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DEFORMATION PREDICTION OF COMPOSITE SPECIMENS SUBJECTED TO THREE-POINT BENDING TESTS

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Abstract: *A computational and experimental study was performed in order to determine the deformations of specimens made of laminated composite material when submitted to three-point bending test.*
The specimens were produced using unidirectional carbon fiber prepreg with different aspect ratios and different lamination schemes. The experimental values for the deformations of the bending tests were obtained using the innovative digital image correlation method.
The computational predictions were performed by two distinct models and compared to the experimental data: the first, developed in ANSYS, uses a solid element, in the laminated structural version, and assumes a displacement formulation; the second, not available in any commercial program, was developed by F. Moleiro [1], *and considers a mixed layerwise formulation that assumes displacements and transverse stresses as independent variables, and therefore it is able to fulfill a priori the C^0 interlaminar continuity of transverse stresses and displacements.*

This work shows that the ANSYS prediction model is fairly accurate for the longer specimens simulations, while better predictive values are obtained using the layerwise mixed model, when shorter specimens are considered.

1 INTRODUCTION

The analysis of structures in composite materials, which inherently exhibit an anisotropic behavior is more complex than traditional isotropic structures. Introduced by its anisotropic behavior, these structures may exhibit complex three-dimensional effects, such as high transverse deformation, zig-zag effects and interlaminar continuity [1].

For compatibility and equilibrium reasons, both displacements and transverse stress must be C^0 continuous functions along the thickness of the laminate (Z). This is addressed in the literature, as the requirements C_z^0 [1, 2].

The models based on layerwise theory (LWT) using a displacements formulation assume that only the displacement field exhibits continuity along the thickness, and evaluate a posteriori, by integration of the three-dimensional equilibrium equations, the interlaminar continuity of transverse stresses, thus fulfilling the requirements C_z^0. The LWT models that assume a mixed formulation are capable of a priori fulfill all requirements C_z^0 at the expense of greater computational effort, assuming both the displacement field and the transverse stresses [1, 2].

The LWT computational model used in this work was developed as part of the PhD thesis of Professor Filipa Moleiro "Least-Squares Mixed Finite Element Models for Analysis of multilayered Composite Plates" [3], which resulted in the paper "Layerwise least-squares mixed finite element models for static and free vibration analysis of multilayered composite plates" [1]. This model aims to accurately reproduce the real bending behavior of laminate composite structures, thus improving the predictive simulations possible to be obtained with the finite element models already developed and implemented in commercial available software, for the analysis of laminate composite structures.

This model, not available in any commercial software, provides with high accuracy the behavior of thick structures. The innovation of this model, as result of mixed formulation, is to a priori fulfill the requirements C_z^0. Unlike other LWT, which evaluate a posteriori the interlaminar continuity of transverse stresses, this model equally assumes as independent variables displacements and transverse stresses through its mixed formulation, allowing a priori satisfy the requirements C_z^0 [1].

This paper aims to computationally and experimentally determine the deformation of thin and moderately thick specimens made of composite material when subjected to three point bending tests, allowing for the comparison between both computational models and the experimental data, assumed as the real deformation of the specimens.

2 MATERIALS AND METHODS

During this work, four different unidirectional carbon fibre prepreg specimens of rectangular cross-section were produced, using an autoclave pressure-temperature curing process. These specimens were then submitted to experimental three point bending tests and the deformation values were assessed using the digital image correlation method for comparison with the computational predictions obtained by both models: the ANSYS commercially available displacement formulation model, and the new layerwise mixed model proposed in [1, 3].

2.1 Materials

The specimens were produced using the T300 carbon epoxy unidirectional prepreg with modified epoxy matrix resin, REM.

The number and orientation layers of the specimen are presented in Table 1.

One of the main difficulties encountered in the computation simulation of composite materials was the proper characterization of the material behaviour. For this purpose, the numerical method proposed and developed by A. Melro [4, 5] was used.

Table 1 – Number and orientation of specimen layers.

Specimen	Number of layers	Layers orientation [º]
P1	8	[0/0/90/90]s
P2	8	[0/0/45/90]s
P3	16	[0/0/45/45/90/90/0/0]s
P4	24	[0/0/0/-45/-45/90/90/90/45/45/0/0/0/0/-45/-45/90/90/90/45/45/0/0/0]

The method accounts for the properties variations resultant from the random fiber distribution in each specimen layer, accurately estimating their true individual elastic properties. For each z-layer distribution considered in the specimens, five random fiber distributions were created according to the proposed algorithm in [5]. For each distribution, the following properties were estimated: E_11, E_22, ν_12, ν_23, G_12, and G_13 G_23, thus allowing for the computation of a mean value for each property (Table 2).

Table 2 – Elastic properties output for the 5 random layers distributions.

	Dist.1	Dist.2	Dist.3	Dist.4	Dist.5	Mean
$\boldsymbol{E_{11}}$ [MPa]	126025	127750	130420	127130	128010	127870
$\boldsymbol{E_{22}}$ [MPa]	8492	8511	8420	8458	8434	8463
$\boldsymbol{\nu_{12}}$	0,244	0,249	0,256	0,247	0,249	0,249
$\boldsymbol{\nu_{23}}$	0,333	0,331	0,338	0,336	0,337	0,335
$\boldsymbol{G_{12}}$ [MPa]	4292	4401	4421	4455	4417	4397
$\boldsymbol{G_{13}}$ [MPa]	4498	4401	4315	4433	4378	4405
$\boldsymbol{G_{23}}$ [MPa]	3186	3197	3146	3166	3153	3170

2.2 Experimental Methods

The performed three point bending tests were intended to evaluate the elastic true deformation of the specimens when subject to a specific load, for comparison with the computational predictions. Experimental tests were conducted in accordance with ASTM D 790 "Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials" [6].

The tests were performed at a rate of 5 mm / min. The experimental assembly used for the support pins and for the load application pin, cylindrical rollers with 10 mm diameter (see Figure 1), with a spam (distance between support pins) of 60mm or 120mm, depending on the specimens dimensions.

Elastic displacement of the specimens was evaluated using a digital image correlation tool, DIC. This method captures successive pictures throughout the load application period, thus assessing the continuous change in the specimens surface, caused by their elastic deformation [7].

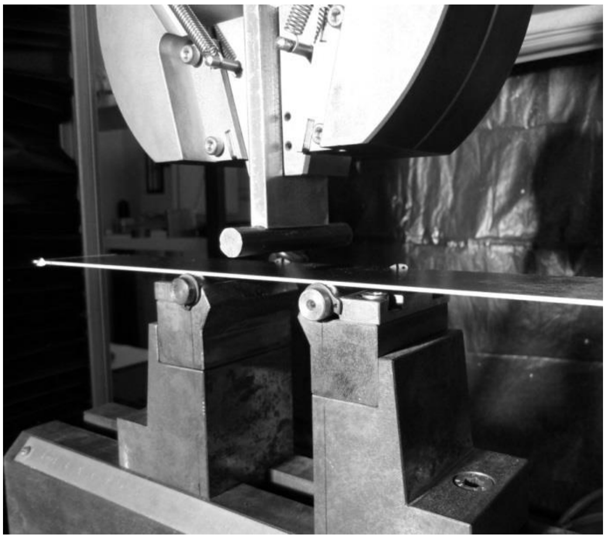


Figure 1 - Detail of support pins, load application pins and specimen before testing.

2.3 Computational Methods

Some of the most relevant and challenging aspects when developing scientific work meant to validate computational predictive models with experimental data consist of building computational models that are able to accurately reproduce the true boundary conditions and the true load application used in the experimental assembly, as well as to simulate the real material properties of the specimens. As the strength and validity of all scientific validation work strongly depends on these three aspects, while developing the finite element models, a great effort was put into reproducing the constraints used in the experimental characterization, as well as into simulating the actual specimens material properties. Additionally, the two models used (ANSYS and layerwise mixed) should be as similar as possible, so that the comparative results obtained between both models and the experimental data is equivalent.

In order to comply with these demands, the mean values of material properties obtained by computer simulation of elastic properties presented in Table 2 were used in both models, and the same approximation of load distribution was considered to replicate the roller interaction with the specimen for both numerical models. This approximation consists of applying the load by a pressure distribution using a sine function in the spanwise direction of the specimen, along the full width of the specimens. The sine function is applied to the nodes correspondent to the diameter of the roller.

For the two rollers on which the specimen rest, provided the distance between them is known (span), it was possible include in the boundary conditions definition the simulation of the true interaction between the rollers and the samples, allowing for the sliding movement of the specimen on the rollers for both implemented models.

2.3.1 ANSYS Model

As the element used in the layerwise simulation is a solid element, the element chosen in the ANSYS simulation was SOLID186 [8], in order to approximate as much as possible both computational models. The element was used in its laminated structural option with pure displacement formulation.

The constraints and loading was applied as described above. A convergence study was performed to determine the total number of elements required for fully converged displacement results. The resultant mesh uses a total of 3200 elements and is increasingly refined in the specimens longitudinal direction towards the area of the sinusoidal load application, Figure 2. In the same figure, it is also possible to observe the boundary conditions applied in the length direction, that simulate the supports over which, the specimen is allowed to slide.

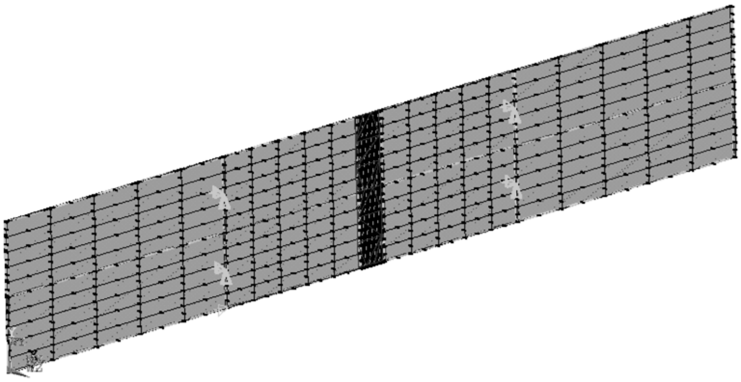


Figure 2 -Mesh refinement and constraints and loading application in ANSYS model

2.3.2 Layerwise Mixed Model

The layerwise mixed model previously developed and applied in this work presents some differences when compared to the most common models available in commercial programs, mainly in the element number and in the element approximation order. In practice, while the commercially available finite element models (*e.g.* ANSYS models) use elements with a relatively low number of nodes, and typically the accuracy of results is obtained by increasing the number of elements used, the layerwise mixed models are more efficient using in general a relatively lower number of elements, and obtain the refinement of results by increasing the element order approximation.

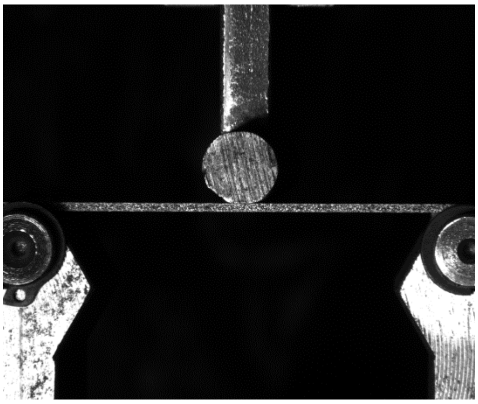
The model refinement can be performed in-plane and/or in the thickness direction. The refinement in-plane can be obtained by increasing the number of in-plane elements and/or by increasing the order of approximation of the in-plane elements. The refinement in the thickness direction can be obtained by increasing the number of layers used to simulate each of the specimen layers and/or by increasing the order of approximation through the thickness of each layer.

Mesh refinement should always begin by establishing a reasonable minimum number of elements in-plane and a minimum number of layers along the specimen thickness, and then focus on increasing the order of approximation of the elements in-plane and/or on increasing order of approximation through the layer thickness, which ultimately increases the number of nodes in each element in-plane and the number of nodes through the thickness of each layer, respectively [3].

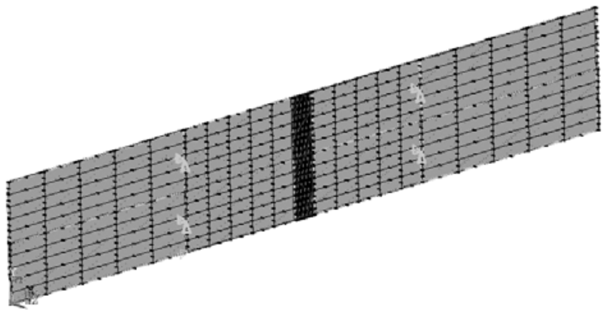
Layerwise mixed model numerical simulations were performed using fourth order elements in-plane (5x5 nodes on each element in-plane) and fourth order in each layer thickness(5 nodes through the thickness of each layer). In order to maintain the in-plane element side ratio near unity, 6 elements were used for specimens with a smallest span, and 10 elements were used for the case for the higher span specimens.

3 RESULTS AND DISCUSSION

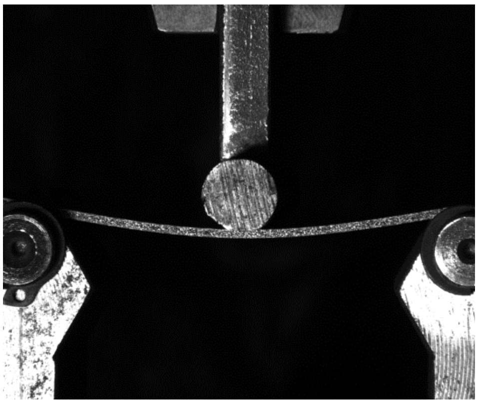
This section presents and compares the deformation results, obtained for each specimen by the three different methods: experimental tests (DIC), and finite elements(ANSYS model and layerwise mixed model). Figure 3 presents shape images of the specimen before and after the load application (undeformed and deformed shape) for the case of the ANSYS computational model and for the experimental test (obtained by DIC). The layerwise mixed model provides only numerical results.



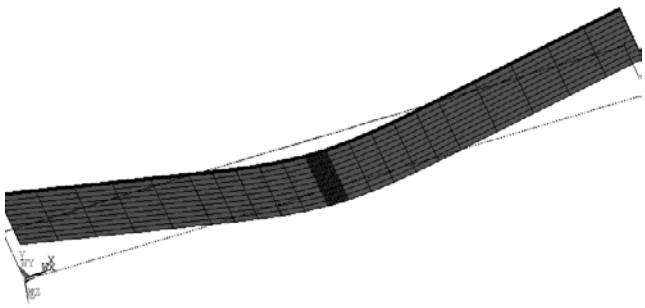
(a) Experimental test before the load application.



(b) ANSYS model before the load application.



(c) Experimental test after the load application.



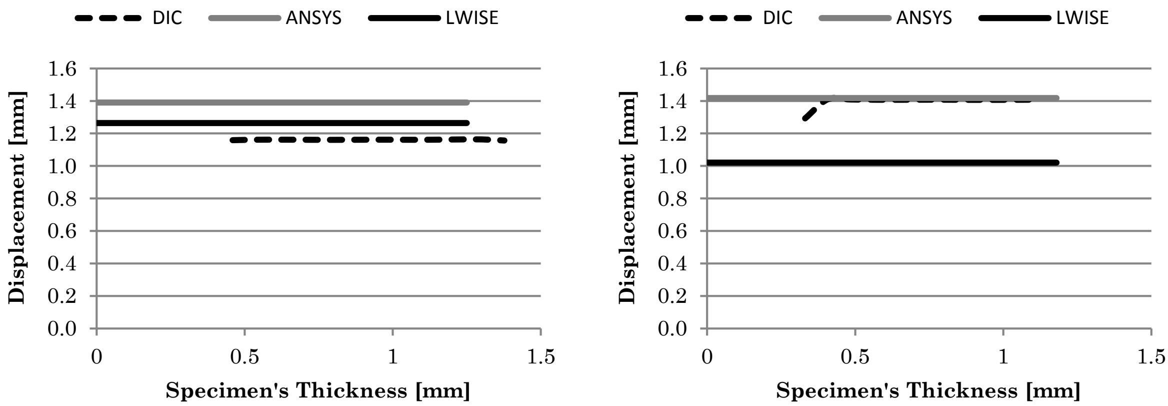
(d) ANSYS model after the load application.

Figure 3 –Comparison between the experimental test and ANSYS model, before and after load application.

Figures 4-7 presents a number of 8 different graphs, comparing the vertical displacement along the thickness of the test specimens obtained experimentally (with the DIC measurement technique), with the numerical predictions provided by both models. For each of the 4 different type of stacks considered, results are presented for the case of 60 mm and 120 mm span specimens, respectively.

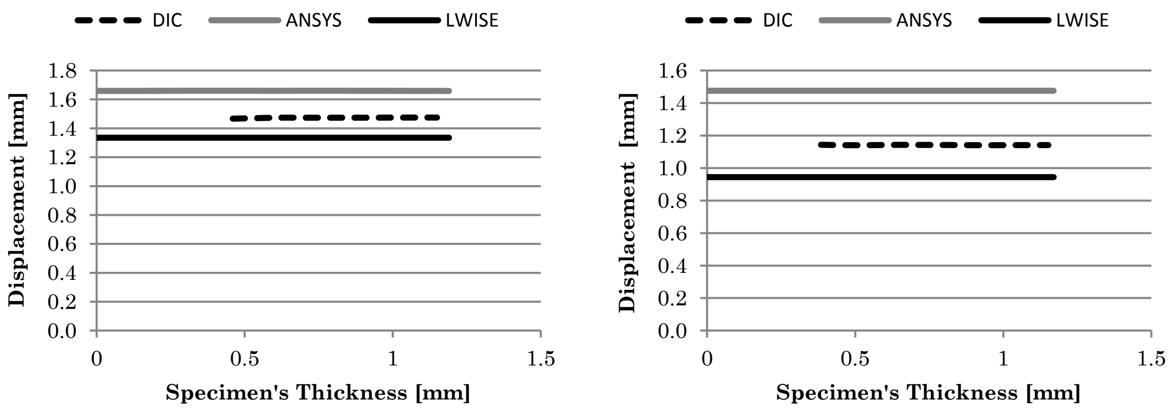
For experimental tests, the pixels used for results processing relate to the area immediately below of roller load application point. For computational methods the displacement values used to obtain the solution correspond to the nodes that are located below to the maximum peak pressure applied by the sine function that simulates the roll.

For each of the 8 presented graphs, the load prescribed is different and was chosen to be a representative value (intermediate value within the wide range of load values tested).



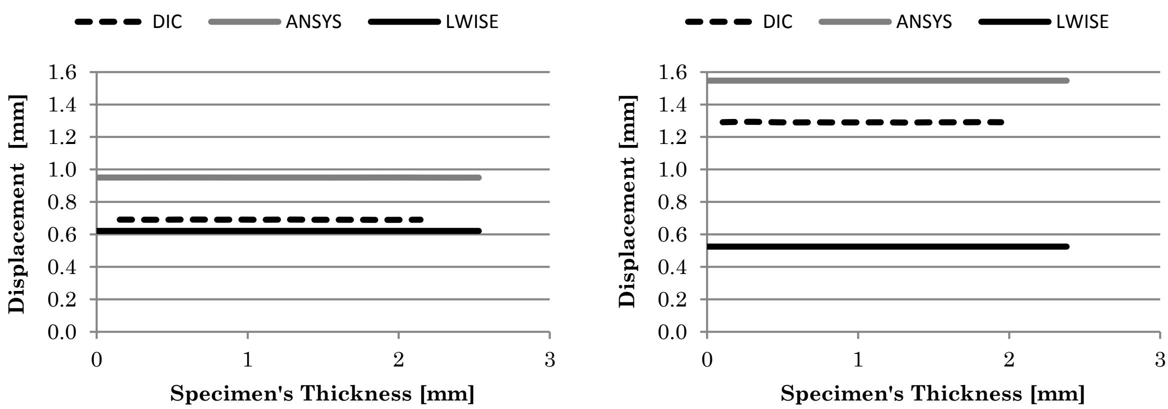
(a) Specimen P1 *span* 60mm at 250,34N. (b) Specimen P1 *span* 120mm at 27,21N.

Figure 4 –Comparison of the experimental (DIC) and computational (ANSYS model and layerwise mixed model) values obtained for P1.



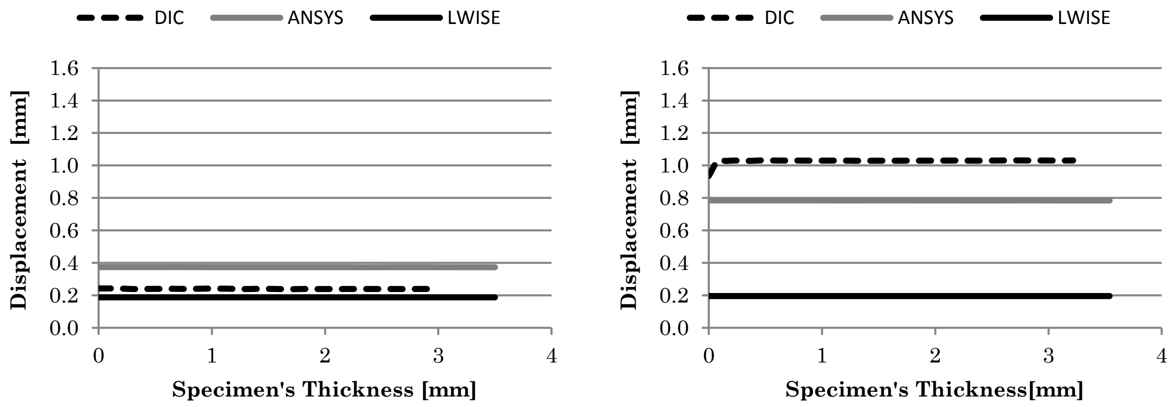
(a) Specimen P2 *span* 60mm at 253,18N. (b) Specimen P2 *span* 120mm at 27,51N.

Figure 5 –Comparison of the experimental (DIC) and computational (ANSYS model and layerwise mixed model) values obtained for P2.



(a) Specimen P3 *span* 60mm at 995,95N. (b) Specimen P3 *span* 120mm ta 178,67N.

Figure 6 –Comparison of the experimental (DIC) and computational (ANSYS model and layerwise mixed model) values obtained for P3.



(a) Specimen P4 *span* 60mm at 995,06N. (b) Specimen P4 *span* 120mm at 292,02N.

Figure 7 –Comparison of the experimental (DIC) and computational (ANSYS model and layerwise mixed model) values obtained for P4.

Table 3 compares for each type specimen, both numerical models predictions with the experimental data. The values of the deformations relate to the surface of the specimens (maximum thickness) and are presented in millimeters with two decimal numbers, reflecting the accuracy of the DIC and as the level to which the ANSYS model convergence was considered. The last four columns of Table 3 refer to the absolute and relative differences between the numerical predictions and the experimental values.

Table 3–Approximation of the models to the experimental values due to the type of each specimen.

		Displacement			Absolute difference [mm]	Absolute difference [mm]	Relative difference [%]	Relative difference [%]
		DIC [mm]	**ANSYS [mm]**	**LWISE [mm]**				
		(A)	**(B)**	**(C)**	**|A - B|**	**|A - C|**	**|A - B|/A**	**|A - C|/A**
P1	**Short**	1,16	1,39	1,26	0,23	0,11	20,19	9,25
	Long	1,41	1,42	1,02	0,01	0,39	0,71	27,51
P2	**Short**	1,48	1,66	1,34	0,18	0,14	12,47	9,48
	Long	1,14	1,48	0,94	0,33	0,20	29,17	17,28
P3	**Short**	0,69	0,95	0,62	0,26	0,07	37,50	10,03
	Long	1,29	1,55	0,52	0,26	0,77	19,85	59,33
P4	**Short**	0,24	0,37	0,19	0,13	0,05	55,72	21,69
	Long	1,03	0,78	0,20	0,25	0,83	23,88	80,99

The ability of one model better approximate reality against another model is itself a complex and treacherous analysis, as the experimental measurements, assumed as the real displacements, may contain errors.

However, it was possible to identify a constant pattern in the results. Apparently the short specimens (60mm span) are best approximated by layerwise mixed model, while longer samples(120mm span) appear to be better approximated by the ANSYS model.

This tendency was expected, the short specimens fall into the context "thick specimen", while and the long specimens are to be considered as "thin specimen." Nevertheless, some caution must be taken in this work in the characterization of the specimens.

In literature, what establishes the thin or thick specimens denomination is the length to thickness ratio of the specimens - a /h. Therefore, very thick specimens to moderately thick have 2<a/ h<10, moderately thick to very thin samples have20<a/ h<500[1].

However, for the cases here addressed, the ratio a/h must be taken carefully, as it may result somewhat compromised due to the extremely low thickness of some of the specimens used (*e.g.* 1 mm). For instance, for P1with a 120 mm span, the ratio a/h =120/1 =120, but for the P4 with equal span of 120 mm, the ratio a /h =120/3= 40. Therefore, despite both being long specimens, according to this a /h criterion P1 is considered thin while P4 is considered moderately thick.

Therefore, it was considered that to analyze the results according to the ratio a/h would not perhaps be the most adequate (considering the width of the specimens used), but according to the "short" and "long" specimens denomination, instead.

It should be noted that there are some variables that may influence the results, and that can introduce deviations between the results obtained by the different methods used in this work. Of particular importance were the facts that the specimens were produced manually, and included processes limitations regarding cutting the pressure-temperature curing, and the cutting of the specimens, which introduced some variability in the results, which determination and quantification is rather complex. In particular, it was found that the P4 specimen was slightly twist. On the other hand, some input parameters in the computational analysis, as the specimen thickness, consisted on values resulting from averages of low sensitivity measurements taken along the specimen length, which can also contribute to an increase of the error in the analysis made. Also layer elastic properties estimation can contribute to increasing the deviation, as well as the use of the experimental equipment DIC bears some uncertainty in the experimental data measured. The DIC equipment uses the digital image correlation technique to determine the displacement field of a given flat surface, on which an image pattern must be applied in order to allow for the identification of image surface image variations. The measurements success is directly related to application of this pattern to the surface of the specimen. The pattern application is manually performed, thus being difficult to control. Typically, a spot pattern is used obtained by spray painting the specimen, which hardly allows to get the ideal quantity, shape and size of spots to ensure consistent and transversal accuracy to the tests.

Additionally, the use of the DIC system also presents some difficulty in following the spots located in the roll / specimen interaction zone. Thus, some specimen points immediately below the load roller, are discolored when the images are being processed, preventing the system from properly follow their movement. Therefore, the results for this region may result less accurate than desired, due to a poor correlation process, to the lack of information on specific pixels, or to the combination of both factors.

The limitations resultant from the use of the DIC are visible in some of the graphs of Figures 4-7, namely the initial values of the deformation, near the load application point, which have an initial evolution that differs from the expected trends (Graphic B of Figure 7) or that show absence of results (Graphic A of Figure 5).

The innovative layerwise mixed model used in this work, has its stronger potential in providing high accuracy previsions for the behavior of thick structures, where other models struggle to obtain accurate results. In fact, during this work it was found that when comparing this model to the numerical model using the ANSYS displacement formulation model, the layerwise mixed model generally obtains displacement predictions that better approximate the experimental results, when short specimens are considered. Nonetheless, for the case of long samples, the ANSYS model obtains results that are closer to the experimental data, which may be attributed to the fact that for the case of thin plates, the advantages of the layerwise mixed model become less relevant as the traditional formulations are fully capable of accurately reproducing the solutions, and the excessive computational effort required for the layerwise mixed formulation bears its cost.

4 CONLUSIONS

Several specimens with different layers thicknesses and directions of unidirectional carbon fiber prepreg were constructed. These samples were subject to three point bending tests, and deformation along the thickness was evaluated using the digital image correlation method (DIC). Experimental tests were numerically reproduced through two different models. One of the models used the commercially available ANSYS® program and the other, the layerwise mixed model proposed under Professor Filipa Moleiro PhD thesis "Least-Squares Mixed Finite Element Models for Analysis of multilayered Composite Plates" [3] which resulted in publication of the article "Least-Squares Layerwise Mixed Finite Element Models for Static and Free Vibration Analysis of Composite Plates multilayered" [1]. This model had been published comparing the results with the exact solutions, but had not yet been subject to experimental validation.

Despite, the existence of differences that cannot be overlooked, it was verified that the layerwise mixed model presented results closer to the experimental data for short specimens, while the ANSYS model presented results closer to the experimental data when long samples are considered. In fact, for the case of short specimens, experimental results were fairly well predicted with the layerwise model, which provided errors around 10% for all cases with exception of P4; and for the case of long specimens, although both models provided overall poor predictions, the ANSYS model resulted slightly better, providing errors that did not exceed 30%.

The discrepancies found in the results, may have been potentiated by some factors that despite, the effort put into reducing the variability of the process were not overcome. This factors affected both, the experimental data, and the numerical predictions as well. In particular, for the experimental tests, the use of DIC depends on the application of the random pattern and bears limitations in assessing the displacements in areas located near the load application roll, and the manufacture of the specimens is difficult to control. Whereas for the computational models, the dimensions of the specimens were based on mean values of measurements, and the layer elastic properties were estimated values.

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