MODELING TRANSVERSE CRACKING IN LAMINATES WITH A SINGLE LAYER OF ELEMENTS PER PLY

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Abstract

This study aims to bridge the gap between classical understanding of transverse cracking in $[0/90]_s$ laminates and recent computational methods for the modeling of progressive laminate failure. Specifically, the study investigates under which conditions a three-dimensional model with cohesive cracks can reproduce the in situ effect for the ply strength. Subsequently, it is shown that it is possible to reproduce matrix cracking with a single element across the thickness of the ply, provided that the interface stiffness is properly selected. By using an interface stiffness that is inversely proportional to the ply thickness, a shear lag deformation is achieved that is equivalent to the opening deformation of a transverse matrix crack.

1 Introduction

The fidelity of progressive damage analysis of laminated composite structures has improved dramatically with the application of the extended finite element method (X-FEM), which provides a tool for the direct insertion of transverse matrix cracks in directions that are independent of mesh orientation [1-3]. Failure analyses with X-FEM are most often performed at the mesolevel, in which each ply is represented by a homogeneous orthotropic material. To capture the proper sequence of load redistributions that result from interactions between matrix cracks and delaminations, each ply must be modeled with separate elements. Therefore, the minimum mesh requirement consists of a single layer of element across the thickness of each ply and a layer of cohesive elements between the plies.

Few developers, if any, have attempted to use more than one element over the thickness of a ply because the computational requirements associated with such small elements render intractable any analysis larger than a small coupon. However, the elliptical opening profile of a transverse crack cannot be represented with a single element.

The main objective of the present study is to investigate the ability of mesolevel X-FEM models with a single layer of elements per ply to capture accurately all aspects of matrix cracking. In this paper, we examine to what extent the model can predict the in situ ply thickness effect on crack initiation and propagation. A follow-up study will include the crack

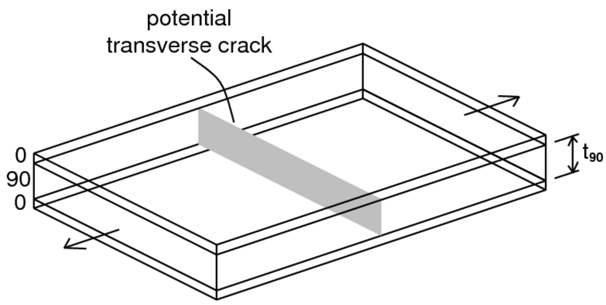

Figure 1. Cross-ply laminate loaded in tension.

density as a function of stress, the stress level for crack saturation, and the interaction between delamination and transverse cracks.

Analyses of $[0/90]_s$ cross-ply laminates subjected to tensile loads are performed. A detailed three-dimensional model composed of several elements through the thickness of each ply is used to obtain the reference solution. In this model, matrix cracks are inserted discretely using X-FEM. The reference results are compared with those obtained with a simplified model in which the thickness of each ply is represented by a single element.

Much attention is given to the detailed model for the reference solution, because advanced numerical methods have never before been applied in such detail to the classical case of transverse cracking in cross-ply laminates. Dedicated analytical models are available to predict the in situ effect [4-5] and the crack progression [6-7], but the extent to which state-of-the-art computational methods can also predict the experimentally observed phenomena has not been properly addressed. One exception is the work of Maimí et al [8] who applied a continuum damage model to model progressive failure in cross-ply laminates. Good agreement with experimental observations in terms of stiffness change during progressive cracking was reported. However, crack propagation in the transverse direction, which is crucial for the in situ effect, was not included in the validation of that model.

This paper is organized as follows. Firstly, the model is briefly described. Secondly, it is examined whether the inhomogeneity of the cross section can be represented for crack initiation. Thirdly, the full three-dimensional model is applied to reproduce the in situ effect. And fourthly, a study is presented on whether it is possible to obtain the same quality of results with a simplified model composed of a single element over the thickness of the ply.

2 Model description

Initiation and propagation of a single transverse crack in a cross-ply laminate is modeled (see Figure 1). The transverse crack is inserted as cohesive X-FEM crack following Van der Meer and Sluys [1]. Delamination is not considered. However, further on in the paper, elastic deformation of the ply interface will be included. There, the interface will be given a constant stiffness K, which is similar to the penalty stiffness normally used in cohesive laws for the initial undamaged state (see e.g. [9]). Material parameters are those reported by Dvorak and Laws [4] for T300/934, with reference to the experiments by Crossman and Wang [10,11]. The in plane dimensions of the simulated domain are 20 by 10 mm^2 and the layup is $[0_2/90_n]_s$ where the thickness of the 90_n block is varied. At least 10 elements are used over the thickness of the transverse ply. Furthermore, a dissipation-based arc-length solver is used for robust analysis [12].

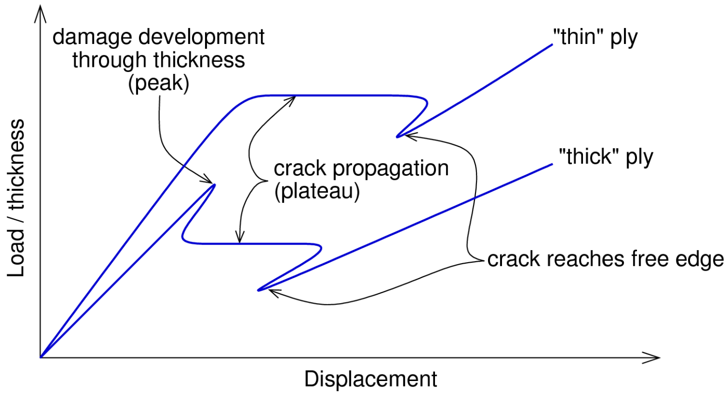

Figure 2. Schematic representation (with exaggerated stiffness loss) of load-displacement relations.

To introduce some of the key features for the discussion of the results, an illustration of the global response is given in Figure 2. Schematic load-displacement graphs are shown with exaggerated stiffness loss. The distinction between thick and thin ply behavior as introduced by Dvorak and Laws [4] is visible in the global response. In the thin ply case, the in situ strength is related to stable crack propagation in transverse direction at a constant load level. In the thick ply case, however, the in situ strength is related to a peak load followed by unstable development of damage through the thickness of the transverse ply. When the equilibrium path is followed through the snapback, a plateau with stable crack propagation is eventually also found in the thick ply case. The stress level at which the peak occurs is independent of the ply thickness, while the plateau rises for decreasing ply-thickness. The thickness for which the plateau has the same stress level as the peak marks the transition between the thick and the thin ply regimes.

3 Initiation with randomness

The in situ strength is understood as the stress level at which a pre-existing defect in the transverse ply develops into a crack. Because of the importance of pre-existing defects for this phenomenon, it is unlikely that a model that does not account for inhomogeneity in the cross section would be able to predict the in situ effect correctly. In this section, three different strategies to generate inhomogeneous fields for the strength and/or toughness (see Figure 3) are compared:

a) This method consists of assigning an uncorrelated (scattered) random strength to each element in the cross section that may be cracked (cf. [8]). The randomness conforms with the very short length scale of stress variations in the transverse ply which are of the order of the fiber diameter – smaller than the size of the finite elements in the present simulations. However, this approach results in mesh-size dependence because the size of the weak spots is equal to the element size. Moreover, the principle stating that elements in a finite element model should be several times smaller than typical variations in the solution is violated.
b) The second option is to use a correlated random field. This field requires a length scale as input – which is hard to relate to reality – but it results in a numerical model that is more well-posed than the scattered field because the input field exists independently of the mesh.
c) The third option is to define a single weak spot. Choices have to be made for the size and shape of the weak spot as well as for its depth. This approach is less predictive because the defect has to be placed at location selected a priori. For the present purpose, however, this may be acceptable since it is known that the transverse cracks grow from the free edge.

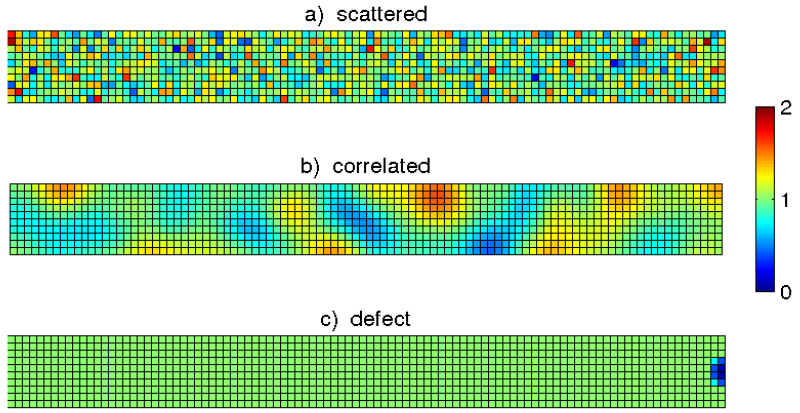

Figure 3. Scaling fields for strength (and possibly fracture toughness) with three different strategies.

Given a certain inhomogeneous scaling field, there is the question of whether it should be applied to strength and/or to toughness. If the weak spot is understood as a void or cluster of voids it is sensible to apply the same reduction to both strength and toughness, whereas when the variations in strength are understood as representing variations in the stress field due to unequal fiber distribution it is more reasonable to apply variations to strength only.

Simulations have been performed to test the different strategies for inhomogeneous fields with a transverse ply thickness of 1 mm (corresponding to a $[0_2/90_4]_s$-layup with elementary plies of 0.125 mm). Because the stiffness loss due to the transverse crack is minimal, the response is visualized by means of load-dissipation graphs, rather than the more usual load-displacement, i.e. the total energy dissipation is used on the horizontal axis. Load-dissipation plots for six different cases are shown in Figure 4: the three different fields described above are each applied firstly to scale only the strength, and secondly to scale both strength and toughness.

Several observations can be made from Figure 4. The case with $t_{90} = 1$ mm is a thick ply case, which can be observed from the sharp load drop that follows the initial peak in all cases. The load drop occurs when damage around the weakest spot of the cross section propagates through the thickness. In the case with the single defect, the load drop is followed by a clear plateau of approximately constant load, representing the phase at which the crack grows from

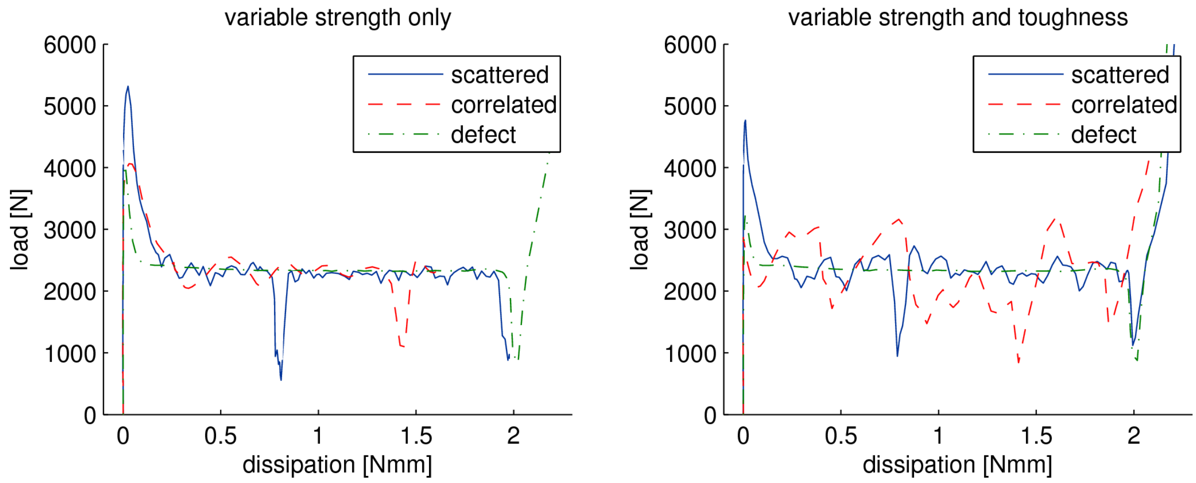

Figure 4. Development of load-level during simulation with spatially varying properties according to the three different fields in Figure 1.

the defect to the opposite boundary. This plateau is the load level that corresponds to the theoretical thin ply strength. Also for the cases with random strength distribution, this propagation load level is retrieved, although there are oscillations around it. These oscillations are much more pronounced when the fracture toughness is also varied, as the toughness is the key parameter for the thin ply propagation stress level. The most pronounced load drops correspond with phases in the simulations where the crack reaches a free edge.

The height of the initial peak is the most important output value of these simulations because it corresponds to the stress level at which the crack would appear in reality and, hence, defines the in situ strength. The particular choice for the inhomogeneous property fields is of great influence on this value. It is in all cases determined by the weakness of the weakest patch of several neighboring elements. The scattered field therefore gives the highest initial value. Varying toughness along with the strength leads to a decrease in the peak load level because damage in the weakest spot develops faster.

The main conclusions in this section are that the type of variation does not influence the averaged propagation stress level (thin ply in situ strength) while it does influence the peak load level (thick ply in situ strength). None of the cases reveal how the characteristics of the variation should be related to the real microstructure, but in all cases there is freedom to calibrate the weakness of the weakest spot. Since none of the three strategies is clearly more realistic, the “defect” strategy is chosen for convenience. Simulations with this strategy are much more efficient and robust because the response is optimally smooth when the crack propagates from a single weak spot through an otherwise homogeneous cross section. Moreover, the results are more easily interpretable because the model is deterministic and because the propagation stress level is obtained as a clear plateau.

4 In situ effect with multiple elements across the thickness of a ply

In this section, a study is presented into modeling the effect of ply thickness on the in situ strength. A single defect is inserted at the free edge as motivated in the previous section. Resulting strength values are compared with theoretical values from Dvorak and Laws [4] and with experimental observations from Crossman and Wang [10,11].

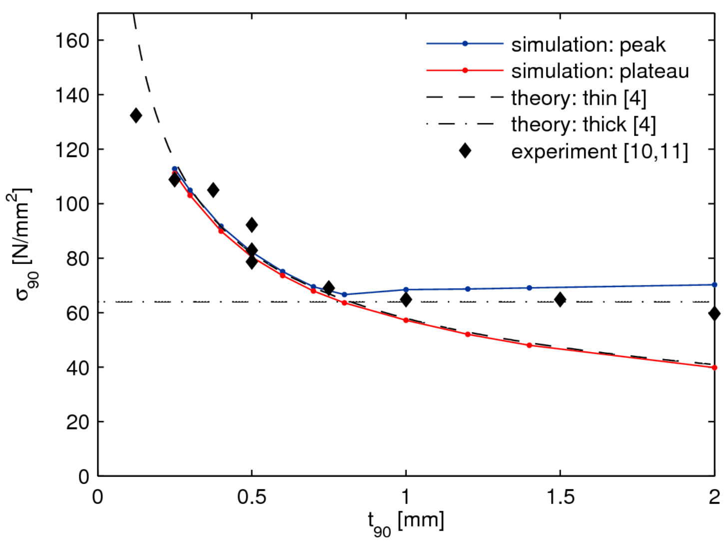

Figure 5. In situ effect as simulated with multiple elements across the thickness.

The applied defect has the same characteristics in all simulations. At its center, which is located at the free edge and mid-height of the transverse ply, the strength and toughness are reduced to zero. The defect has a radius of 0.25 mm over which the properties gradually increase to their normal values. The strength and toughness away from the defect are equal to 120 N/mm^2 and 0.17 N/mm respectively. Of these, the latter is used as a fitting parameter for the thin ply regime where it is noted that the best fit has been obtained with a value that is lower than the 0.22 N/mm that gave the best fit with the analytical model by Dvorak and Laws. The input strength works as a cap value for the maximum in situ strength that can be obtained.

Results are shown in Figure 5. It can be observed that the in situ effect is captured very well in the simulations. The increase in strength as the ply thickness decreases is captured, as well as the constant strength for thicker plies. The transition between the thin ply range and the thick ply range is characterized in the simulations as the transition between stable and unstable crack growth. In the thick ply cases, the peak load level is higher than the load level at which the crack propagates in a stable manner as illustrated in Figure 2.

5 In situ effect with single element across the thickness of a ply

Next, the number of elements is reduced by using only one element across the thickness of each ply (counting the 90 ply block with variable thickness as a single ply). The displacements can vary only linearly through the ply thickness, which means that, as long as the interface is rigid, transverse cracks cannot open. As a consequence, there is no energy release due to insertion of a discontinuity and the in situ effect cannot be reproduced. However, this changes when the interface is modeled as elastic (see Figure 6). In that case, there can be significant crack opening without delamination. The transverse ply can unload near the crack and elastic energy is being released as the crack propagates in transverse direction.

The propagation load level or thin ply strength that is obtained here depends on the value of the dummy stiffness of the interface as well as on the fracture toughness. When the dummy stiffness is made inversely proportional to the ply thickness, the trend in the strength follows that of theory accurately, as illustrated Figure 7. While in the previous section the toughness was a fitting parameter, here a range of toughness values can match the data if the dummy stiffness is scaled with the same value for all thicknesses. The results shown in Figure 6 are obtained with a fracture toughness of 0.22 N/mm and interface stiffness $K = 2.35G_{23}/t_{90}$. Regarding the thin ply strength, the in situ effect is captured very well. For the thick ply strength, however, the constant value from theory and experiments is not obtained. The thick ply strength is related to propagation in thickness direction and this event cannot be captured with a single element. The trend of increasing strength for increasing ply thickness is due to the fact that in these simulations the initial defect is smeared out over the thickness, which means that the weak spot becomes less weak when the thickness increases.

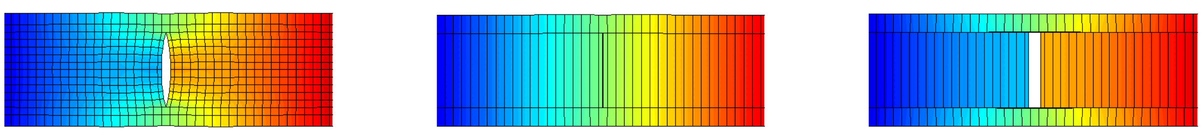

Figure 6. Side view of final deformation for three different cases: multiple elements across the thickness (left), single element with rigid interface (middle) and single element with deformable interface (right); shading indicates displacement in load direction.

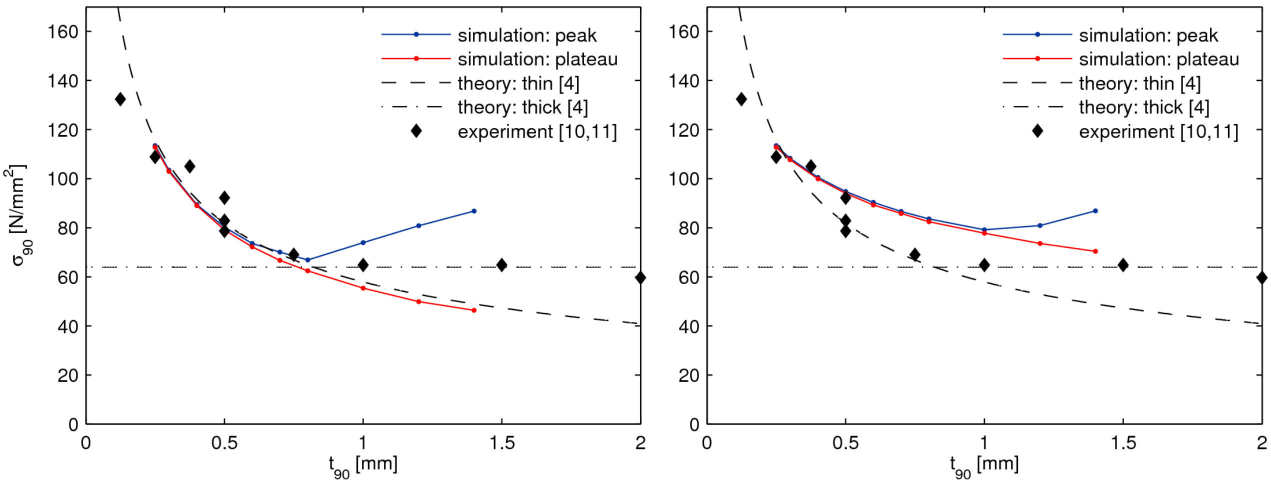

Figure 7. In situ effect as simulated with single element through the thickness of the transverse ply; with interface stiffness inversely proportional to the ply thickness (left) and with constant interface stiffness (right)

To show that the proportionality of the dummy stiffness to the ply thickness is crucial, additional results are presented for a case where a single value for the dummy stiffness is used for the whole range of thicknesses (see Figure 7). For these simulations a value of $K = 40{\cdot}10^3$ N/mm^3 was used, which corresponds to the value for t = 0.3 mm from the previous series. In this case, the in situ effect is captured much less realistically.

6 Conclusions

In this paper, it has been shown for the first time that the in situ effect with respect to the transverse strength in composite laminates can be captured with cohesive zone analysis. For initiation of failure, a weak spot must be present in the potential crack plane. The most convenient choice is to predefine a single defect with reduced strength and toughness on the free edge.

The load level at which the crack grows in transverse direction depends on the thickness of the ply and on the fracture toughness. Besides this load level associated with transverse propagation, another critical load level exists which is associated with propagation in thickness direction. This second critical load level is influenced by the magnitude of the predefined defect, but not by the ply thickness. For thin plies, the in situ strength is governed by transverse propagation, while through-thickness propagation is critical for thick plies.

Stress relaxation due to crack opening plays an important role in the crack propagation which governs the thin ply in situ strength. This crack opening cannot be captured when only one element is used through the thickness. However, when shear lag is introduced by making the interface deformable, the dependence of the propagation load level on the thickness can be captured with cohesive a method with a single element per ply. Crucial for a proper in situ effect is that the stiffness of the interface is inversely proportional to the thickness of the transverse ply. For the thick ply strength, which is related to through-thickness damage growth, a single element through the thickness does not suffice.

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