the cusp formation process more realistically. For this purpose, the Thick Level Set (TLS) method as proposed in [4] is evaluated with respect to its 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. Due to plastic behavior of polymers prior to failure, the plasticity model proposed by Melro et al. [5] is implemented in the TLS framework and a new loading scheme is devised so that it allows for permanent deformation.

2. Thick level set method

The TLS to model damage growth in solids was originally proposed by Moës et al. [6, 7] in the context of continuum damage model. The model contains a non-local treatment to avoid spurious localization. This is performed by integrating local values of energy over the width of a transition zone (damage band). In this zone, the damage variable (d) is not a direct function of local strain as in conventional continuum damage models. Instead, a band of damage with a predefined length (l_c) is considered where the damage, which varies from 0 to 1, is defined as a function of level set field ϕ (Figure 1). Because the damage evolution is separated from computation of displacement, the TLS is a robust method which can handle multiple branching and merging cracks.

Van der Meer and Sluys [4] extended this continuum model by introducing a special interphase material and a strength-based initiation parameter for simulating cusp formation at the core of a sandwich in a shear test. However, this was done for a constitutive law with linear elastic behavior apart from damage growth.

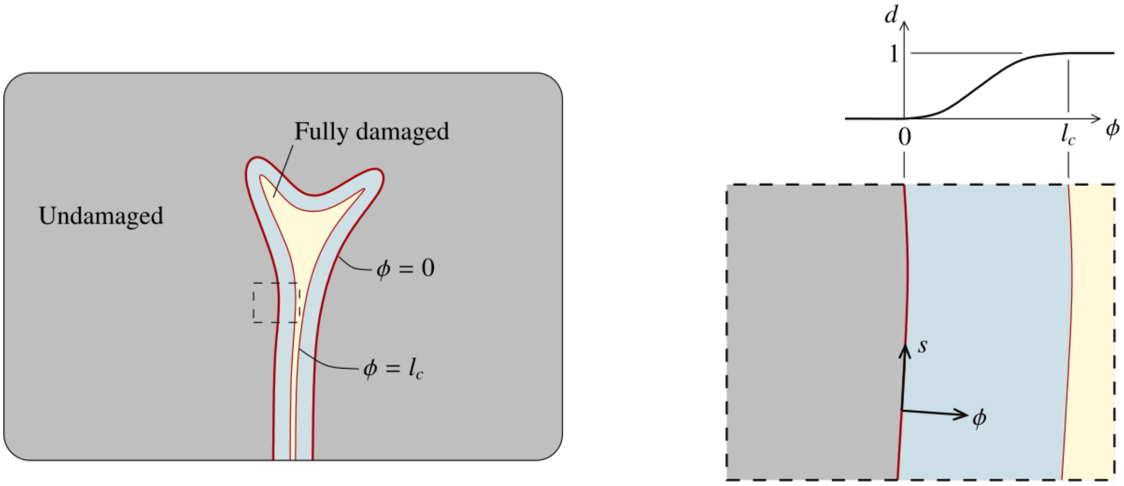


Figure 1. The Thick Level Set (TLS) method describes damage d as a function of level set field ϕ [4].

In the present work, a new loading scheme is adopted. In previous version of the TLS [4, 6, 7], the loading scheme is based on a unit load analysis in each time step, which assumes a secant unloading. Therefore, the framework of TLS must be adapted in order to include plasticity (permanent strain). In this case, the relation for front increment a_n becomes:

$$a_n = \frac{1}{\mu}\left\langle \frac{Y}{Y_c} - 1 \right\rangle_+ \tag{1}$$

where Y is the configuration force, Y_c is the material resistance to damage growth, and μ is a constant that can be interpreted as viscous resistance against crack growth. Brackets are used to denote the positivity condition, which reflects the irreversibility of crack growth.

Update of level set is then simple since level set field is defined as a signed distance function and the increment field is normal to the level set. Using forward Euler discretization, the update is performed as:

$$\phi \leftarrow \phi + a_n \, \Delta t \tag{2}$$

where Δt is the time increment computed as:

$$\Delta t = \min\left\{\Delta t_0, \; \frac{h}{2\max\{a_n\}}\right\} \tag{3}$$

Δt_0 being the default and maximum time increment and h being the characteristic size of the smallest element. In combination with a loading scheme in which the prescribed displacement for the subsequent time step can be adapted accordingly [8]:

$$u \leftarrow u + \Delta u_0 \frac{\Delta t}{\Delta t_0} \tag{4}$$

This ensure the stability of the explicit level set update and makes it possible to capture sharp load drops.

The elasto-plastic constitutive model by Melro et al. [5] is used. The paraboloidal yield surface is capable of accounting for different tensile and compressive yield strengths with independent hardening curves. The paraboloidal yield criterion requires the experimental determination of both tensile and compressive yield strengths of the bulk material, as well as their evolution with relation to the equivalent plastic strain. The difference in terms of performance between the TLS versions for a typical shear test setup is shown in Figure 2.

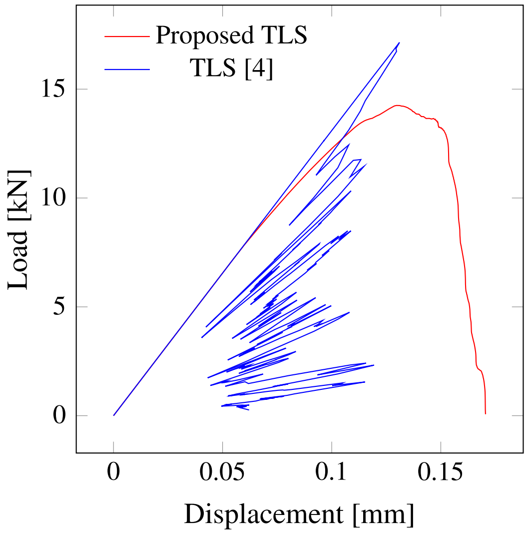


Figure 2. Load-displacement response for both current and proposed TLS framework in a typical shear test.

3. Results

The test case in this work is inspired by rail shear test simulated by Van der Meer and Sluys [4] as a model for mode II delamination. The case consists of a sandwich with stiff faces and a weak core (Figure 3).

The faces are loaded in opposite direction such that the core is sheared. This setup tries to mimic the delamination process in composites, where the stiff faces represent the plies and the core represents the resin-rich region around the ply interface. In addition, three different cross-sections are considered as depicted in Figure 5. These variations in cross-section concept are identical to those of the specimens that have been observed to produce cusp-like features on Polyvinylchloride (PVC) foam material as reported in [3]. The curvature and width of profiles mimic the influence of fiber radius and the inter-fiber spacing respectively in composites.

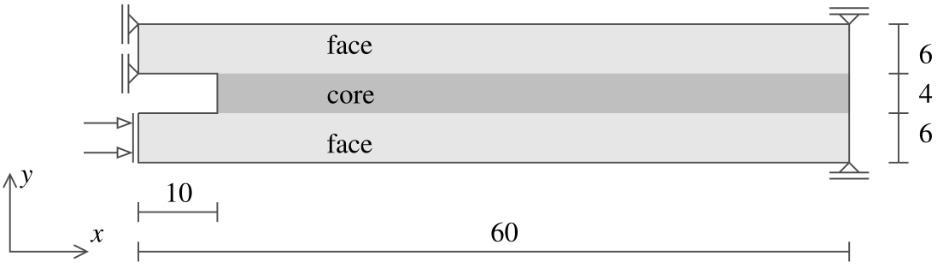


Figure 3. Rail shear test (dimensions in mm) [4].

Young's modulus, Poisson's ratio and fracture energy of the core material are, respectively, $E = 3760$ MPa, $\nu = 0.3$ and $G_c = 0.9$ N/mm. For plasticity, a plastic Poisson ratio of 0.39 is used and the fundamental hardening curves are given in Figure 4 [4, 5]. For the face material, the properties are $E = 200 \cdot 10^3$ GPa, $\nu = 0.3$ and $G_c = 1.8$ N/mm.

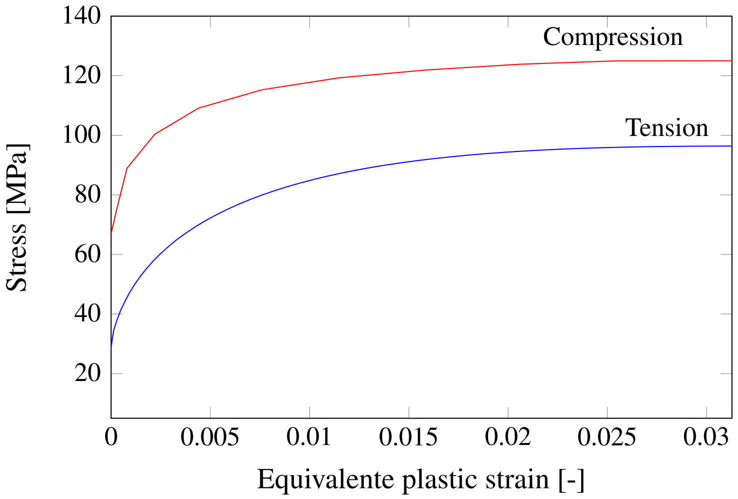
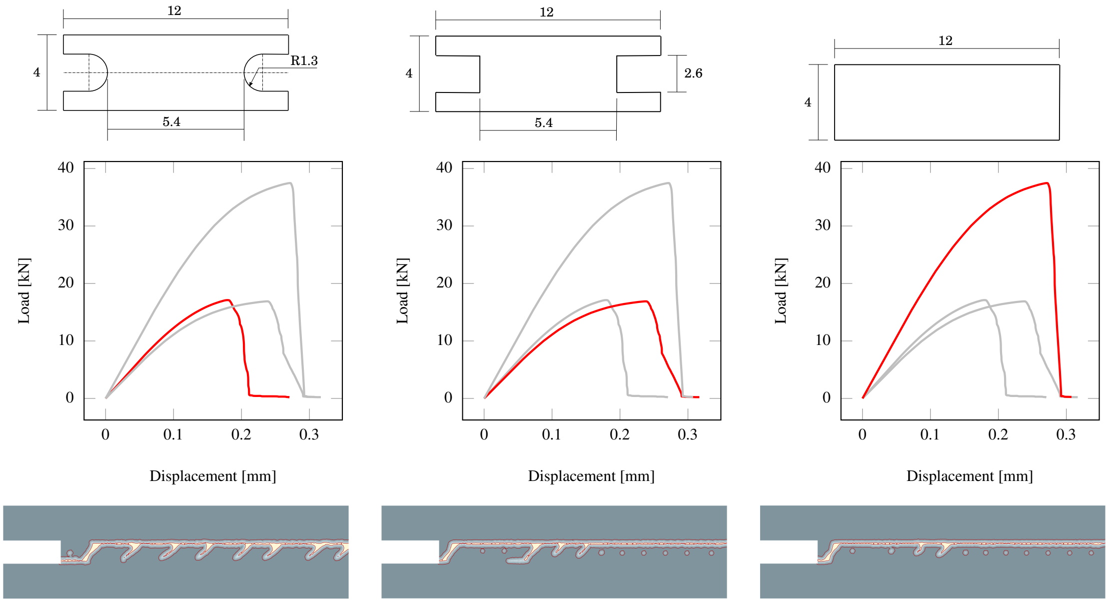


Figure 4. Input hardening curves for plasticity model.

As shown in Figure 5, the change in profile shape has a considerable influence on the fracture morphologies and equilibrium curves. For the curved configuration, it is evident that a number of randomly spaced S-shaped cracks along the specimen length, which eventually coalesced to form cusps, is larger than square and flat configurations. Rogers [3] reported the same trend for PVC foam specimens in shear loading. The initial stiffness of the flat specimen is higher than the curved and square configuration because of the flexibility that is introduced by side grooving and falls off rapidly after the maximum load. Cusp development comparable to that in composites is more pronounced in curved-profile configuration only, suggesting that the curvature of fibers plays an important role in cusp formation.



(a) Curved (b) Square (c) Flat

Figure 5. Cross-section profile (dimensions in mm), load-displcament curve and crack distribution for Curved (a), Square (b) and Flat (c) configurations, respectively.

4. Conclusions

Two improvements are added in the most recent version of TLS method to model cusp formation under mode II delamination: the elasto-plastic constitutive model for epoxy resin by Melro et al. [5] is combined with the TLS damage formulation and a new loading scheme to take into account permanent strain and be used along with displacement control method.

By varying the profile geometry of the core, different load-displacement curves and fracture morphologies were produced. Cusp development comparable is more pronounced in curved-profile configuration only. In this study, cusps formed via the propagation and coalescence of S-shaped cracks that initiated as a series of parallel cracks along the model length.

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