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A FINITE ELEMENT MODEL OF DELAMINATION IN CROSS-PLY LAMINATES

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Abstract. A finite element model was developed for the modelling of progressive delamination in a cross-ply laminate made of polymer composite layers with continuous fibres. Three-dimensional solid elements were used to model the orthotropic layers in the macromechanical model. The delamination was initiated by a sharp notch, which was placed at the center part of a rectangular composite plate. The in-plane load was tension, applied incrementally in time. The delamination process was modeled by the help of a meso-scale finite element model, and special interface elements were used in the vicinity of notch tip between the layers. The solid interface elements with special material behavior were applied to model damage progression during the delamination of layers. The analysis predicted a narrow delamination zone at the notch tip, also verified by experimental measurements.

Mathematical Subject Classification: 74A40, 74A45
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1. Introduction

Damage in fibre-reinforced composites exhibits a wide range of forms. Various failure modes, which can occur in long fibre composites, were described by Cantwell and Morton [1]. One of the most frequent modes of failure is delamination, which could lead to overall damage of the composite structure. Several kinds of approaches can be found in the literature on this problem. Some authors treat the damage zone as a crack, and apply methods of fracture mechanics. An early work was presented by Griffith et al. [2], who investigated the splitting in a $0°$ lamina due to tension. Another way is a progressive damage modeling, which predicts the effect of notch size on tensile strength and the behaviour of different lay-ups. Chang and his co-worker [3] applied this method to model the damage process. An energy approach was also used in some models, when the strain energy release rate was investigated during the delamination. A quite new and effective method is the interface modeling approach, which is applied in various finite element models. Special interface elements were used to model the progression of delamination between layers under investigation (Mi et al. [4]). This method was also applied by Wisnom and Fu-Kuo Chang [5], creating a macro-mechanical model of a notched rectangular plate. Plane stress elements were to represent the plies in the cross-ply laminate, and 2 node non-linear interface elements were to represent the behavior of the inter-laminar matrix and to model the splitting and delamination at the notch tip.

In the present paper a rectangular composite laminate with lay-up [90/0]S is investigated, and there is a sharp notch at the center (see Figure 1). The notch is extended along all the four layers, and has no gap before loading. The in-plane load increases tension load parallel to x-axis and perpendicular to the notch. First a macro-scale FE model is created to determine the overall behavior of the rectangular plate. Next a meso-scale FE model is applied in the vicinity of notch tip. The finite element analysis is used for modelling the damage process. According to the above mentioned earlier investigations and experimental measurements by Spearing and Beaumont [6], two kinds of damage occur: an axial split of 0° layer and a delamination are progressing near the notch tips. The aim of the analysis is to determine the relationship between the axial load and the extent of the damaged area.

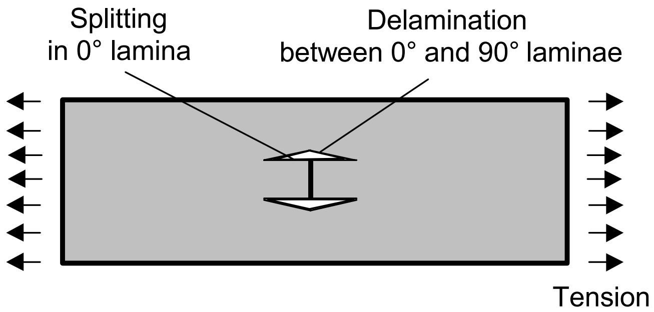

Figure 1. Splitting and delamination in the laminate

The arrangement and dimensions of the plate are given in Figure 2. The x-y plane is the mid-plane of the plate. This structure has three planes of symmetry, therefore

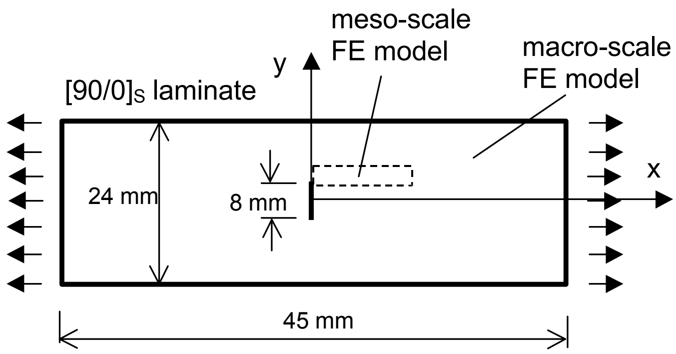

Figure 2. The notched laminate and the FE model

only one eighth of the total is modelled in the macro-scale analysis. The symmetric mechanical mechanical behavior is ensured by kinematic boundary conditions along the planes of symmetry. The macro-mechanical model consists of two orthotropic layers of 0.14 mm thickness each, which are meshed by 8 node 3D solid elements (see Figure 3).

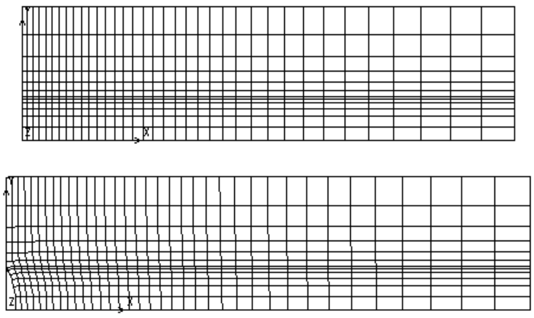

Figure 3. Undeformed and deformed meshes of macro-scale model (hundredfold distortion is for displacements)

The material properties are orthotropic linear elastic ones, for T300/914 composite with 60% fibre volume fraction: $E_{11} = 135$ GPa, $E_{22} = E_{33} = 9.6$ GPa, $G_{12} = G_{13} =$ 5.8 GPa, $G_{23} = 3.1$ GPa, $\nu_{12} = \nu_{13} = 0.31$, $\nu_{23} = 0,38$. This model does not consider any damage process; it is to help the proper selection of borders for the meso-scale analysis. Moreover, the stress-concentration near the notch tip - responsible for split and delamination - can be studied this way.

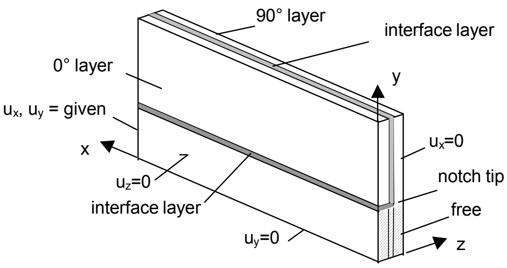

Figure 4. The meso-scale model with the kinematic boundary conditions

The meso-scale model relates to the part of the notch tip, where the damage is expected. It consists of 90^o and 0^o layers of 0.125 mm thickness each, and an interface layer of 0.03 mm is between them for modeling the delamination. Within the 0^o layer, another interface strip of 0.03 mm is placed for modeling the splitting (see Figure 4). Both composite layers and the interface layers are meshed by 3D solid elements with 8 nodes. The composite layers have linear elastic, orthotropic properties with the same elastic constants as in the macro-scale model. The interface elements have isotropic, elasto-plastic damage material properties. Its elastic behaviour is as for matrix material, plastic yield limit is determined by matrix material yield test. The elasto-plastic deformation in the interface is limited until the strain energy density reaches its critical value. This is determined by the fracture energy density, forming an area under the material curve (Figure 5). As the splitting and delamination processes are controlled by mode II and mode III shear stresses, the fracture energy for those modes is applied in the computation. Referring to Spearing's measurement [6], 0.4 N/mm fracture energy per unit area is applied. The common nodes of the interface elements and the composite elements work together until the damage occurs. After having been damaged, the nodes become inactive, the nodal forces vanish for the interface elements involved.

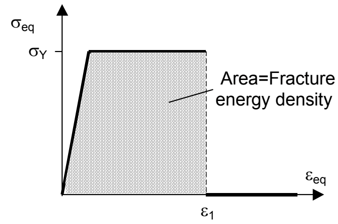

Figure 5. The meso-scale model with the kinematic boundary conditions

The kinematic loads on the surfaces of the meso-scale model are determined by using the macro-scale model, and are applied incrementally starting from zero. Non-linear static analysis was applied, using Cosmos/M software. An external procedure was created for evaluation of the damage criterion of the interface elements, and for modification of the state (from active to inactive) of the damaged nodes, and for restarting the computation. For each load increment, an iteration is necessary to reach an equilibrium.

2. **Results**

The splitting process starts at the notch tip when the tension load is quite low. Due to the delamination, the damaged nodal points form an increasing narrow, triangular

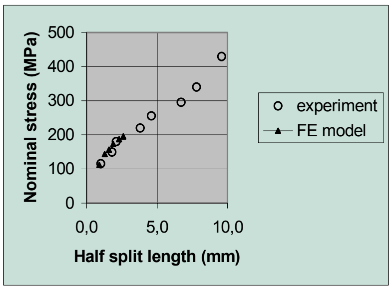

Figure 6. Relationships between half split length and nominal axial stress in the 0 $^\circ$ layer, far away from the notch

domain at the notch tip as it was detected by experimental measurement [6] (see Figure 1). As the model dimensions and material behavior parameters in this finite element model were very close to those in the measurement, it became possible to compare the experimental and computational results. The relationship between the half split length and nominal stress (that is x in the 0^o layer, far from the notch) is shown for both cases (Figure 6). According to this diagram, the correlation between the computed and measured values is good.

3. **Concluding remarks**

Macro- and meso-scale finite element models were created for a rectangular plate made of cross-ply laminate with a notch in the center. Using an interface element approach, our models were available for modelling the synchronous damage processes at the notch tips (that is splitting in the 0° layer and delamination between 0° and 90° layers). While other researchers, like Mi et al., [4] applied 4 node solid elements, or Wisnom et al., [5] did 2 node elements, we followed the damage processes by 8 node solid finite elements. The interface elements had special elasto-plastic damage material properties to describe the progressive splitting and delamination. Our model was also suitable for predicting the extent of the damaged domain as function of tension load. The shape and the extent of the delaminated region are in good agreement with the experimental measurement, known from the paper by Spearing and Beaumont [6].

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