

PAPER • OPEN ACCESS

Interlaminar failure investigations on delamination growth of composite laminates

To cite this article: I Hudisteanu *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **591** 012038

View the [article online](#) for updates and enhancements.

Interlaminar failure investigations on delamination growth of composite laminates

I Hudisteanu, N Taranu, D N Isopescu, V Munteanu, D Ungureanu and M C Scutaru

“Gheorghe Asachi” Technical University of Iasi, Faculty of Civil Engineering and Building Services, Department of Civil and Industrial Engineering, Blvd. Mangeron, No. 1, 700050, Iasi, Romania

E-mail: iulianahudisteanu@ce.tuiasi.ro

Abstract. The investigation of the interlaminar damage evolution on multi-layered composites as well as the numerical modelling techniques available for the simulation of the interface delamination are still a current concern. The complexity of modelling the mechanical behaviour and fracture modes of composite laminates is increased because of the anisotropic behaviour of the material, the fibre arrangement or other important parameters, such as stacking sequence, fibre orientation angle and the configuration of the composite laminates. Different failure modes may occur on multi-layered composites, which can lead to significant stiffness and strength reduction or to the complete loss of the load carrying capacity. The interlaminar stresses are the main factors responsible for the initiation and growth of the interlaminar failures such as delamination. They may occur as a result of manufacturing defects, low-velocity impacts or as an effect of the presence of the free edges. The delamination onset can lead to serious problems such as the premature buckling of the laminates, moisture infiltration, and stiffness degradation or even to progressive delamination growth and the separation of the layers of the composite laminates. The paper presents the numerical modelling of a multi-layered composite subjected to the tensile opening fracture mode as well as the investigation of the delamination growth. The purpose of the analysis is to study the delamination evolution on a symmetric composite laminate, starting from a pre-existing initial crack, at the interface between the adjacent layers from the middle plane. The numerical modelling approach for the simulation of the delamination evolution is conducted based on the *Cohesive Zone Method*. The results are presented in terms of the total displacement jump and equivalent stress distributions on the layers of the composite laminates.

1. Introduction

The composite laminates are defined as unidirectional layers of fibre reinforced composite materials, with similar or different orientation angles, stacked together in the thickness direction to ensure the mechanical properties required by the design [1-3].

A recent and growing concern is directed to the analysis of various failure modes of the multi-layered composites. Delamination failure has a significant importance since it might lead to the reduction of the load carrying capacity of the multi-layered composite structures. Experimental and numerical investigations of the delamination crack propagation on a cross-ply composite laminate, made of graphite fibers embedded in an epoxy resin, under static loading conditions are performed in [4]. The obtained experimental results were in good agreement with the numerical ones, being



presented graphically in terms of *force - opening displacement*. The numerical model for simulating the delamination evolution was conducted based on the *Cohesive Zone Method*.

The interlaminar failure through delamination is investigated from the point of view of the free edges influence, as well as from the effect of the matrix cracking in the transverse direction on the corresponding layers [5].

Since the numerical methods are continuously improved and, hence, an increased confidence in their capabilities is achieved, in many cases the numerical modelling of composite materials replaces the experimental tests, which are costly and time consuming [6, 7]. Valuable guidelines regarding the main approaches and the analysis of the progressive failure that occurs in multi-layered composites using *Finite Elements Method* (FEM) are given in [3].

2. Approaches of the numerical simulation of delamination growth

The interlaminar stresses and, consequently, interlaminar damages on composite laminates lead to specific failure modes at the interface between adjacent layers, such as delamination.

Three interlaminar fracture modes, figure 1, known from the linear-elastic fracture mechanics of the materials, are characterized by a separation or a shear of the cohesive zone corresponding to the adjacent plies [8, 9]. Therefore, a *Mode I* delamination failure or an *opening* fracture mode represents a normal separation breakage in which the crack extension occurs by separating the surfaces corresponding to the adjacent laminas involved.

The interlaminar shear fracture of the composite laminates is produced when the delamination evolution between the laminas is achieved through *in-plane shear* or *sliding* (*Mode II*) and *out-of-plane shear* or *tearing* (*Mode III*).

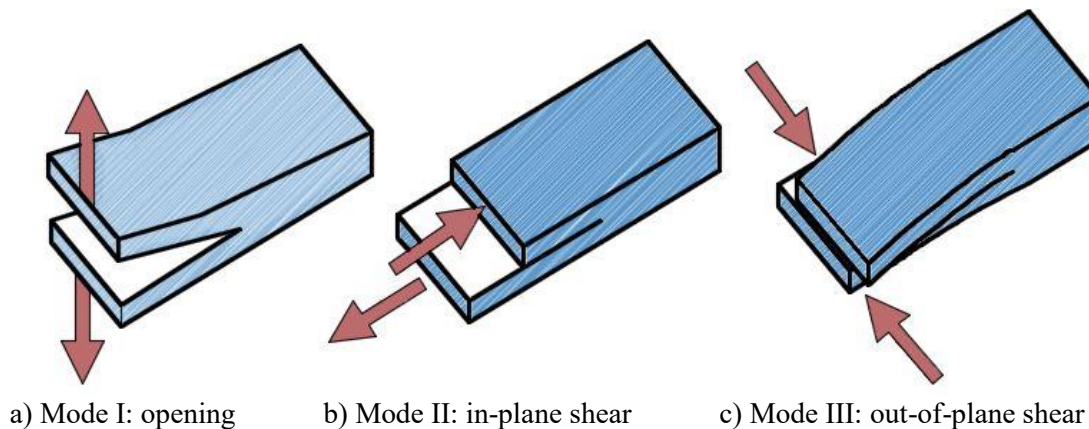


Figure 1. Fracture mechanics failure modes.

The fundamental concept of the progressive failure analysis of composite laminates is based on the assumption that the nonlinearity of the composite material is due to the intralaminar or interlaminar damage onset, as a consequence of the stiffness reduction [3].

The interface represents an important factor that should not be neglected when the mechanical behaviour of multi-layered composites is analysed, because of the risk of interlaminar failure. The simulation of the delamination growth on composite laminates is a necessity in the evaluation of their structural integrity. The basic approach is to predefine an initial crack at the interface of two adjacent layers and to monitor the propagation evolution under certain loading conditions. The *Finite Element* specialized software capable of modelling the delamination growth of composite laminates utilizes implemented methods from fracture mechanics that permit the simulation of the crack extension along a specified or arbitrary trajectory.

Two different modelling techniques, available in ANSYS Software, are generally used to simulate the interlaminar damage evolution, such as delamination: *The Virtual Crack Closure*

Technique (VCCT) and *The Cohesive Zone Method (CZM)*. Both methods use special finite elements, *contact* type or *interface* type, along a separation zone, in order to permit the modelling of the delamination evolution.

2.1. Virtual Crack Closure Technique (VCCT)

The Virtual Crack Closure Technique (VCCT) is a method based on the linear-elastic fracture mechanics theory, which can be used to evaluate the delamination failure of composite laminates. Generally, this theory provides two alternative criteria for the analysis of the linear-elastic fracture of the materials: *the energy release rate* and *the stress intensity factor* [10].

The VCCT method is based on the energy criterion, determining the energy release rate G , which is identified by the required energy to propagate an existing crack. The hypothesis of this technique is that the energy required for a crack to separate a surface is the same with the energy needed to close the same surface.

The finite element approach of the VCCT method, implemented in the ANSYS software [11], is shown in figure 2, described by the corresponding parameters used for the determination of the *Mode I* and *Mode II* energy release rates, G_I and G_{II} .

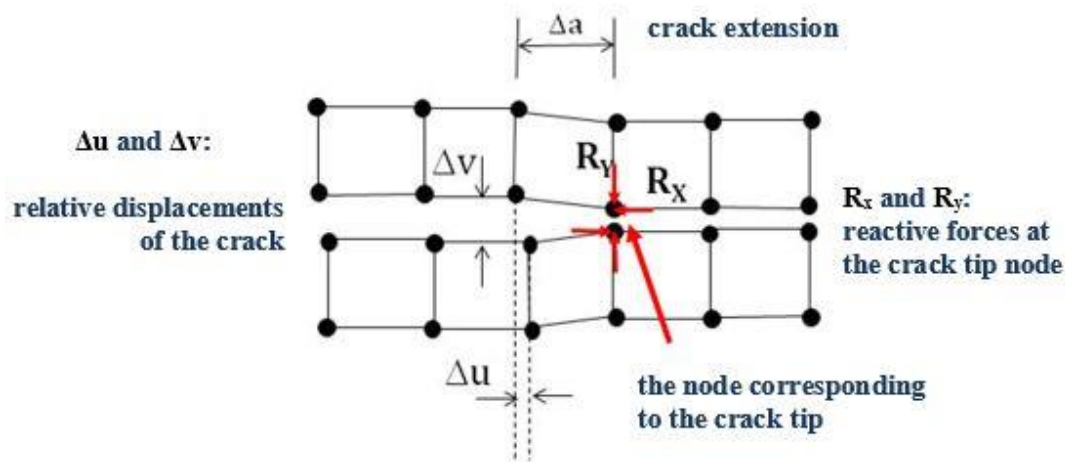


Figure 2. Modelling principle description used in VCCT method [9].

Depending on the loading mode, the energy release rate for a two-dimensional crack representation is determined according to equations (1):

$$G_I = -\frac{1}{2 \cdot \Delta a} \cdot R_y \cdot \Delta v \quad (1a)$$

$$G_{II} = -\frac{1}{2 \cdot \Delta a} \cdot R_x \cdot \Delta u \quad (1b)$$

Therefore, the failure criterion applied in this approach is the energy release rate criterion, according to which the crack evolution occurs in the following condition, equation (2):

$$G_{I(II)} \geq G_{cr} \quad (2)$$

where G_{cr} is the *critical energy release rate*, being a material constant.

The inconvenient aspect of using this method for the evaluation of the interlaminar failure is the necessity of precisely specifying the crack details, such as: localization, dimension, total number of cracks occurrence. Moreover, the *VCCT* method uses a linear elastic criterion.

The first reference work in which the *VCCT* model is proposed and developed was realized by Rybicki and Kanninen [12]. The potential energy release rate is determined based on the reactive forces at the crack tip and the relative displacements jump. The *VCCT* method is continuously improved and used in the numerical modelling of the interface delamination of composite laminates [13-16].

2.2. Cohesive Zone Method (CZM)

The most frequently used method for modelling the interface delamination of composite laminates is the *Cohesive Zone Method (CZM)*, which is considered a “bridge” between the strength criteria and the energetic models of the fracture mechanics [3].

The mathematical model of the *CZM* was first introduced by Dugdale and Barenblatt in the early ‘60s [17, 18] and it is permanently improved, an increasing growing interest being noticed nowadays [19-23].

The *CZM* is defined by the constitutive relation between the traction separation forces which act on the interface of two adjacent layers and the corresponding displacement jump at the crack tip, determined by a gradual failure of the cohesive zone.

The cohesive zone model does not refer to a physical material, but it describes the cohesive reactive forces which withstand the separation of the cohesive zones and of the interatomic links between the materials, as well as the delamination evolution. Therefore, the reactive force develops an increase until reaching a maximum, F_{cr} , and as the cohesive surfaces separate, it is reduced to zero, resulting in a complete separation of the adjacent layers, δ_f . The variation of the reactive force with respect to the displacement jump at the crack tip is graphically represented by the traction-separation curve. Figure 3 shows the most common used traction-separation laws for the numerical modelling of the cohesive zones [24, 25].

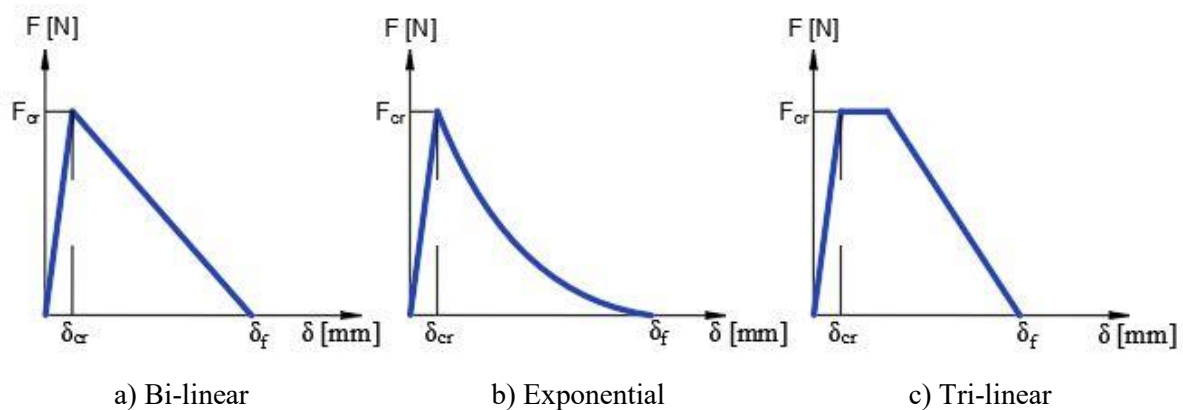


Figure 3. Traction-separation curves for cohesive zone modelling.

The exponential traction-separation law leads to the closest results to those obtained by experimental tests [26], the main advantage being the nonlinear behaviour of the interlaminar damage onset and damage evolution, which is taken into consideration. The *cohesive zone* concept can be used in the study of the mechanical damage behaviour of the single or double lap joints of pultruded members by *debonding* [27], but also in the prediction of the complex interlaminar fracture modes of various configurations of composite laminates [28] by *delamination*.

Unlike the *VCCT* method, in the case of the *CZM* method it is not necessary to define the initial crack, as this is generated automatically as a separation environment between the open surfaces or the delaminated layers and those that are in progress to be delaminated.

3. Numerical model description

In this paper, a *Mode I* delamination type analysis is performed in the ANSYS Workbench and ANSYS Composite Prep/Post.

The geometry and the characteristic elements corresponding to the fracture mode are shown in figure 4, where: $L=85\text{mm}$, $b=25\text{ mm}$ – represent the length and the width, respectively, of the composite laminate; $2H$ represents the total thickness of the element; P or Δ represents the tensile load or the imposed displacement, respectively, which acts normal to the both sides of the free edge of the exterior layers; δ – the total normal displacement jump of the crack tip; $a=10\text{mm}$ is the initial crack length. The analysed composite laminate is a symmetrical quasi-isotropic multi-layered structure having the configuration $[0/30/60/90/-60/-30]_s$.

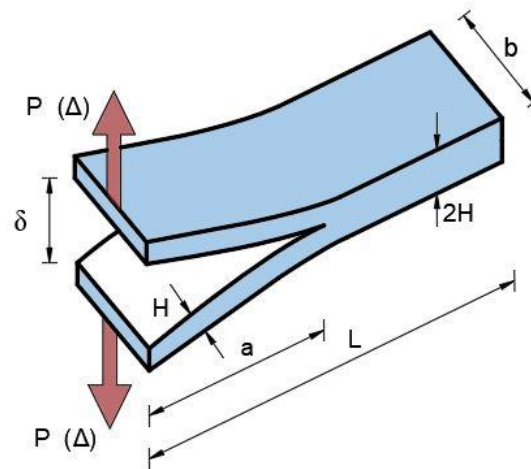


Figure 4. Geometry description for *Mode I* interlaminar fracture.

The mechanical properties of the unidirectional layers made of S glass fibers embedded in an epoxy resin are given in table 1.

Table 1. Mechanical properties of *S glass-epoxy* composite laminae, [29].

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

The necessity of modelling composite structures with 3D solid finite elements appear in the following situations: (1) when thick composite laminates are investigated; (2) when interlaminar stresses represent a major interest; (3) when studies are performed with regard to delamination failure; (4) when the free edge effect is analyzed.

Therefore, the finite element used for modelling the layers of the laminated composites is SOLID185, defined by 8 nodes and 3 degrees of freedom on each node, while for the interface, the associated finite element is INTER205, with 8 nodes and 3 degrees of freedom per node, shown in figure 5.

These finite elements are able to simulate the interface zone between two adjacent layers and, subsequently, the delamination process of composite laminates by measuring the progressive increase of the displacement jump between the nodes that were initially coincident.

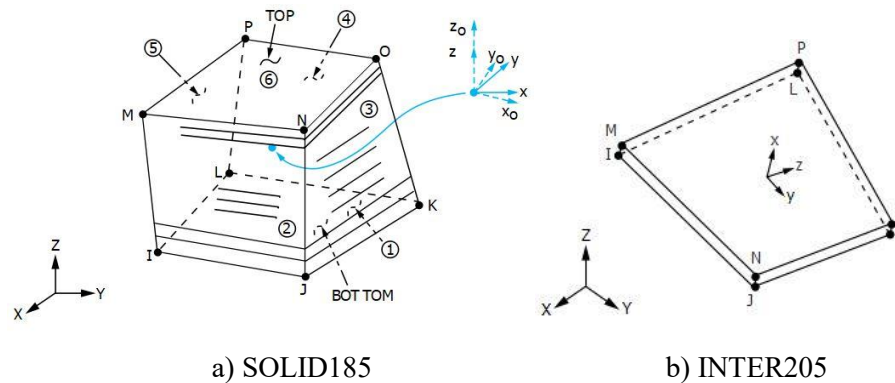


Figure 5. Finite elements used in the numerical modelling [11].

4. Results and discussion

In order to illustrate the delamination onset on the defined crack, after a certain number of trials an initial displacement equal to 40 mm is imposed to the analyzed quasi-isotropic laminate in a *Mode I* fracture type or an *opening mode*. The resulted total opening displacement jump is equal to 52.12 mm and the deformed shape of the multi-layered element is shown in figure 6.

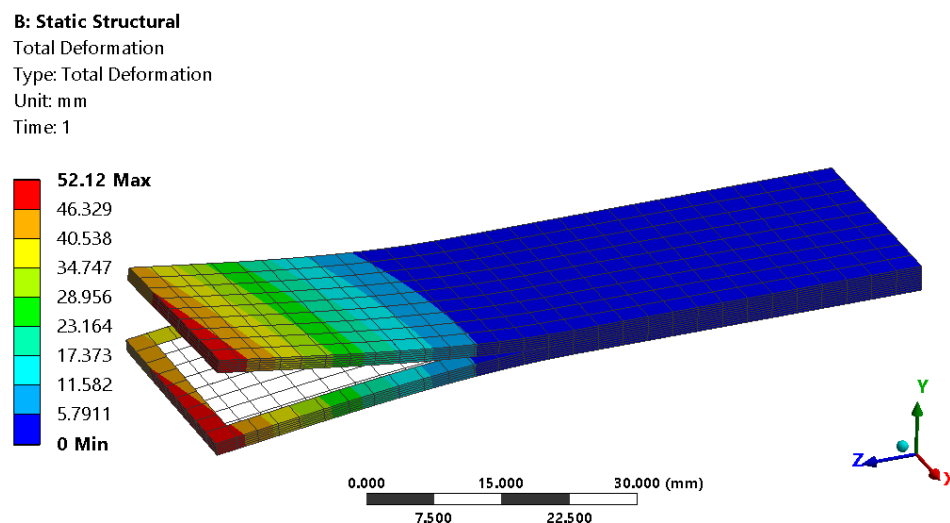


Figure 6. Opening displacement jump for the quasi-isotropic composite laminate.

The equivalent stress distributions and the stress field around the crack tip delamination growth are shown in figures 7-8.

The obtained results show that the maximum equivalent stresses occur on the exterior layers of the quasi-isotropic laminate. The delamination onset and evolution are directed from the loaded free edge towards the fixed end.

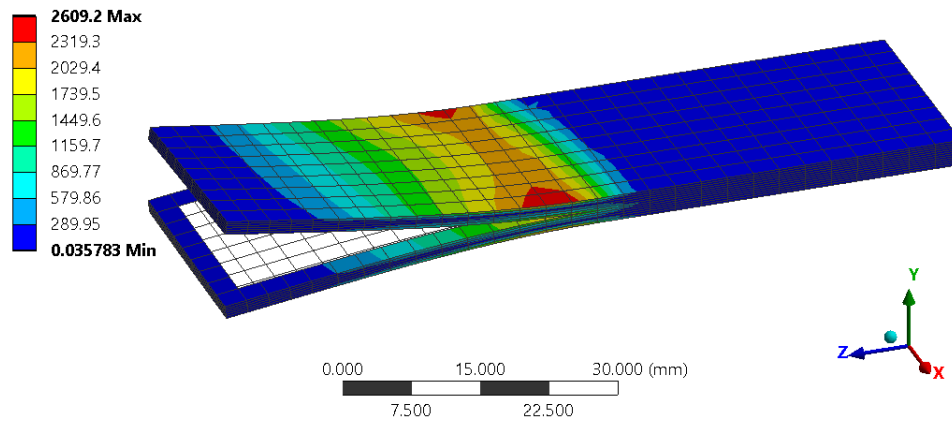


Figure 7. Equivalent stress distributions on the quasi-isotropic laminate for the initial displacement.

Figure 8 presents the longitudinal section and the cross-section along the vicinity of the interlaminar delamination in order to enable a better visualization of the stress field. The equivalent stress distributions are symmetrical with respect to the middle plane of the composite laminate, with maximum values around the crack tip, but also on the exterior layers of the element.

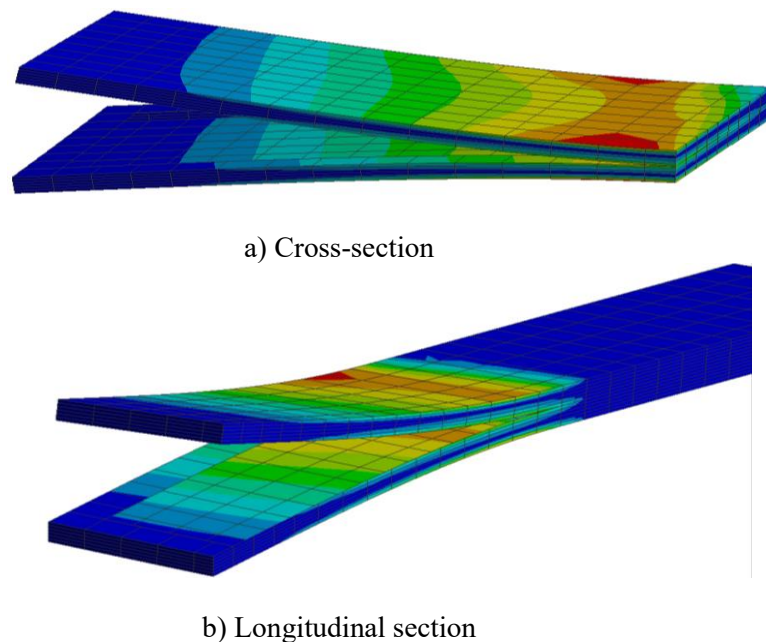


Figure 8. The stress field around the crack tip for the quasi-isotropic laminate.

The analysis of the delamination process is performed until reaching an ultimate imposed displacement of 180 mm. At this point, the reactive forces can no longer resist to the interlaminar failure occurrence.

Figure 9 shows the relation between the opening displacement jumps and the corresponding reactive forces which resist to the separation of the cohesive surfaces, known as the traction-separation curve. The obtained results are in good agreement with the diagrams available in the literature, a similar traction-separation curve being noticed [30].

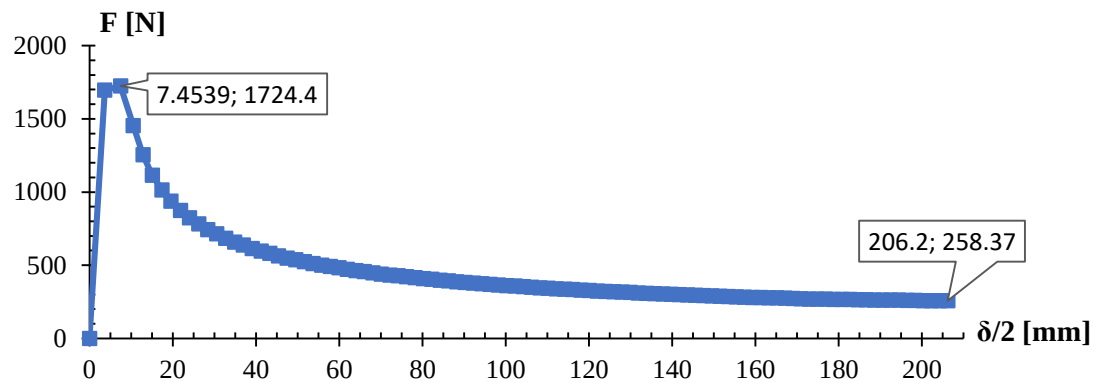


Figure 9. Traction-separation curve of quasi-isotropic laminate for ultimate displacement $\Delta=180$ mm.

The ultimate opening displacement jump and the deformed shape of the quasi-isotropic laminate, corresponding to the ultimate imposed displacement $\Delta=180$ mm, is shown in figure 10.

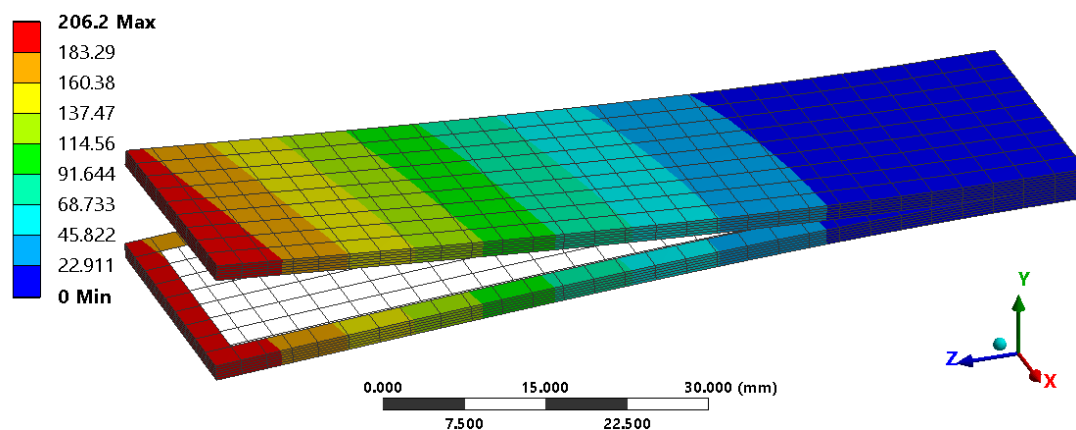


Figure 10. Ultimate opening displacement jump, [mm], for quasi-isotropic laminate, $\Delta=180$ mm.

The equivalent stress distributions of the quasi-isotropic laminate, corresponding to the ultimate imposed displacement $\Delta=180$ mm, are illustrated in figure 11. The increase of the maximum values is noticed when compared to the stress distributions corresponding to the initial imposed displacement, while the tendency of stress variation is very similar, with greater values on the exterior layers.

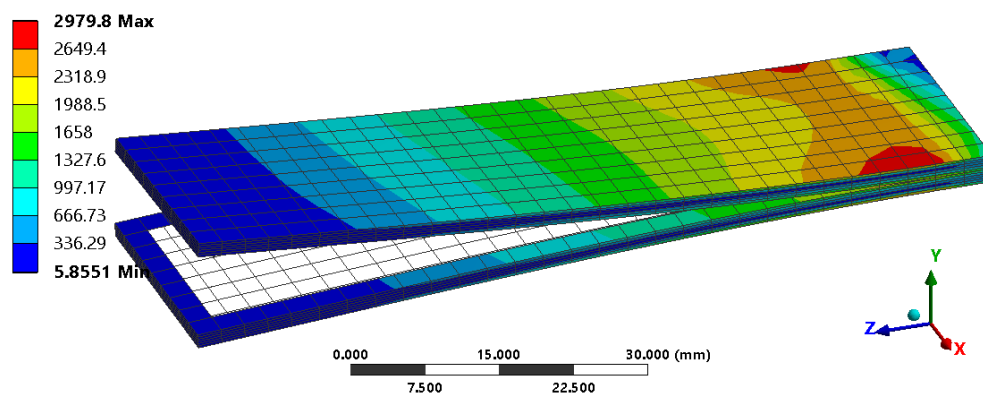


Figure 11. Stress distributions for the quasi-isotropic laminate for ultimate displacement $\Delta=180$ mm.

5. Conclusions

The paper presents the numerical interlaminar failure investigations on delamination onset and delamination growth for a quasi-isotropic composite laminate subjected to a *Mode I* fracture type or an *opening mode*. The interlaminar stresses are the mainly responsible for the interlaminar damage evolution such as delamination, but also the stacking sequence influence is very important.

The approaches that may be considered in the numerical simulation of the delamination growth, such as the *Virtual Crack Closure Technique* (VCCT) and the *Cohesive Zone Method* (CZM), are also discussed in the paper. The adopted numerical approach for simulating the delamination evolution on the studied quasi-isotropic laminate is the *Cohesive Zone Method* (CZM). The numerical analysis presented in the paper is focused on the delamination evolution on a symmetric composite laminate, having a pre-existing initial crack, at the interface between the adjacent layers from the middle plane.

The results obtained are the opening displacement jump at the crack tip, stress distributions on the layers of the composite laminate and the exponential traction-separation curve. The variation of the opening displacement jumps with respect to the corresponding reactive forces which resist against the separation of the cohesive surfaces is in good agreement to the results available in the literature.

6. References

- [1] Herakovich C T 1998 *Mechanics of Fibrous Composites* (University of Virginia, USA: Wiley & Sons)
- [2] Daniel I M and Ishai O 2006 *Engineering mechanics of composite materials* 2nd ed (New York: Oxford University Press)
- [3] Girao Coelho A M 2016 *Arch. Computat. Methods Eng.* **23** 363
- [4] La Saponara V, Muliana H, Haj-Ali R and Kardomateas G A 2002 *Eng. Fract. Mech.* **69**(6) 687
- [5] Lierni Zubillaga E 2014 *Experimental and analytical study of delamination caused by free-edges and experimental and matrix cracks in laminated composites* phd thesis (Girona, Spain)
- [6] Taranu N, Banu C, Oprisan G, Budescu M, Munteanu V and Ionita O 2010 *Rev. Rom. Mat.* **40**(4) 323
- [7] Bejan L, Taranu N and Sarbu A 2010 *J. Optoelectron. Adv. M.* **12**(9) 1930
- [8] Sun C T and Jin Z H 2012 *Fracture Mechanics* (Oxford: Academic Press) 105
- [9] Goanta V 2006 *Fracture Mechanics in romanian* (Iasi, Romania: Tehnopress)
- [10] Almi S and Lucardesi I 2018 *Nodea-Nonlinear Diff.* 25-43
- [11] ANSYS® Documentation (ANSYS, Inc)
- [12] Rybicki E F and Kanninen M F 1977 *Eng. Fract. Mech.* **9**(8) 931
- [13] Chang Y S, Choi J B and Kim Y J 2004 *KSME Int. J.* **18**(11) 1996
- [14] Elisa P 2011 *Adv Compos Materials - Analysis of natural and man - made materials* ed P Tesinova (InTech) 463
- [15] Woo K S and Ahn J S 2015 Implementation of Virtual Crack Closure Technique for damaged composite plates using higher-order layerwise model *Adv.Mat. Sc. Eng.* 684065
- [16] Farkash E and Banks-Sills L 2017 *Int. J. Fracture* **205**(2) 189
- [17] Dugdale D S 1960 *J. Mech. Phys. Solids* **8**(2) 100
- [18] Barenblatt G I 1962 *Adv. Appl. Mech.* **7** 55
- [19] Park K and Paulino G H 2011 *Appl. Mech. Rev.* **64**(6) 06802
- [20] Hemanth R and Naresh B 2014 Delamination behaviour and experimental validation of glass fabric/epoxy matrix and carbon fabric/epoxy composites in mode-I loading *Mech. Eng.: An Internat. J.* **1**(1) 23
- [21] Park K, Choi H and Paulino G H 2016 *Mech. Res. Commun.* **78** 71
- [22] Kumar D, Roy R and Kweon J H 2016 *Appl. Compos. Mater.* **23**(3) 397
- [23] Amiri-Rad A and Mashayekhi M 2017 *Appl. Compos. Mater.* **24** 751
- [24] Dogan F, Hadavinia H, Donchev T and Bhonge P S 2012 *Cent. Eur. J. Eng.* **2**(4) 612
- [25] Fereidoon A, Memarian F and Ehsani Z 2013 *Fuller. Nanotub. Car. N.* **21**(8) 712
- [26] Li Y, Stapleton S E, Simon J W and Reese S 2016 *Exp. Mech.* **65**(8) 1477
- [27] Ungureanu D, Taranu N, Isopescu D N, Lupasteanu V, Mihai P and Hudisteanu I 2017 *Rev.*

- Rom. Mat.* **47**(4) 522
- [28] Hudisteanu I, Taranu N, Isopescu D N, Bejan L, Axinte A and Ungureanu D 2017 *Rev. Rom. Mat.* **47**(2) 252
- [29] Hudisteanu I, Taranu N, Isopescu D N, Entuc I-S, Oprisan G and Ungureanu D 2018 *IOP Conf. Ser.: Mat. Sci. Eng.* **400** 042031
- [30] Barbero EJ 2014 *Finite Element Analysis of Composite Materials using ANSYS* 2nd ed (Boca Raton: CRC Press, Taylor & Francis Group)