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To cite this article: I Huditeanu *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **586** 012028

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Interlaminar damage numerical modelling based on delamination growth of multi-layered composites

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Abstract. A growing interest is nowadays directed towards the numerical modelling and monitoring of the interlaminar damage evolution of composite laminates, but also to the numerical mathematical models and techniques for simulation of the interface delamination. Modelling and investigation of the mechanical behaviour and fracture modes of the multi-layered composites is a complex issue, since other important parameters, such as fibre orientation angles, stacking sequences and configuration of the composite laminates are added to the anisotropic character of the composite materials. Different failure modes may occur on multi-layered composites, while the delamination type fracture may lead to a considerable decrease of the load carrying capacity of the composite structures. Interlaminar stresses, which occur in composite laminates as an effect of the presence of the free edges, have a major influence on the delamination onset and the delamination growth. The paper summarizes the numerical methods and the approaches considered in the simulation of the delamination growth of composite laminates. The obtained results are figured in terms of the opening displacement at the interface crack tip and stress distributions on the plies of the multi-layered composites.

1. Introduction

The multi-layered composites are composed of unidirectional layers of fibre reinforced composite materials, stacked together to ensure the required mechanical properties, such as strength, and the in plane and bending stiffness [1-3]. The prediction of damage occurrence in composite laminates is a present concern, since various configurations are increasingly used in engineering applications.

Depending on the loading, specimen defects or mechanical properties of the material, various failure modes, such as fibre breakage, matrix cracking or interface debonding and delamination, may occur in multi-layered composites [4-7].

Nowadays, a growing interest is directed towards the analysis of the mechanical behaviour and damage evolution of composite laminates, especially of the delamination; an increasing number of mathematical models and theories, as well as experimental tests have been proposed, [8-13].

Delamination failure occurs at the interface between two adjacent layers and might lead to a considerable decrease of the load carrying capacity of the laminated composites. The interlaminar stresses have a major influence on the interlaminar damage onset and delamination growth.

2. Numerical modelling description

A balanced symmetric specially orthotropic composite laminated structure having the configuration $[0/15/30/45/90/-45]_s$ is investigated in this paper. The numerical analysis is performed in ANSYS Workbench and ANSYS Composite Prep/Post [14], the multi-layered composite having the total length of 85 mm, the width equal to 25 mm and an initial crack length of 10 mm. The fibre orientations of the



corresponding layers of the analysed configuration of a multi-layered composite are defined with respect to the local system of axes. It forms an angle θ with respect to the x axis, which is considered a positive angle in the (x, y) plane and negative in the (x, -y). The definition of the model for each elementary layer is represented in Fig. 1.

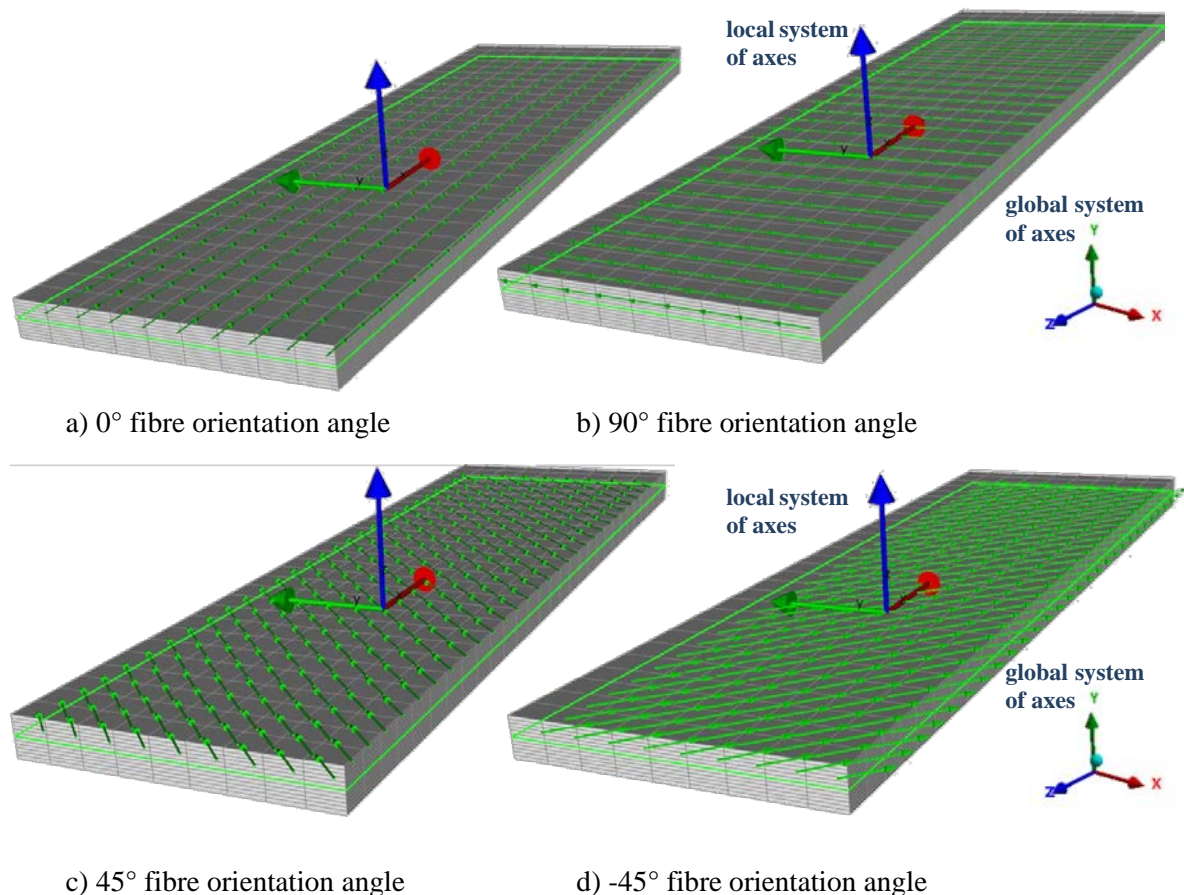


Figure 1. Several fibre orientation angles of the balanced laminate (according to ANSYS)

Depending on the fibre orientations and the adopted configuration, the stacking sequence is defined in ANSYS Composite Pre-processing. Moreover, an interface is considered between the adjacent layers, located at the middle plane, for tailoring a delamination failure towards a specified trajectory. The interface is essential to establish a delamination numerical modelling analysis type.

The initial crack separates the open interface from the free edge (caused by a pre-existent delamination or due to some manufacturing defects) to the undamaged interface. The investigation of the delamination evolution is presented in Fig. 2. Several details, such as the local axes and the pre-meshed crack definition, as well as the specified trajectory of the delamination evolution are presented.

Since the interlaminar failure is investigated and the stress state of interest is a three-dimensional one, the numerical model is also conceived using 3D finite elements. Therefore, a through-thickness mesh is realized on the plies of the composite laminates, as represented in Fig. 3.

The boundary conditions of the numerical model are illustrated in Fig. 4. The composite laminates are fixed at one end, while at the free edge, two opposite and equal remote displacements, acting perpendicular to the exterior layers, are imposed.

The balanced composite laminate is made of unidirectional layers consisting of S glass fibers embedded in an epoxy resin, with the mechanical properties of the laminae presented in Table 1.

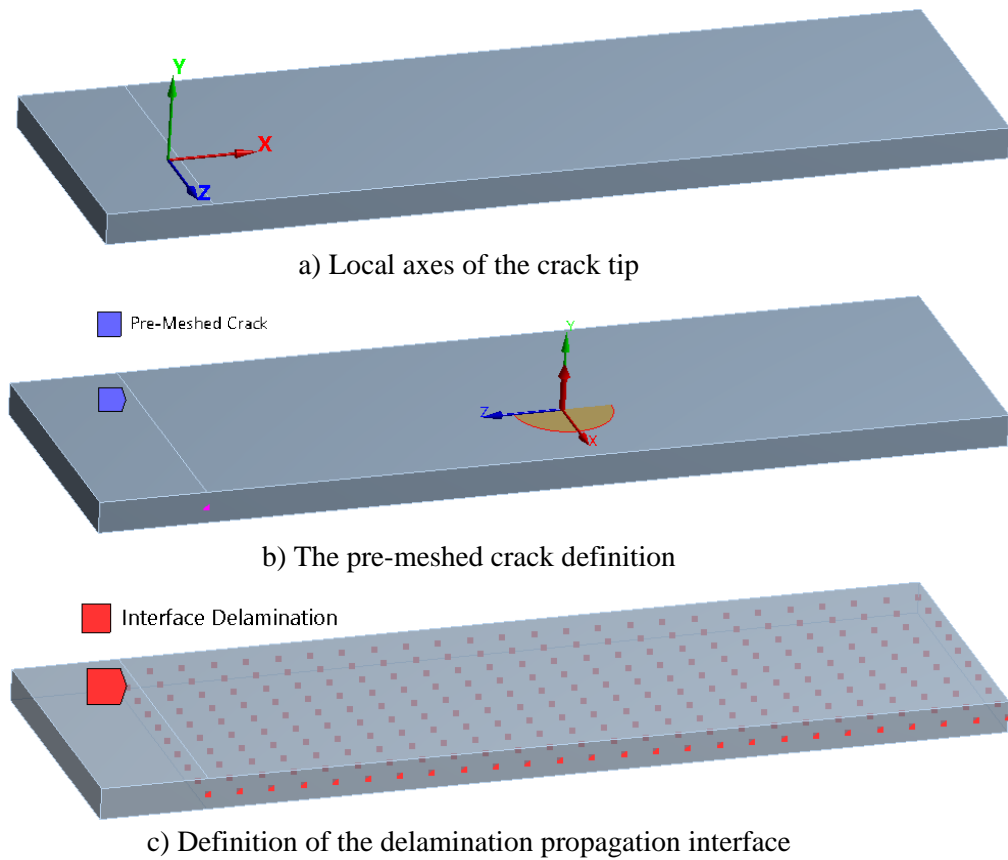


Figure 2. Initial crack and direction of propagation definition of interlaminar damages at the interface

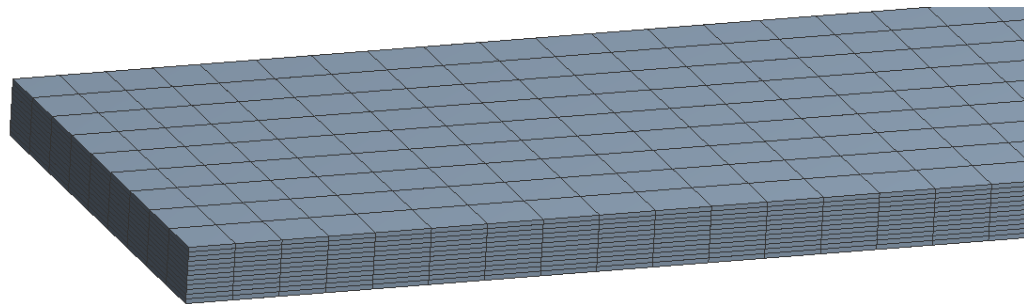


Figure 3. Through-thickness mesh on the plies of the composite laminate

Table 1. Mechanical properties of *S glass-epoxy* composite laminae* [15]

E_1	E_2	G_{12}	ν_{12}	f_{1t}	f_{1c}	f_{2t}	f_{2c}	f_{12s}
[GPa]	[GPa]	[GPa]		[MPa]	[MPa]	[MPa]	[MPa]	[MPa]
52.94	13.93	5.07	0.292	2836	1122	62.53	125.1	58.29

*where: E_1 and E_2 represent the longitudinal and transverse modulus, respectively; G_{12} – the in-plane shear modulus; ν_{12} – the in-plane major Poisson's ratio; f_{1t} and f_{1c} are the longitudinal tensile and compressive strength; f_{2t} and f_{2c} represent the transverse tensile and compressive strength, respectively; f_{12s} represent the in-plane shear strength.

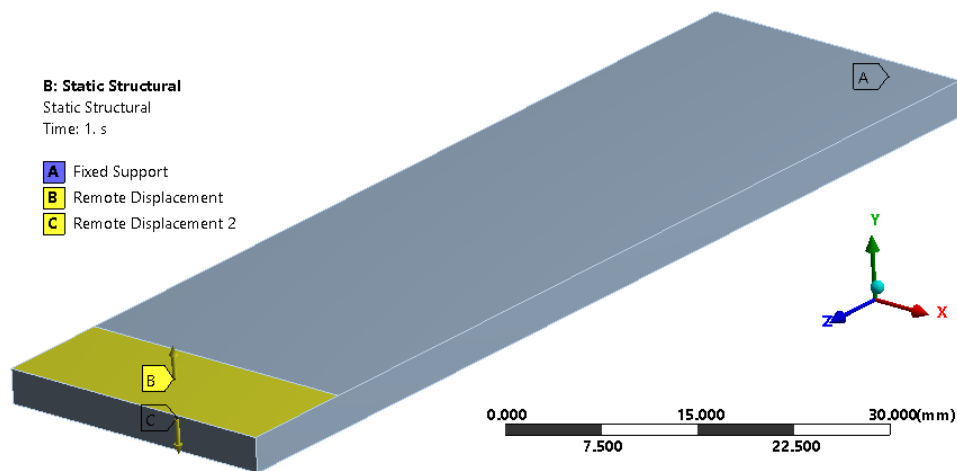


Figure 4. Boundary conditions corresponding to the numerical model

3. Results and Discussion on Interlaminar Delamination Growth

In order to perform a delamination behaviour analysis, an initial displacement equal to 40 mm, in an opening mode fracture type, established after a number of trials, is imposed to the balanced laminate. The initial crack opening and the contour plot of equivalent stresses as well as the state of stresses on the close vicinity of the crack tip delamination growth are presented in Figs. 5-7.

The separation of the layers adjacent to the interface and the propagation of the delamination is initiated from the loaded free edge towards the fixed end.

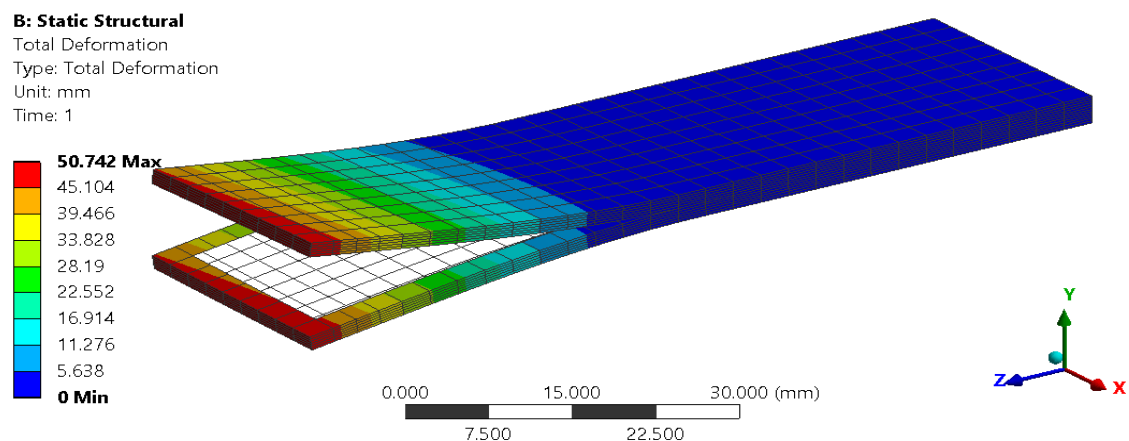


Figure 5. Opening displacement at the crack tip

The obtained results show that the opening displacement at the crack tip corresponding to the initial imposed displacement is 50.742 mm, while the maximum equivalent stresses occur on the exterior layers of the balanced laminate. For an improved visualization of the stress distributions on the laminae of the balanced laminate, a cross-section and a longitudinal section of the multi-layered structure is represented in the vicinity of the crack tip. The displacement jump and the stress distributions are symmetric with respect to the middle plane.

Subsequently, the interlaminar damage evolution and the final delamination are investigated. This ultimate displacement is described by the stage when the reactive force can no longer resist the delamination process.

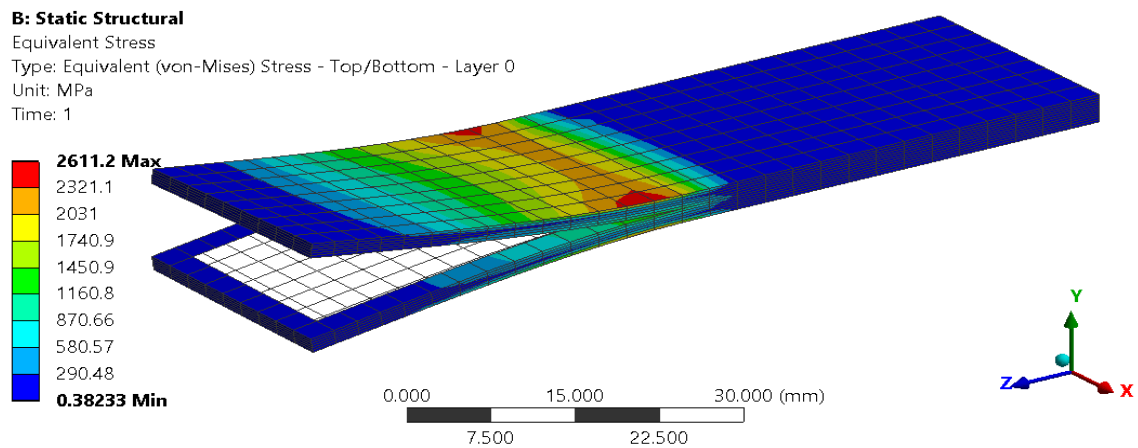
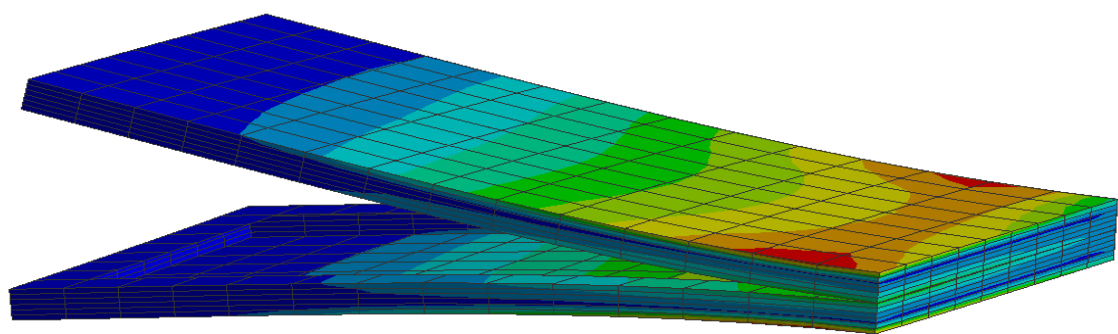
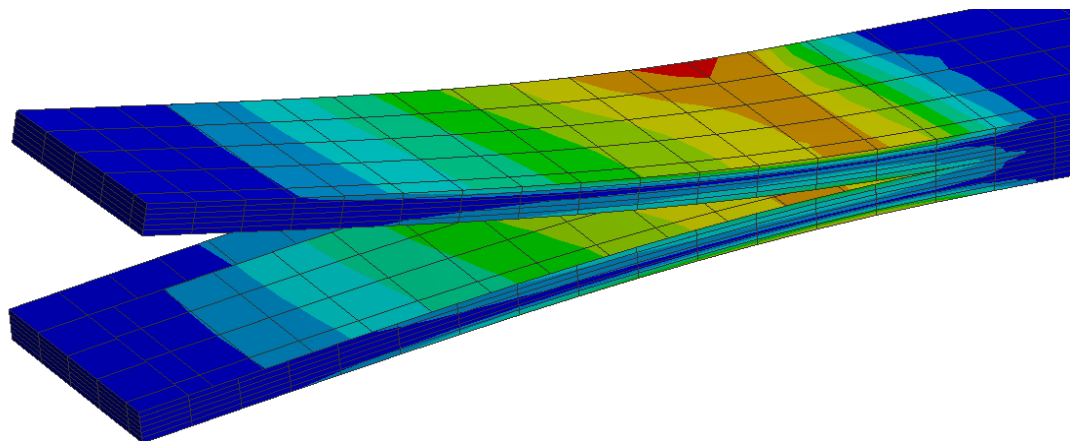


Figure 6. Stress distributions on the balanced laminate for the initial imposed displacement



a) Cross-section



b) Longitudinal section

Figure 7. Stress state in the close vicinity of the crack tip for the balanced laminate

The traction-separation curve for the considered laminate is illustrated in Fig. 8, for an ultimate imposed displacement of 200 mm. This diagram shows the relation between the displacement jumps and the reactive forces that resist against the separation of the cohesive surfaces.

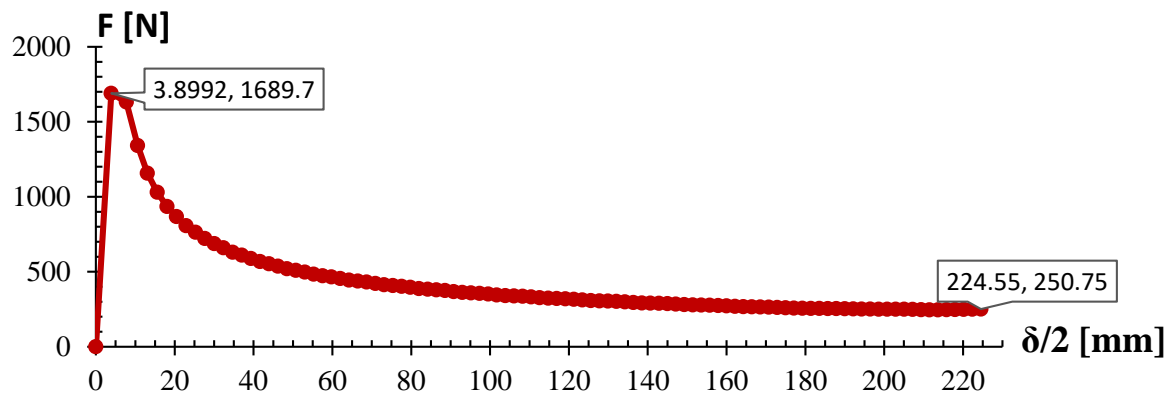


Figure 8. Traction-separation curve of balanced laminate for ultimate displacement $\Delta = 200$ mm

The results obtained are in good agreement with those available in the literature [16], the traction-separation curve having the same variation.

The maximum displacement jumps corresponding to the last failure stages and the stress distributions are shown for the ultimate imposed displacements of 200 mm, Figs. 9-10.

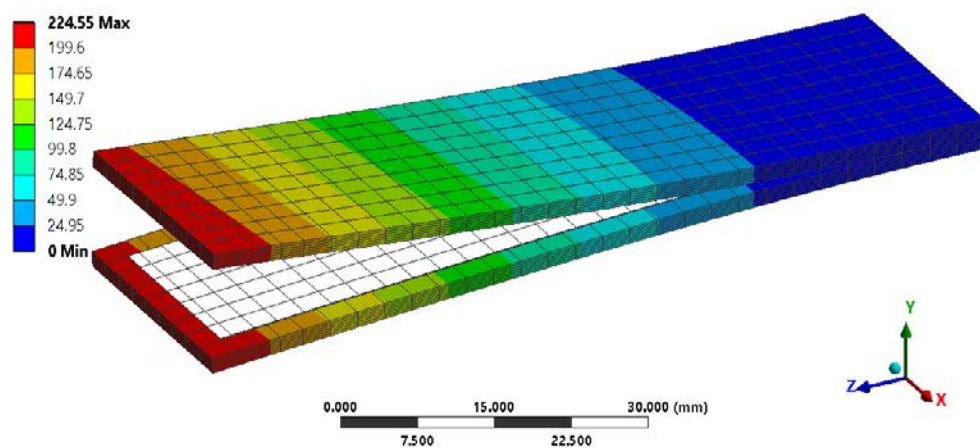


Figure 9. Ultimate crack tip opening displacement, [mm], for balanced laminate, $\Delta=200$ mm

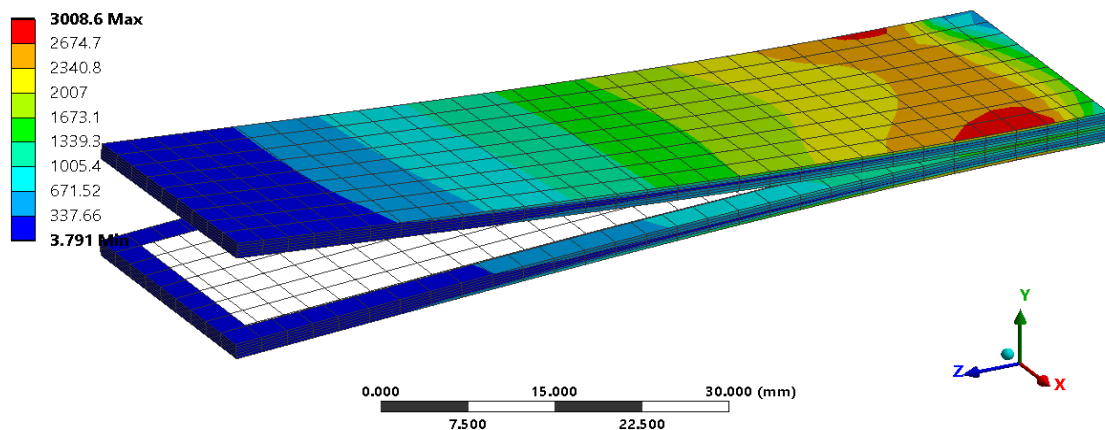


Figure 10. Equivalent stress distribution for the balanced laminate for ultimate imposed $\Delta=200$ mm

4. Conclusions

The numerical modelling of the interlaminar damage onset and the damage evolution for a balanced composite laminate is presented in the paper, as an effect to the imposed displacements in an opening mode fracture type, in order to analyse the delamination propagation.

The results are figured in terms of displacement jumps and distribution of equivalent stresses on the plies of the laminate for an initial imposed displacement up to the final delamination of the considered adjacent laminas.

The simulation of the delamination behaviour of the composite laminates is often required, since the interlaminar failure occurs frequently in multi-layered composite elements.

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