Towards the mesh insensitive modeling of composite damage in an explicit crash simulation

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ABSTRACT

The usage of advanced composite materials is a fundamental step towards the energy efficient design and construction in broad range of industrial applications. However, this requires a profound knowledge about the nonlinear macroscopic properties of the material, which is among others driven by inelastic material behavior of the individual constituents and a variety of characteristic damage mechanisms. Especially for safety relevant parts this includes a reliable modelling of the post critical softening behavior of the material. Since a direct modeling of the microscopic and mesoscopic material structure is not feasible in numerical analysis of a composite part, robust effective material models need to be applied. To this end, a hybrid composite material model has been developed. The present contribution aims to summarize the fundamental ideas and formulations. The constitutive model is subsequently used for a multitude of numerical examples.

1. INTRODUCTION

The proper modelling of damage and failure mechanisms of composite materials is mandatory for the CAE based design of lightweight structures. The macroscopic effects of multiple damage mechanisms is caused by a gradual development over the characteristic length scales of the material (cf. Figure 1). For common fiber reinforced polymers, the material degradation starts at the microscale in terms of cracks in the matrix phase and at its interface to the embedded fibers. Such localization regions evolve under further loading and spread on the mesoscale over the roving boundaries. A coalescence of such cracks finally cause the failure of the macroscopic composite part.

Due to the discrepancy in length scale it's not feasible to model these microscopic structure on the macro scale. Effective, homogenized damage and failure models are commonly used instead. While classical failure models [2] aim to detect the point of damage initiation, more advanced continuum damage approaches [3] also allow for a prediction of the post critical softening regime. However, such continuum based models suffer from a conditional mesh dependence [4].

In order to circumvent this drawback, a multitude of advanced approaches are presented in the literature. Without the claim of completeness, the most common approaches can be classified as nonlocal continuum formulations [5, 6] and advanced discretization techniques such as the extended finite element method (XFEM) [7]. Since all of these methods suffer from certain drawbacks that prevent a large scale application,

Excerpt from ISBN 978-3-00-053387-7

for instance in a crash analysis. An intermediate solution has been found in the formulation of a hybrid continuum/cohesive composite material model. The approach is based on the ideas given in [8] and has been extended by Pineda and Waas [9].

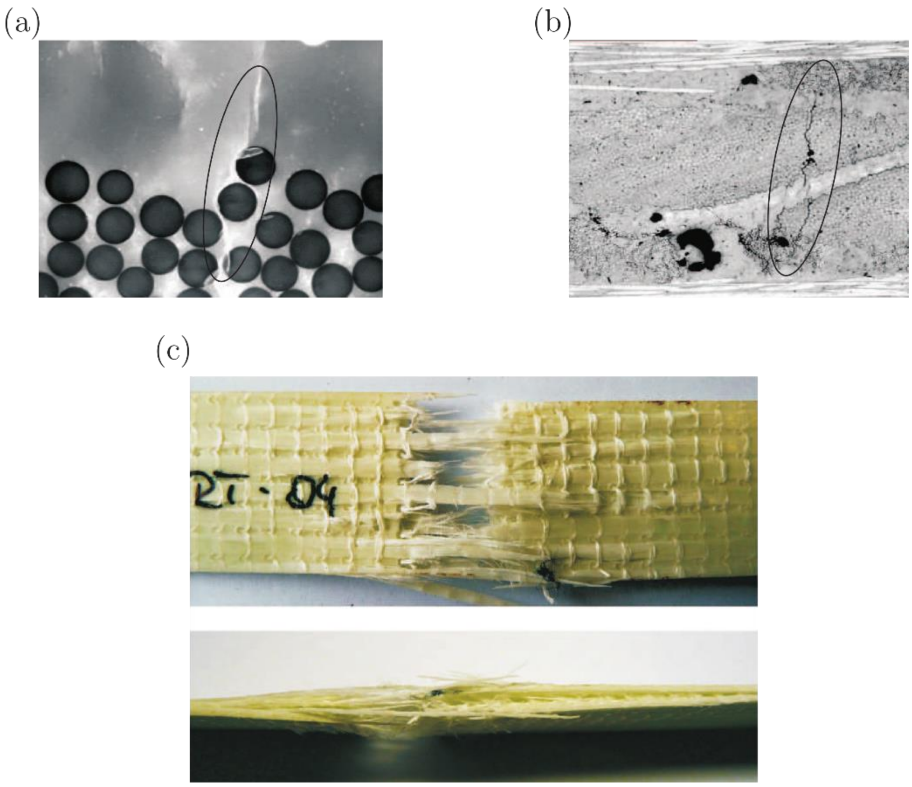

Figure 1: Damage regions in glass fiber reinforced polyproylene on the: (a) micro scale, (b) meso scale and (c) macro scale [1].

2. MODEL DESCRIPTION

The fundamental assumption of the implemented composite material model is the internal transition from a continuum formulation to a cohesive like constitutive relation (cf. Figure 2).

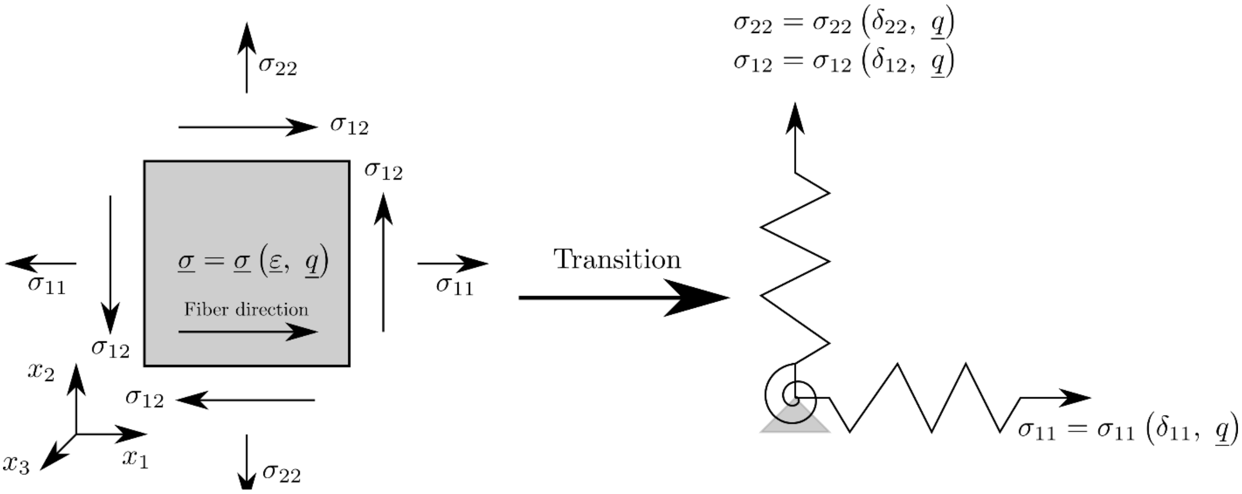

Figure 2: Transition from a continuum to a cohesive formulation.

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The transition from continuum stress strain relations to cohesive traction-separation laws is accomplished once individual criteria for fiber failure and in-plane matrix and shear failure are met. Fiber damage is initialized based on the definition of a critical tensile X_T and compression X_C strain.

$$\left(\frac{\varepsilon_{11}}{X_T}\right)^2 = 1 \; for \; \varepsilon_{11} \geq 0$$

$$\left(\frac{\varepsilon_{11}}{X_C}\right)^2 = 1 \; for \; \varepsilon_{11} < 0$$

Matrix and in-plane shear damage are initialized by a combined failure criteria defined by a critical matrix tensile Y_T and compression Y_C strain as well as a critical in-plane shear strain Z.

$$\left(\frac{\varepsilon_{22}}{Y_T}\right)^2 + \left(\frac{\gamma_{12}}{Z}\right)^2 = 1 \; for \; \varepsilon_{22} \geq 0$$

$$\left(\frac{\varepsilon_{22}}{Y_C}\right)^2 + \left(\frac{\gamma_{12}}{Z}\right)^2 = 1 \; for \; \varepsilon_{22} < 0$$

The constitutive relation prior damage is free of choice. In the current version of the model an elasto-plastic formulation is used.

Once the above mentioned failure conditions are met, the continuum constitutive relations for the in-plane stresses are replaced by traction-separation laws. In the case of linear degradation, the in-plane stresses are given by

$$\sigma_{11} = \left|\sigma_{11}^C\right| \mathrm{sign}(\varepsilon_{11}) \left(1 - \frac{\left|\sigma_{11}^C\right| l_e^f \left(\lambda_{11} - \left|\varepsilon_{11}^C\right|\right)}{2G_{IC}^f}\right),$$

$$\sigma_{22} = \left|\sigma_{22}^C\right| \mathrm{sign}(\varepsilon_{22}) \left(1 - \frac{\left|\sigma_{22}^C\right| l_e^m \left(\lambda_{22} - \left|\varepsilon_{22}^C\right|\right)}{2G_{IC}^m}\right),$$

$$\sigma_{12} = \left|\sigma_{12}^C\right| \mathrm{sign}(\gamma_{12}) \left(1 - \frac{\left|\sigma_{12}^C\right| l_e^m \left(\lambda_{12} - \left|\gamma_{12}^C\right|\right)}{4G_{IIC}^m}\right).$$

Here, σ_{ij}^C and ε_{ij}^C are the stresses and strains at damage initiation. The subsequent degradation is controlled by the characteristic element length l_e^m and l_e^f, the energy release rate for the individual failure modes G_{IC}^f, G_{IC}^m and G_{IIC}^m as well as the internal history variables λ_{ij}. The inclusion of the mesh size in combination with the length dependent energy release rate leads to the a characteristic length for the softening behavior. The loading parameters λ_{ij} assure the irreversibility of the degradation and are defined by

$$\lambda_{ij} = \max_{0 \leq \tau \leq t}\left(\left|\varepsilon_{ij}(\tau)\right|\right).$$

The influence of the failure and damage parameters on the individual stress-strain relations is shown in Figure 3 for the case of linear degradation. In the case of unloading (e.g. $\left|\varepsilon_{ij}\right| < \lambda_{ij}$) the secant stiffness of the maximum damage point is used for a linear elastic stress-strain relation.

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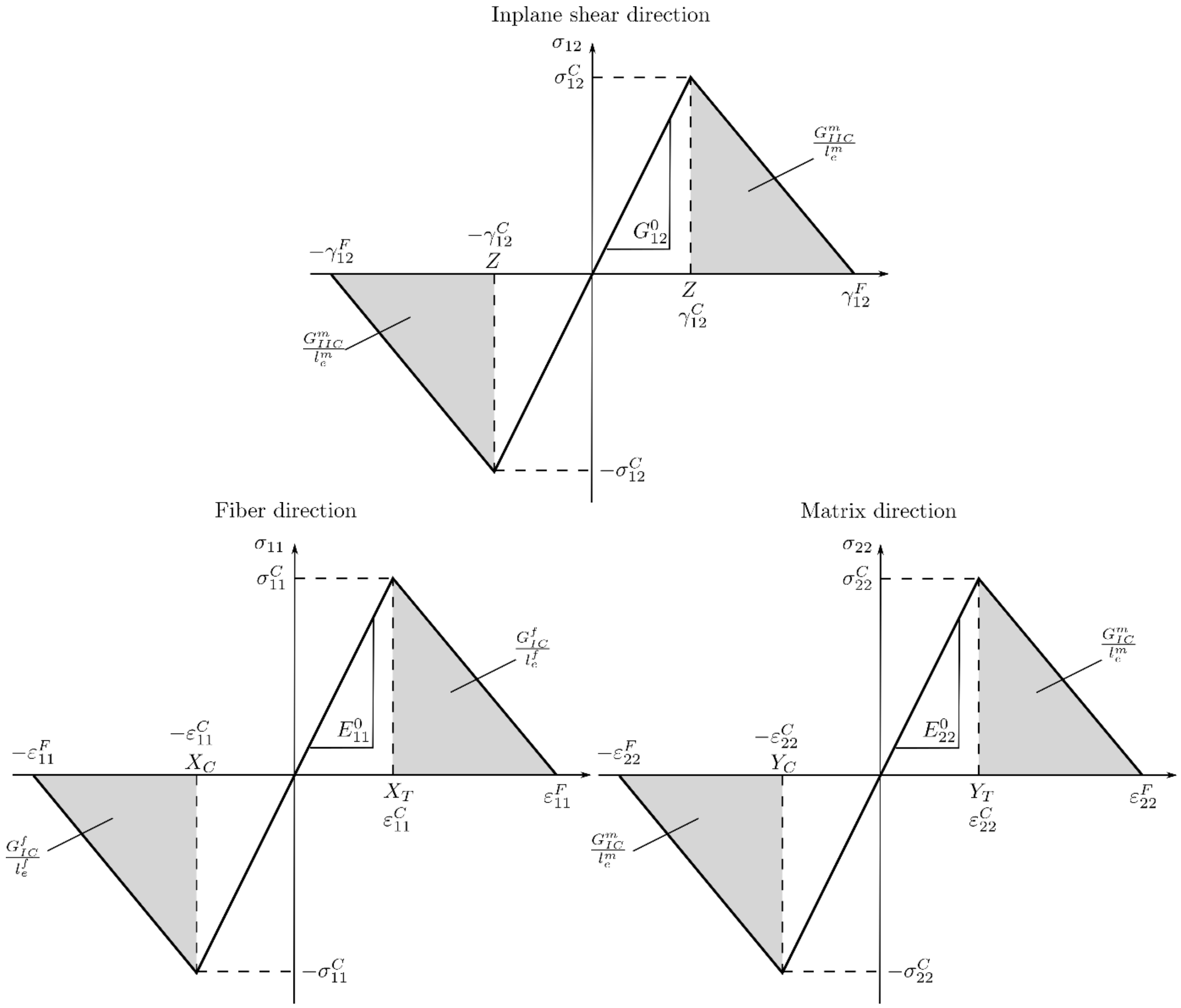

Figure 3: Stress-strain pattern for the hybrid continuum/cohesive composite damage model.

3. MODEL EVALUATION

In a first step the derived model is evaluated in a simple tensile test as shown in Figure 4.

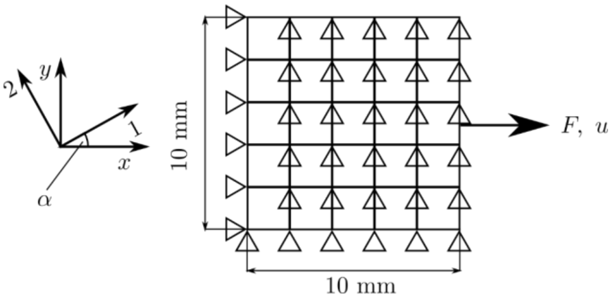

Figure 4: Tensile test - model setup.

The model is analyzed using four different mesh densities (element length h = 5, 2.5, 1.25, 0.625 mm). The structure is loaded monotonically by prescribing the nodal displacement in x direction at the positive x side of the model.

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The material parameters that are used have been chosen to model a unidirectional reinforced composite material (e.g. carbon fiber, epoxy). An equivalent set of parameters has been identified for a standard continuum damage model (Ladevèze).

For an angle of α = 0° (tension in fiber direction) and a single element with an edge length of h = 10 mm the resulting force-displacement curves are given in Figure 5. In a qualitative manner, both models show a similar post-critical softening behavior. Refining the model using the above mentioned element sizes, subsequently leads to the force-displacement curves given in Figure 6. We notice that the continuum based Ladevèze approach shows a strong mesh dependence whereas the cohesive based softening of the hybrid model is mesh insensitive due to its internal characteristic length scale.

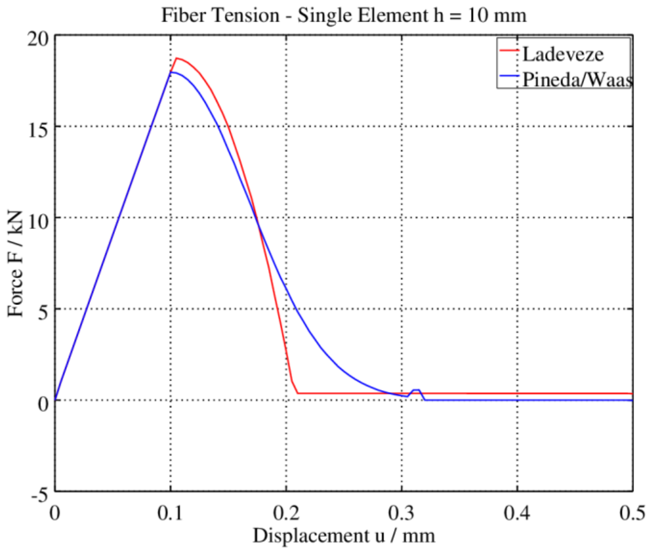

Figure 5: Comparison of the Ladeveze and the hybrid Pineda/Waas model response for fiber tension in a single element.

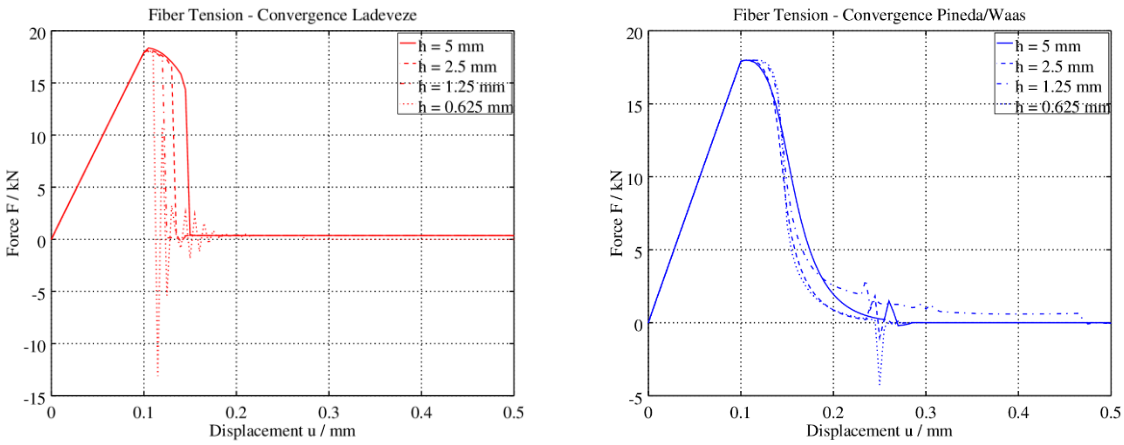

Figure 6: Comparison of the Ladeveze and the hybrid Pineda/Waas model response for fiber tension and varying mesh densities.

The same behavior is obtained analyzing a tensile loading in matrix direction (α = 90°). The resulting force-displacement curves of a single element and different mesh densities are given in Figure 7 and Figure 8, respectively.

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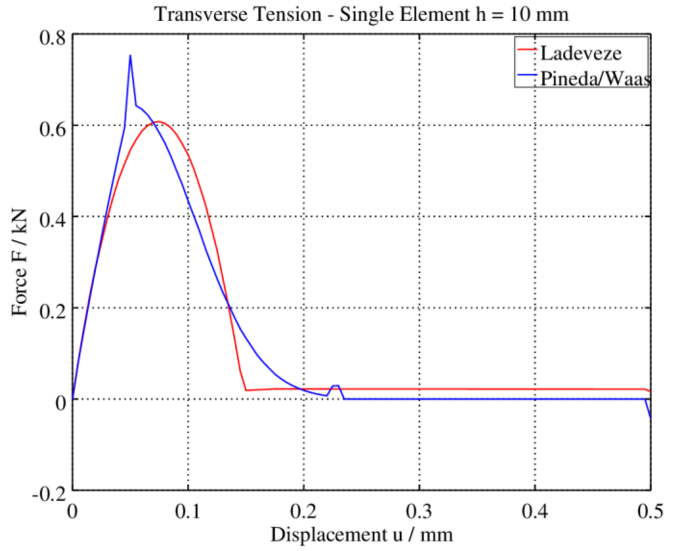

Figure 7: Comparison of the Ladeveze and the hybrid Pineda/Waas model response for matrix tension in a single element.

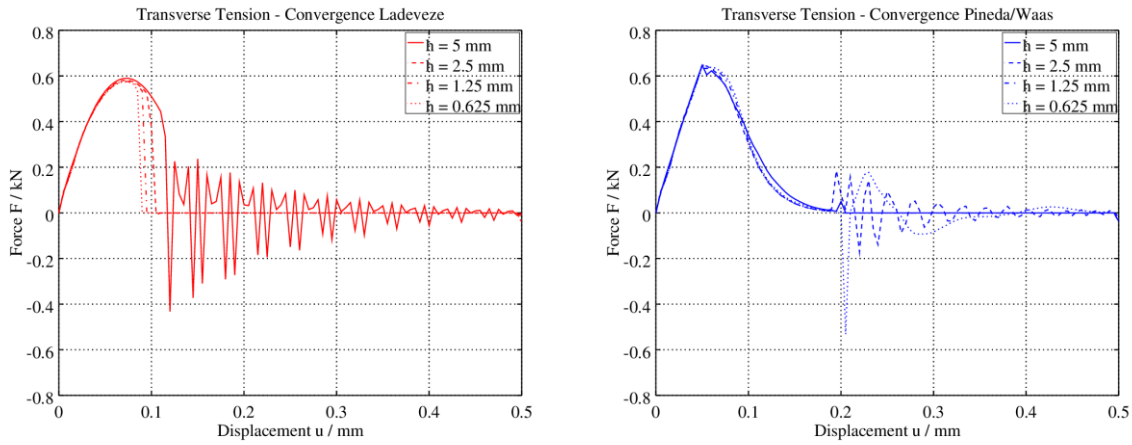

Figure 8: Comparison of the Ladeveze and the hybrid Pineda/Waas model response for matrix tension and varying mesh densities.

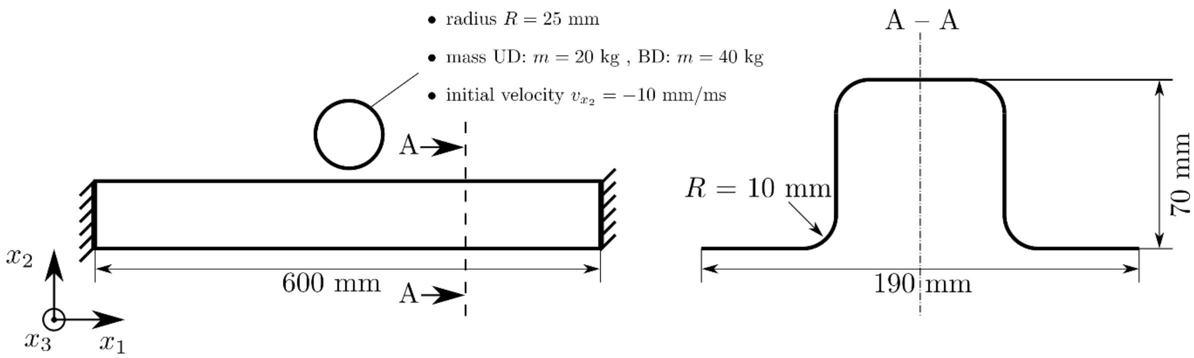

Figure 9: Hat profile crash test - model setup.

Finally, the derived material model is evaluated in an idealized crash simulation. To this end, a composite hat profile is impacted by a rigid tube as shown in Figure 9. Again two different lay-ups, as given in Table 1, have been analyzed. The given layer angles are with respect to the longitudinal axis of the profile.

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Table 1: Lay-up configurations for the hat profile crash test.

ID	Stacking sequence	Thickness / mm
Laminate 1 (unidirectional - UD)	$[0°]_8$	4.0
Laminate 2 (bidirectional - BD)	$[0° / 90° / 0° / 90°]_S$	4.0

The same material parameters as in previous test case have been used in order to allow for a comparison with a standard continuum damage model (Ladevèze). The mesh sensitivity of the results has been analyzed based on three distinct mesh densities with an element edge length of h = 10, 5, and 2.5 mm.

In a first step the performance of the unidirectional Laminate 1 is analyzed. The resulting force-displacement curves of the impactor are shown in Figure 10, both for the Ladevèze and the hybrid Pineda/Waas model. It can be seen that for the hybrid Pineda/Waas model the contact force as well as the impact distance is insensitive with respect to the used mesh size, whereas the results of the continuum damage model (Ladevèze) show no convergence upon mesh refinement.

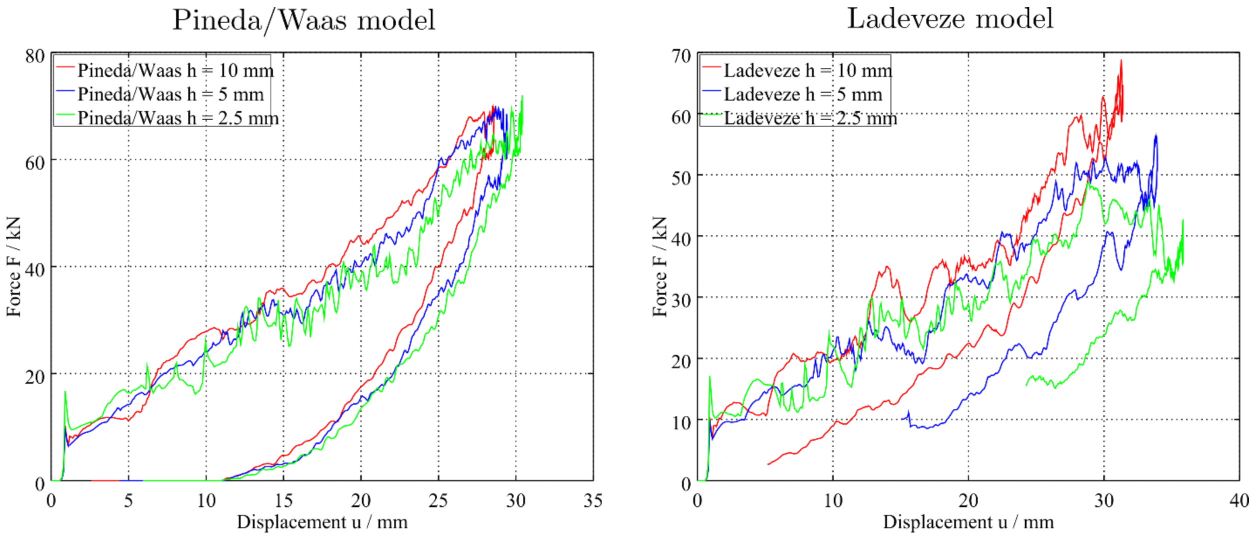

Figure 10: Hat profile crash test - Laminate 1: Contact force vs. crash distance for three distinct mesh sizes.

Analyzing the second, bidirectional Laminate 2, the force-displacement curves given in Figure 11 are obtained. The increased stiffness due to the bidirectional layup leads to a reduced impact distance. However, still the continuum damage model shows a slight variation of the force level for the three different mesh densities, whereas the hybrid Pineda/Waas model again assures converged results independent of the mesh size.

4. CONCLUSION

An advanced composite damage model has been formulated and implemented. The hybrid approach allows for an internal transition from a continuum formulation to a cohesive formulation at the point of damage initiation.

The model has been evaluated for simple uniaxial test cases as well as for an advanced crashing model. In both cases it showed superior performance over a standard continuum damage model in terms of mesh insensitivity.

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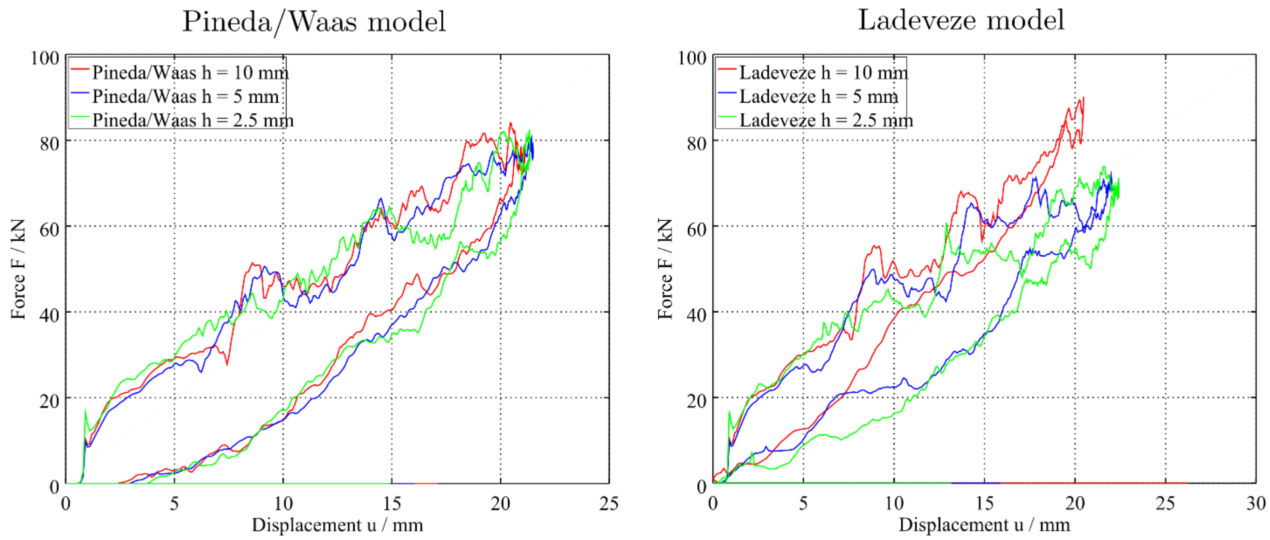

Figure 11: Hat profile crash test - Laminate 2: Contact force vs. crash distance for three distinct mesh sizes.

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