Virtual testing of composite plates under flexural loadings

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New segments start to use composite materials looking for materials lighter and more strength, among other characteristics. Most composite materials exhibit high sensitivity regarding loads and effects, but this is not taken into consideration in selecting the material structure. Such unfavourable factors include technological defects of different types, local temperature effects, etc. All these factors decrease the resistance to theoretical effects, carrying capacity, longevity, and structural integrity. Thus, composite materials constitute a new challenge for several sectors of the scientific community, and their introduction to engineering represents a challenge for researchers and academics. Therefore, this study proposes the development and application of a computational model to evaluate the residual strength of carbon fibre reinforced polymer (CFRP) plates, to simulate the progressive damage behaviour observed during the bending test. Numerical analyses are performed via the Finite Element Method to predict the progressive damage in the laminate structures by using ABAQUS™ software linked to the implemented UMAT (User Material Subroutine). The experiments are carried out on specimens of rectangular plates of composite materials with two different stacking sequences and thicknesses to evaluate the influence of these factors on the flexural response. Finally, numerical and experimental results are compared to verify the potentialities and limitations of the virtual testing proposals.

Keywords: *Composite plate, Progressive damage model, four-point bending test, residual strength, Finite element method (FEM)*

INTRODUCTION

Composite structures have wide applications in various types of industries, such as aerospace, naval, medical, automotive, and high-performance sports equipment, among others (Oladele *et al.*, 2020; Ngo, 2020). The main reason for the increasing use of this material is the ability to combine the mechanical properties of two different types of materials, giving the possibility to manufacture lightweight structures with higher strength and stiffness (Bhudolia *et al.*, 2021). Thus, further studies are necessary to investigate the application of this type of material to resist different load types, such as impact, traction, compression, bending, as well as other loads that can cause damage to the structure, affecting the integrity of these components.

The development of design tools for application in composite materials has been studied since this type of material started to be applied in the aircraft industry, but there is still a lack of tools to predict the degradation of composite materials and their lifetime in operation (Turon *et al.*, 2005). The microstructure of composite materials is inhomogeneous and anisotropic and there are three different types of damage mechanisms, such as fibre breakage, matrix cracking, and fibre-matrix delamination. A constitutive model to predict the damage behaviour of composite materials in service should account for several factors that influence mechanical properties. Fibre breakage has been considered a failure criterion, which is not a good assumption, once the fibre does not fail catastrophically, but failure happens progressively. Degradation of composites in service is very different from isotropic materials, mainly in effects on mechanical properties. Damage before failure in composite materials leads to a loss of stiffness and strength more relevant than in isotropic materials, so a progressive damage model takes into account this loss of strength and stiffness that composites face in service (Turon *et al*., 2005). According to Ribeiro *et al.* (2013), the outstanding mechanical properties added to the recent improvement in the composite material manufacturing process allow a wide application of composites mainly in the civil aeronautical industry, although a specific point has been an obstacle, the prediction of damage to these structures during service. Several studies have been carried out related to the prediction of damage, however, as the phenomenon involving the failure of composite is very complex, there is still a lack of information to be filled on this subject. In this scenario, the use of computational tools that provide numerical analysis via the finite element method (FEM) is a good and suitable alternative to solve the damage model. In addition, the inherent anisotropy of composite materials has an advantage,

making it possible to obtain the stiffness and strength desired during the composite structure design, but on the other hand, as a disadvantage, the inherent anisotropy makes it more difficult to predict a failure in a composite structure. Thus, the failure prediction in composite structures under loadings, that are similar to those experienced during service needs further investigation (Angélico, 2009). Ferreira (2014) developed a computational model to simulate progressive damage in carbon/epoxy composite structures. The model was developed in ABAQUS™ software and implemented with User Material Subroutine (UMAT) via FEM. As the prediction of the progressive damage in a composite structure is something very complex to study, the main objective of the work was to develop a simple and accurate tool to predict the damage computationally, reducing the need for experimental tests.

Falzon *et al.* (2017) explained that the load-bearing of a composite structure is significantly affected by microscopic cracks and, according to continuum damage mechanics, these microscopic cracks and voids from within the material under loading, before the macroscopic fracture, and these cracks and voids decrease the load-bearing area of the structure which leads to a reduction in transmitted stress in the damaged material. In this context, the development of a Progressive Damage Model (PDM) can be applied in studies of composites with different boundary conditions. Phadi *et al.* (1997) presented a method to study the non-linear behaviour, first ply failure, and ultimate collapse of laminated composite plates with clamped edges, subjected to transverse pressure. Model predictions correlate well with experimental data for different aspect ratios. Turon *et al.* (2005) developed a progressive damage model for unidirectional composite laminates based on physical fibre fragmentation and then formulated it into a thermodynamically consistent model. The model is valid in the early stages of fibre fragmentation and assumes parallel behaviour of fibre and matrix and the absence of local load sharing in the vicinity of a broken fibre. Tita *et al.* (2008) presented an investigation of the low-velocity impact of carbon fibre-reinforced epoxy laminated composite thin disks. Finite element analysis (FEA) was developed, using Hill's model and material models implemented by UMAT (User Material Subroutine) into software ABAQUS™, to simulate the failure mechanisms under indentation tests. Ribeiro *et al.* (2012) presented a damage model and progressive failure analysis that requires simple experimental tests and that achieves good accuracy. The model was implemented as a UMAT (User Material Subroutine), which is linked to finite element software, ABAQUS™, to predict the behaviour of the composite structures. The new material model can predict the behaviour of composite structures for off-axis unidirectional filament wound coupons under tensile or more complex loads cases. Li *et al.* (2014) investigated low-velocity impact responses and impact-induced damages evaluation problems for the stiffened composite laminated plates based on the progressive failure model and layerwise/solid-elements method (LW/SE). Several numerical examples are carried out to demonstrate the excellent predictive capability of the current method and to study the influence of parameters on the impact responses and impact-induced damages.

Ribeiro and De Medeiros (2015) applied a material model to simulate low-velocity impact analysis on filament winding composite cylinders made of epoxy resin reinforced by carbon fibres. The damage mechanisms were evaluated by a material model, which was implemented as a FORTRAN subroutine (VUMAT - user material subroutine for explicit integration analyses) and linked to the ABAQUS™ software. In this investigation, several cases, such as mesh density, element type, contact algorithm, and damping effects, are investigated to verify the influence of these parameters. Yang *et al.* (2017) performed a numerical analysis creating a progressive damage model based on the Hashin failure criteria and cohesive zone method, considering gradual stiffness degradation rules. The main goal is to evaluate the flexural behaviour and damage evolution of the composite plates subject to the three-point bending tests, after the development of the computational model, the results were compared with data obtained from the experimental analysis. Khashaba *et al* (2019) developed a computational model to predict the progressive damage, with aid of the ABAQUS™ package in composite pinned joints with different clearances made of cross-ply glass fibre/epoxy. A big advantage of developing a model to predict failure computationally is the fact that is a non-expensive procedure. The implementation of the progressive damage analysis was based on the Hashin failure criteria and the Riccio property degradation rules, if failure any lamina of the composite material, the properties of that specific lamina are updated according to the Riccio property degradation rules. Sridharan and Pankow (2020) carried out finite element numerical simulations of both low velocity and high-velocity projectile impact on composite laminates. Two separate progressive material damage models were investigated in the commercial finite element codes Abaqus/CAE and LS-Dyna. The Abaqus/CAE models used a VUMAT subroutine while MAT162 was chosen due to its wide adoption for impact problems in LS-Dyna.

On the other hand, the role of transverse shear is very important in composites, as the material is weak in shear due to its low shear modulus compared to extensional rigidity. Hence, an accurate understanding of their structural behaviour is required, such as deflections and stresses. According to Yang *et al.,* (2017), bending loads are the major internal stress, that can cause delamination in composite laminates, emphasizing the importance of the study. The model was created in ABAQUS™ and the mechanical properties were implemented aided with a UMAT (User Material Subroutine), making the progressive damage accounted for in the model by reducing the strength and stiffness of the elements gradually. One very effective way to evaluate the progressive damage in a composite structure is applying to the structure a loading such flexure, and a usual method to make that is through three-point bending tests, or a four-point bending test, these are standardized procedures to apply and evaluate flexure in composite plates. Reddy *et al.* (2012) carried out several finite element analyses for various side-to-thickness ratios, aspect ratios, and modulus ratios to study the effect of transverse shear deformation on deflection and stresses of laminated composite plates subjected to uniformly distributed load.

This work evaluates the progressive damage failure in composite plates during a four-point bending test, where flexure is applied to the plates with different stacking sequences and thicknesses. Numerical analyses are performed via the Finite

Element Method to predict the progressive damage in laminate structures using ABAQUS™ software linked to the implemented UMAT (User Material Subroutine). The experiments are carried out on specimens of rectangular plates of composite materials with two different stacking sequences and thicknesses to evaluate the influence of these factors on the flexural response. Finally, numerical and experimental results are compared to evaluate the potentialities and limitations of the proposed model.

MATERIALS AND METHODS

This work is based on two main steps, the first is the development of a computational model to simulate de composite plates under flexure load with progressive damage failure, and in the second step, to make a comparison between the results obtained with the computational analysis, with the results acquired by experimental test by De Medeiros (2016).

Experimental analyses were performed on composite plates. The plates are manufactured of 8 and 12 plies stacked in $[0]_8$ and $[0/15/-15/0/15/-15]_s$ lay-up configurations, respectively. The specimens are manufactured by filament winding method. The composite plates are made of carbon fibre with epoxy resin (Carbon Fibre Reinforced Polymer – CFRP). Table 1 showed the nominal plate geometries and stacking sequence.

Table 1 – Dimensions of the curved and flat plates

Plate	Length(mm)	Width(mm)	Thickness(mm)	Stacking sequence
Curved	303.84	245.88	2.21	$[0]_8$
Flat	304.14	245.21	3.33	$[0/15/-15/0/15/-15]_s$

As the carbon fibre composite plates are made by filament winding process with stacking sequence $[0]_8$, a small curvature can be observed in the plates. To better simulate the experimental analyses, computational models were developed with geometry obtained from 3D Coordinate Measurement System applied to real plates. In Figure 1 and Table 2, it is possible to observe the geometry determined by using this technique. So, to develop a feasible virtual model, there is a slight difference in C_1 and C_2 in the computational models.
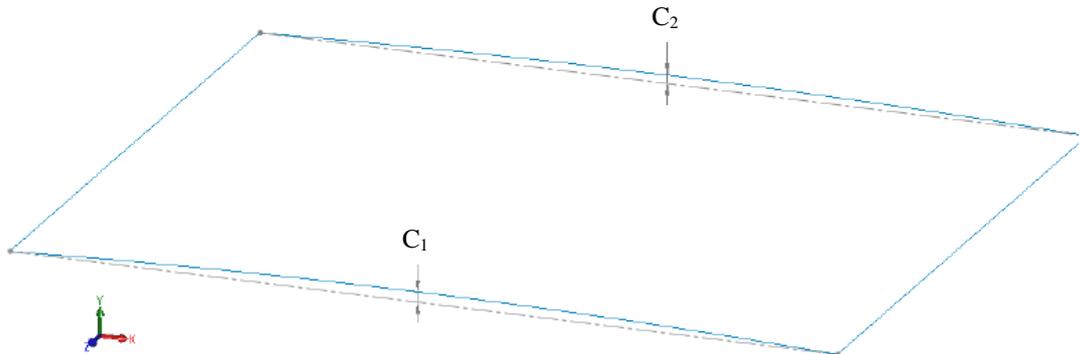

Figure 1: Geometry with curvature effects (De Medeiros, 2016)

Table 2 – Values of C_1 and C_2 given by the ATOS compact scan machine used in the computational models (De Medeiros, 2016)

Plate	C_1 (mm)	C_2 (mm)
P07	4.06	4.22
P08	4.38	4.64

The specimens were evaluated by four-point bending tests under quasi-static conditions. The tests were conducted according to the standard ASTM D6272–10 (ASTM, 2010). The four-point bending load is applied for a constant cross-head rate of 1.0 mm/min on the specimen. The tests are performed using a universal testing machine, Instron 5985. The equipment is used to measure load and deflection during four-point flexure. In addition, Linear Variable Differential Transformer (LVDT) transducers are used to get the deflection of the plate and compare it to the universal machine cross-head measurements (Fig. 2a), to check the reliability of the data obtained from the testing machine. The distance between the supporting devices (support span) is 180 mm, and the distance between the loading devices (load span) is 90 mm (Fig. 2b). The span-to-thickness ratio is selected to be approximately 81:1 for the curved plate, and approximately 54:1 for the flat plate, this large ratio ensures that shear effects are negligible (De Medeiros, 2016).
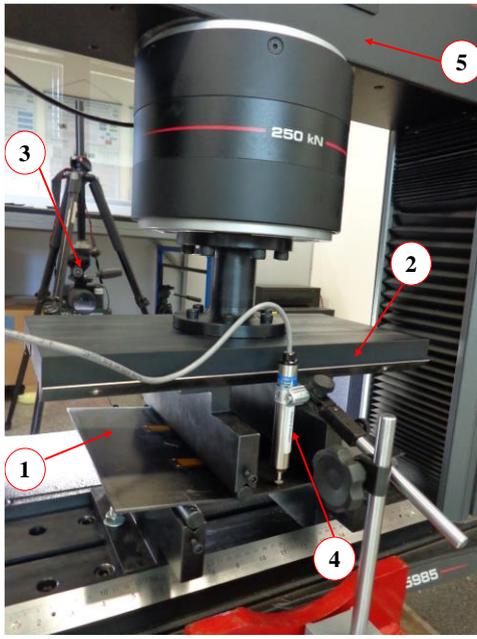
1 – Specimen

2 – Flexural device

3 – DIC

4 – LVDT

5 – Universal Testing Machine
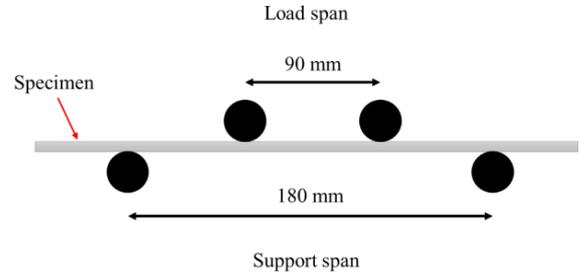
(a)   (b)

Figure 2: Experimental test used in the carbon fibre composite plates (a) Experimental setup for the flexural test, (b) Test setup scheme according to ASTM D6272-10, displaying load and support spans (De Medeiros, 2016).

Progressive Damage Model

The damage model is used to predict the failure and damage caused by bending loading on the composite specimens, which is quantified at the mesoscale. The model equations were written for a homogenized lamina, which is considered an orthotropic material. Three material directions are specified: direction 1 (aligned to the fibres); direction 2 (normal to the fibres and in the ply plane) and direction 3 (normal to the ply plane 1-2). The behaviour of the composite laminated structures depends on the behaviour of each homogenized lamina, including the damage mechanisms of the fibres and the matrix (epoxy resin). The model was designed to predict the intralaminar failures, *i.e.*, it does not cover interlaminar damage from delamination. Failure mechanisms are independent of the fibre failure, and do not influence the matrix, and vice-versa. However, the fibre failure will result in the lamina degradation properties, leading to affect matrix damage and therefore fibre damage. More information can be found in Ferreira (2014).

The damage model equations, presented in Table 3, were implemented as a user material subroutine for implicit simulations (UMAT) in the FORTRAN language.

Table 3 – Material and progressive failure model (Ferreira, 2014)

Failure criteria	Failure type	Degradation law
$\dfrac{\sigma_{11}}{X_T} \geq 1$	Fibre tension	$E_{11} = E_{110} \cdot (1 - d_1)$
$\dfrac{\lvert \sigma_{11} \rvert}{X_{CO}} \geq 1$	Fibre compression	$E_{11} = \dfrac{X_{CO}}{\lvert \varepsilon_{11} \rvert}\left(1 - f(\varepsilon_{11})\right) + f(\varepsilon_{11}) \cdot E_{110}$
$f \geq 0$	Matrix tension	$E_{22} = E_{220} \cdot (1 - d_2)$
$f \geq 0$	Matrix compression	$E_{22} = \dfrac{\sigma_{22y}}{\varepsilon_{22}}\left(1 - g(\varepsilon_{22})\right) + g(\varepsilon_{22}) \cdot E_{22_0}$
$f \geq 0$	Shear	$G_{12} = G_{120} \cdot (1 - d_6)$

Considering σ_{11} the stress in the fibre longitudinal direction, σ_{22} the stress in the matrix transversal direction, X_{CO} the fibre elastic limit under compression, X_T the fibre strength under tension, E_{11} the secant young modulus in the longitudinal direction in the inelastic region for the fibre, E_{110} the young modulus in the elastic region, d_1, d_2, d_6 are damage variables, ε_{11} the strain in the longitudinal direction, $f(\varepsilon_{11})$ linear adjustment obtained by the compression curves in 0°, E_{22} the inelastic matrix secant modulus, E_{22_0} initial young modulus, ε_{22} matrix transversal strain, $g(\varepsilon_{22})$ parameter obtained by the stress-strain experimental curves adjustment under 90° compression, G_{12} shear modulus on the plane 1-2, G_{120} initial shear modulus.

It is possible to represent the behaviour of the matrix by a damaged surface, *i.e.*, the area where there is no failure on the matrix, by

$$f = 1 - \left(\frac{\tau_{12}{}^2}{S_{12y}{}^2} + \frac{\sigma_{22}{}^2}{Y_{CO}{}^2} \right), \tag{1}$$

where σ_{22} is the transversal stress, τ_{12} is the shear stress, S_{12y} is the linear elastic limit under shear, and Y_{CO} is the linear elastic limit on the transversal fibre direction (Ferreira, 2014).

The choice for this material is due to the fact that they are commonly applied in composite aeronautical structures, and have been increasingly applied. The material properties are very similar to the material selected by Tita *et al.* (2008), and Ribeiro *et al.* (2012). This material was manufactured from prepreg M10 from Hexel^{TM}, made of carbon fibres by epoxy resin, the elastic and strength properties of the material are shown in Table 4. In addition, the fibre volume ratio was around 63%.

Table 4 – Material properties of the composite plates (Tita, 2003; Ribeiro *et al.*, 2012)

Elastic Properties	
Young's Modulus longitudinal E_{11}	127 GPa
Young's Modulus transversally E_{22}	10 GPa
Young's Modulus perpendicular E_{33}	10 GPa
Shear Modulus in plane 1-2 G_{12}	5.44 GPa
Shear Modulus in plane 1-3 G_{13}	5.44 GPa
Shear Modulus in plane 2-3 G_{23}	3.05 GPa
Poisson's ratio in plane 1–2 v_{12}	0.34
Poisson's ratio in plane 1–3 v_{13}	0.34
Poisson's ratio in plane 2–3 v_{23}	0.306
Strength Values	
Tensile Strenght limit in fiber Direction X_T	1400 MPa
Compression limit in fiber Direction X_C	930 MPa
Tensile Strenght limit in transverse direction Y_T	47 MPa
Compression limit in transverse direction Y_C	130 MPa
Shear Strength S_{12}	53 MPa
Shear Strength S_{13}	53 MPa
Shear Strength S_{23}	89 MPa
Fibre Volume Fraction	
Fibre volumetric fraction vf	60%
Density ρ	$1580 \, Kg/m^3$

Computational Model

To evaluate the computational material behaviour, a finite element analysis using ABAQUS^{TM} and the UMAT was performed. A three-dimensional, doubly-curved, four-node reduced integration shell elements with six degrees of freedom (DOF) per node (defined as S4R - ABAQUS^{TM} – Abaqus, 2014) was used to model the composite specimen. Figure 3 shows the boundary conditions used in this analysis.
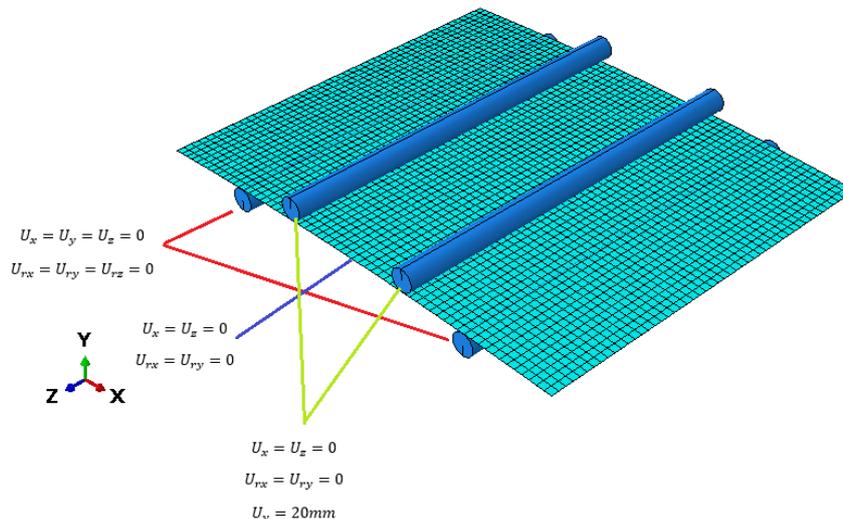

Figure 3: Boundary conditions used in the computational analysis

The plate was modelled with 2926 quadrilateral elements and 3036 nodes. The FE model for carbon fibre composite plates flexural tests has the same dimensions as the coupons used for experimental tests. To define the boundary conditions, the loads and supports are following the ASTM D6272-10 standard for bending tests.

RESULTS

According to De Medeiros (2016), the four-point bend tests are more appropriate than three-point bending in the present study, for several reasons. In three-point bending, the point of load application is at the location of greatest damage and may cause more damage to the specimen. Four-point bending is best suitable for material specimens that experience larger deformation during testing, as the load is distributed in two indenters.

Figure 4 shows the stress computational response for $[0]_8$ and $[0/15/-15/0/15/-15]_s$ carbon fibre composite plates, respectively.

(a)   (b)
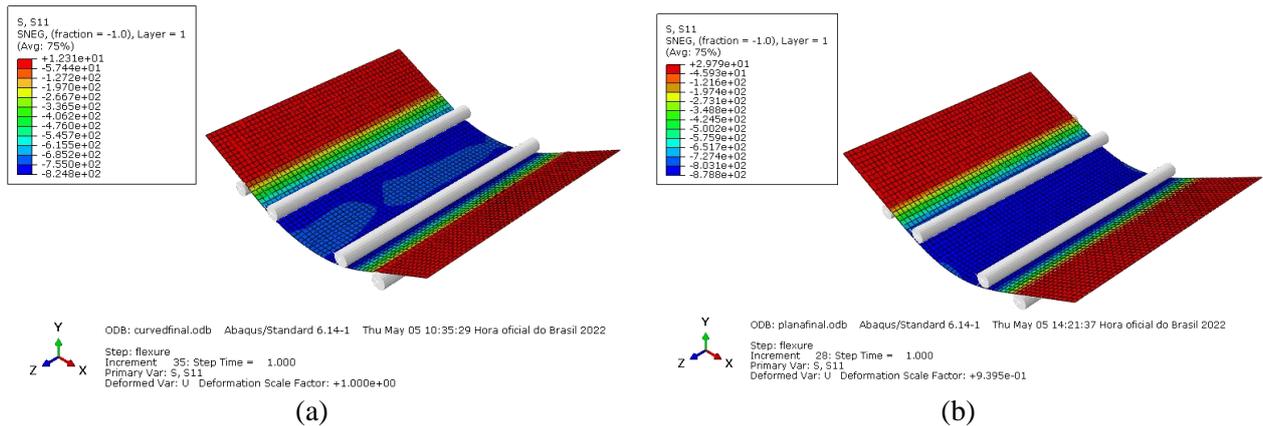
Figure 4: Computational stress for the composite plate (a) with stacking orientation $[0]_8$, and (b) with stacking orientation $[0/15/-15/0/15/-15]_s$.

Figure 5 presents the computational response for $[0]_8$ and $[0/15/-15/0/15/-15]_s$ carbon fibre composite plates, under a four-point bending test, respectively. The blue part represents the fibre damage (SDV5) and the red one, the intact structure. It is possible to observe that for the $[0]_8$ stacking sequence, the damage is located mainly around the support position, but also with lower magnitude in the centre of the plate. However, for the $[0/15/-15/0/15/-15]_s$ stacking sequence, the damage is located around the support, but with a higer magnitude in the centre of the plate in comparison with the plate $[0]_8$.
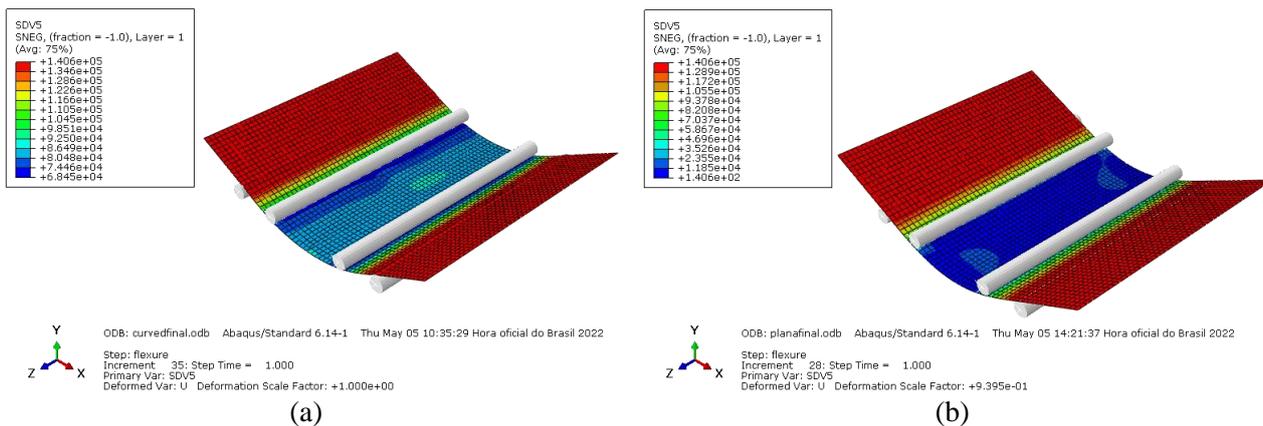

(a)   (b)

Figure 5: Computational response SDV5 (fibre damage) for the failure analysis composite plate (a) with stacking orientation $[0]_8$, and (b) with stacking orientation $[0/15/-15/0/15/-15]_s$.

Figures 6 and 7 show the computational and experimental force *vs.* displacement curves for $[0]_8$ and $[0/15/-15/0/15/-15]_s$ composite plates, respectively. The numerical and experimental results showed some differences. The differences between the experimental results and the computational analysis (Continuous Damage Model – UMAT) can be explained because of the uncertainty values in the numerical models such as total and each layer thickness, and curvature due to the manufacturing process of the plates. Futhermore, due to the continuum

damage mechanics formulation that takes into account the damage in the fibre and the matrix, however, the damage provided by delamination is neglected, and the magnitude of the time step in the discretisation during the computational analysis.
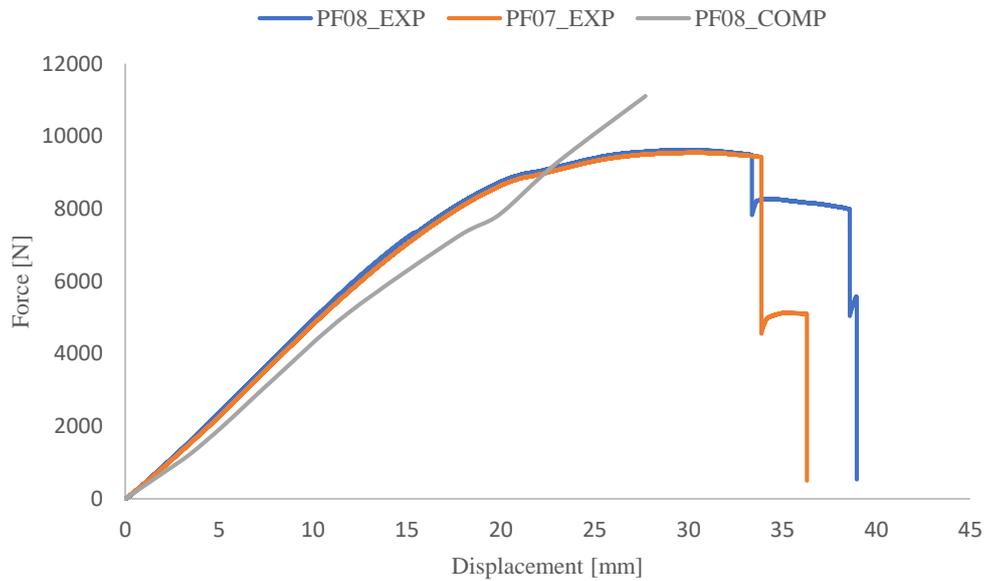

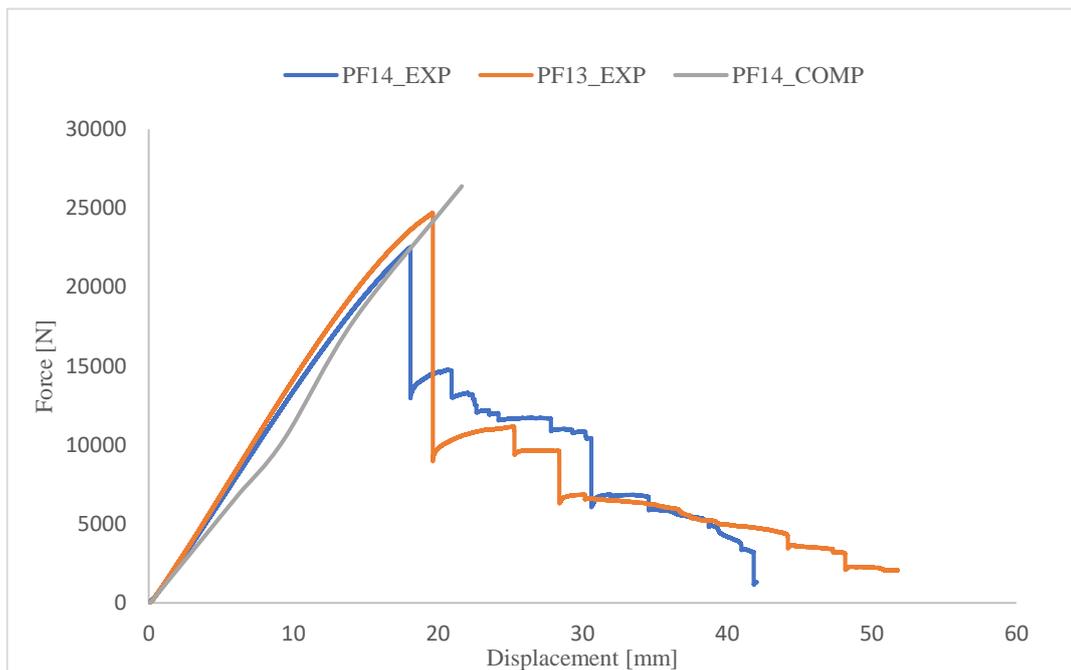Figure 6: Experimental and computational force *versus* displacement for the carbon fibre composite specimens $[0]_8$.

Figure 7: Experimental and computational force *versus* displacement for the carbon fibre composite specimens $[0/15/-15/0/15/-15]_s$

CONCLUSION

Progressive damage failure on the composite plates during a four-point bending test was analysed, where flexure is applied in plates with different stacking sequences and thicknesses. Numerical analyses are performed via the Finite Element Method to predict the progressive damage in the laminate structures by using ABAQUS™ software linked to the implemented UMAT (User Material Subroutine). The numerical and experimental results showed some differences due to the materials parameters and discretization used in the computational model. In addition, the continuum damage mechanics formulation neglected the delamination effects. Further verification for the material parameters, mesh, and delamination effect will be done to improve general conclusions about the progressive damage model. However, there is a good perspective for the application of this model for composite structures.

ACKNOWLEDGMENTS

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