SIZE EFFECTS ON THE TENSILE AND COMPRESSIVE FAILURE OF NOTCHED COMPOSITE LAMINATES

G. H. Erçin[1*], P. P. Camanho[2], S. Mahdi[3], P. Linde[4], J. Xavier[5], M. Bessa[2]

[1] *Instituto de Engenharia Mecânica e Gestão Industrial (INEGI) Universidade do Porto Rua Dr. Roberto Frias, 4200*-465 Porto, Portugal, *web page:* http://www.inegi.up.pt
[2] *Faculdade de Engenharia da Universidade do Porto (FEUP) Universidade do Porto Rua Dr. Roberto Frias, 4200-465 Porto, Portugal*
[3] *AIRBUS OPERATIONS SAS 316, Route de Bayonne 31060 Toulouse Cedex 03 France*
[4] *AIRBUS Operations GmbH Kreetslag 10 21129 Hamburg Germany*
[5] *CITAB/UTAD, Engenharias I Apartado 1013, 5001-801 Vila Real, Portugal*
** e-mail: hgulsum@inegi.up.pt*

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Abstract

An experimental and analytical investigation of the effect of size on the strength of composite laminates with central holes loaded in tension and compression is presented. Specimens with different hole sizes and with constant width-to-diameter ratios were tested is tension and compression under quasi-static loading and the strength reduction for increasing sizes was quantified. In addition, centered cracked specimens loaded in tension and in compression were tested to obtain the laminate fracture toughness. This laminate property is required for the strength prediction method. The applicability of available strength prediction methods (point-stress method and cohesive model) to simulate the effect of size on the strength of notched composites is discussed.

1. Introduction

The understanding of the scaling effects on the strength of polymer composites is essential for the design of large-scale composite structures. The main objective of this work is to evaluate the effects of size on the tensile and compressive response of polymer composites and to assess the applicability of exciting strength prediction methods. An experimental and analytical investigation of the effect of size effect on the strength of open-hole laminates loaded in tension and compression is presented. The test results include tensile and compressive tests in unnotched specimens and in open-hole specimens. Digital Image Correlation system was used to measure the strain field on the test specimens and to track the onset and propagation of the failure mechanisms that occur on the surface ply. The analytical implementation of the point stress model (PSM), cohesive zone model (CZM) and the Finite Fracture Model (FFM) and the corresponding validation are presented.

2. Manufacturing Process

The material used for this investigation is the Hexcel T800/M21 pre-impegrated CFM. Two lay-ups are selected: $[90/+45/0/-45]_{3s}$ and $[90_2/0_2/+45_2/-45_2/90/0/45/-45]_s$. The material was cured according to the Hexcel's specifications. After curing the two laminates, the specimens were cut considering the necessary geometries and specimen number for each test case. The Open Hole test matrices for the two laminates are given in Tables 1 & 2.

Ref.	l	t	w	d	w/d	Condition	# of specimens	Standard
OHT1	250	3	12	3	4	RT/D	3+1	ASTM D 5766
OHT2	250	3	20	5	4	RT/D	3+1	ASTM D 5766
OHT3	250	3	28	7	4	RT/D	3+1	ASTM D 5766

Table 1 Open-Hole Tension test matrix for the two laminates.

Ref.	l	t	w	d	w/d	Condition	# of specimens	Standard
OHC1	305	3	12	3	4	RT/D	3+1	ASTM D 6484
OHC2	305	3	20	5	4	RT/D	3+1	ASTM D 6484
OHC3	305	3	28	7	4	RT/D	3+1	ASTM D 6484

Table 2 Open-Hole Compression test matrix for the two laminates.

3. Open Hole Tension

Specimens with a width-to-diameter ratio (w/d=4) for 3 different geometric configurations are tested by using MTS servo hydraulic machine following the ASTM standard D 5766 [4]. The Aramis DIC system is used to measure the strain field in the specimens. One specimen of each configuration is tested by using Aramis on one side and a strain gauge on the other side. For the strain gauge installations, “Vishay c2A-13-125LW-350” type of strain gauge is used. The strain gauges are installed near the hole, in the vertical direction for the OHT specimens and in the center of the specimen in the vertical direction for the UT specimen. The test results for the $[90/+45/0/-45]_{3s}$ are shown in Table 3 and for the $[90_2/0_2/+45_2/-45_2/90/0/45/-45]_s$ are shown in Table 4. The remote failure stress ($\sigma\infty$) is defined using the failure load measured in the tests (Pmax) and the measured values of the specimen thickness (t) and width (w) as: $\sigma\infty =$ Pmax /(tw).

Specimen Ref.	w (mm)	d (mm)	σ (MPa)	Ɛ (µm/m)	STDV (MPa)
OHT1_mean	12	3	555.38	7842.35	12.56
OHT2_mean	20	5	535.97	4948.35	12.21
OHT3_mean	28	7	495.86	3097.08	15.20

Table 3 OHT test results for the ICOMP – Lam#1 - $[90/+45/0/-45]_{3s}$ specimens.

Specimen Ref.	w (mm)	d (mm)	σ (MPa)	Ɛ (µm/m)	STDV (MPa)
OHT4_mean	12	3	567,05	5940,40	19,71
OHT5_mean	20	5	532,52	3792,65	12,77
OHT6_mean	28	7	523,61	2739,02	12,22

Table 4 OHT test results for ICOMP – Lam#2 - $[90_2/0_2/+45_2/-45_2/90/0/45/-45]$s specimens.

The hole size effect for the $[90/+45/0/-45]_{3s}$ is shown in Figure 3 for the open hole tension specimens with the hole sizes of 3mm, 5mm and 7mm.

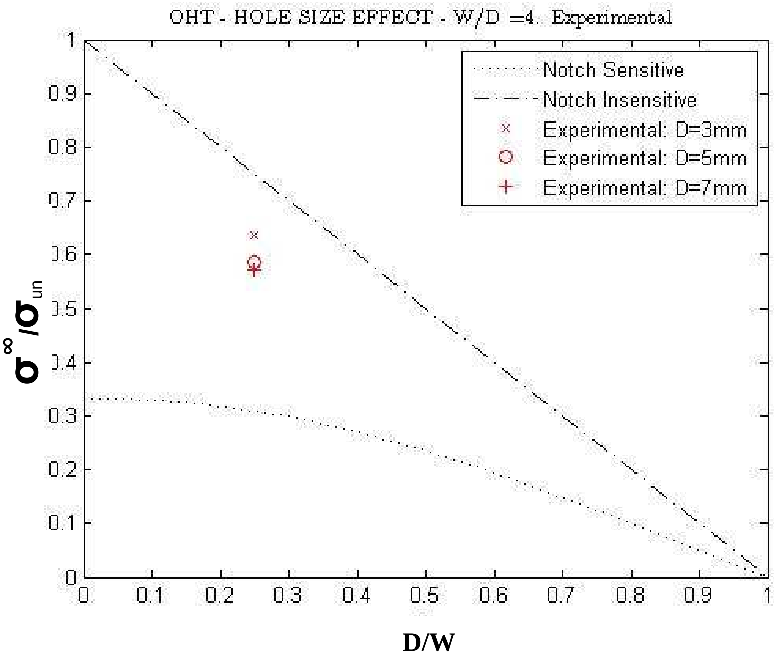

Figure 1 Hole Size Effect Plot

The experimental results presented in Table 3 and Figure 3 clearly identify a size effect for the [90/+45/0/-45]$_{3S}$: an increase in the hole diameter from 3mm to 7mm results in a reduction in the strength of 10.7%.

4. Open Hole Compression

Open-Hole compression tests were performed using both Aramis and Strain Gages and therefore the tests results are obtained from the MTS Load Cell data, Aramis – DIC data and the Spider - Catman program. Specimens with a width-to-diameter ratio (w/d=4) for 3 different geometric configurations are tested by following the ASTM D6484 / D6484M - 09 [7]. For both laminates one specimen from each configuration are analyzed by comparing the data obtained by the Aramis and the strain gages. In Table 5 and Table 6 the test results are given for the [90/+45/0/-45]$_{3s}$ and [90$_2$/0$_2$/+45$_2$/-45$_2$/90/0/45/-45]$_s$ laminate.

Specimen Ref.	σ (Mpa)	SG1 Ɛ (µm/m)	SG2 Ɛ (µm/m)	DIC Ɛ (µm/m)	STDV (Mpa)
OHC1_mean	334.45	4382.64	4241.93	4791.2	39.36
OHC2_mean	279.82	2861.62	4527.55	1889.79	13.58
OHC3_mean	258.82	2405.22	1009.48	952.17	5.26

Table 5 OHC Test Results of the [90/+45/0/-45]$_{3s}$ laminate obtained from Aramis and Strain Gages

Specimen Ref.	σ (MPa)	SG1 Ɛ (µm/m)	SG2 Ɛ (µm/m)	DIC Ɛ (µm/m)	STDV (MPa)
OHC4_mean	325.43	4187.35	4504.74	3673.02	19.58
OHC5_mean	299.65	2852.88	2667.57	2696.78	15.07
OHC6_mean	283.36	1825.82	1856.23	2050.57	12.59

Table 6 OHC Test Results of the [90$_2$/0$_2$/+45$_2$/-45$_2$/90/0/45/-45]$_s$ obtained from Aramis and Strain Gages

In Figure 5 the hole size effect on the strength of the OHC specimens for the laminate [90/+45/0/-45]$_{3s}$ are given for the three different hole diameters.

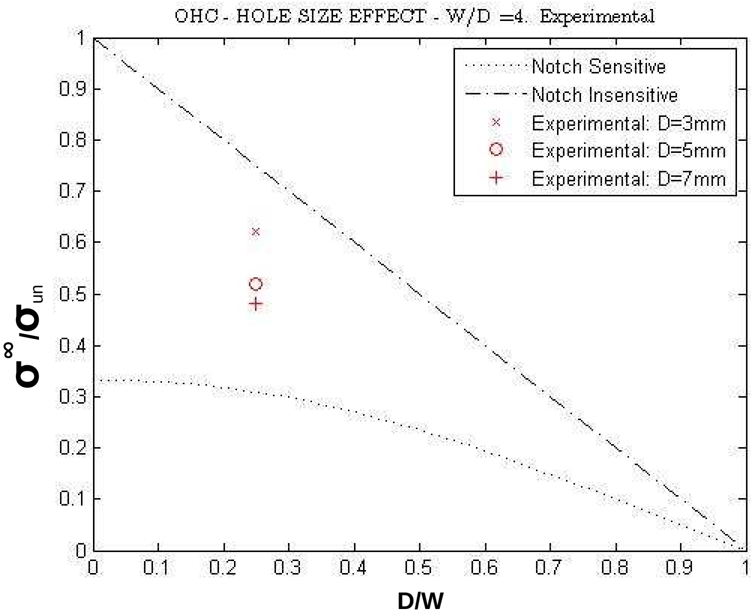

Figure 5 Hole Size Effect Plot for the OHC

The experimental results of the [90/+45/0/-45]$_{3s}$ presented in Table 5 and Figure 5 clearly identify a size effect: an increase in the hole diameter from 3mm to 7mm results in a reduction the strength of 22.6%.

5. Application of the analytical models

5.1 Two-parameter methods: Point-Stress Model (PSM)

The Point-Stress Model (PSM) proposed by Whitney and Nuismer [6], considers that ultimate failure occurs when the stress at a given distance from the hole boundary (r_{ot} or r_{oc}), reaches the plain strength (X^L_T or X^L_C) of the laminate. Failure is predicted using the characteristic distance and the respective longitudinal tensile or compressive strength of the ply. Figures 6-9 show the analytical predictions and the corresponding test results. The specimen with a hole diameter of 5mm was used to calculate the characteristic distance. [25]

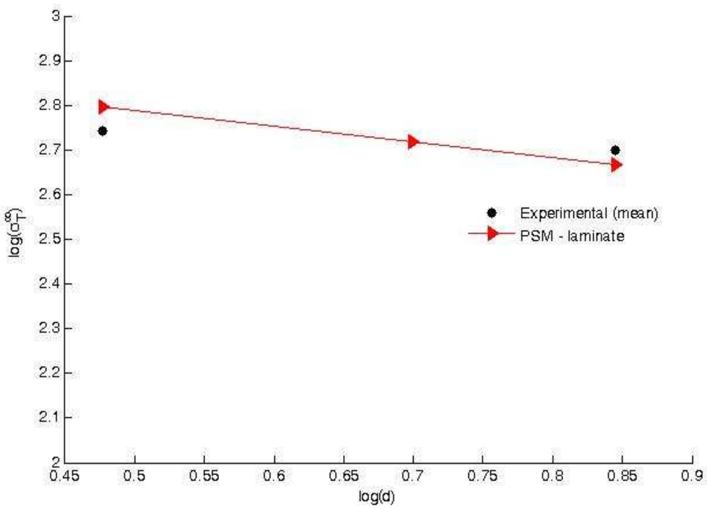

Figure 6 Point Stress Model for the T800/M21 [90/+45/0/-45]3s OHT Tests

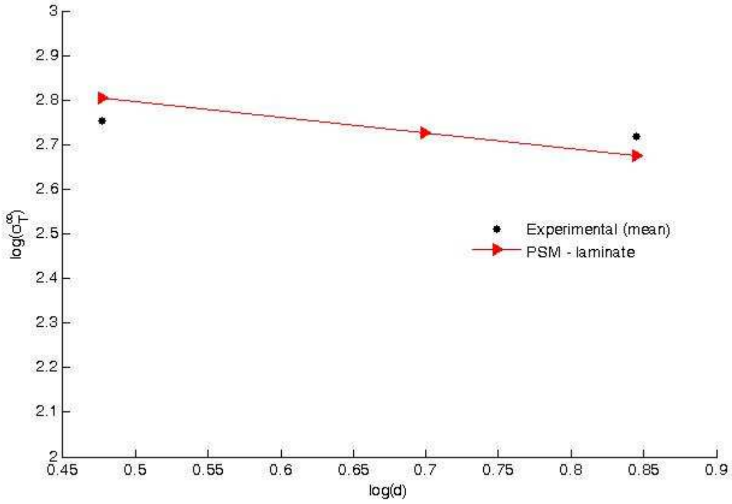

Figure 7 Point stress Model for the T800/M21 $[90_2/0_2/45_2/\text{-}45_2/90/0/45/\text{-}45]_s$ OHT Tests

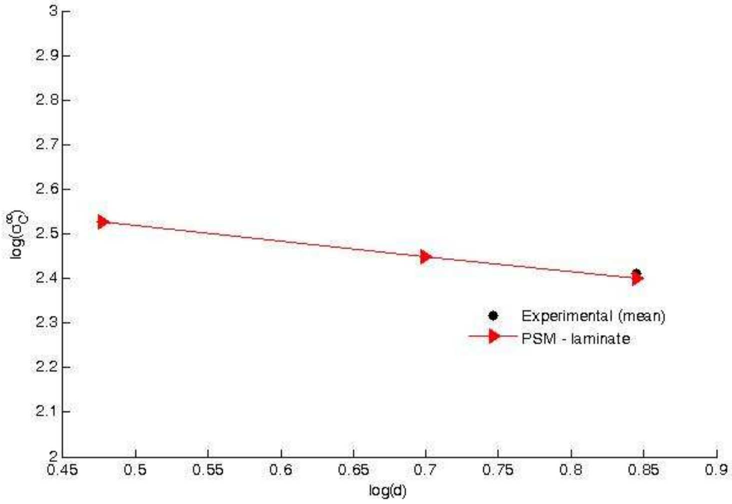

Figure 8 Point stress Model for the T800/M21 $[90/+45/0/\text{-}45]_{3s}$ OHC Tests

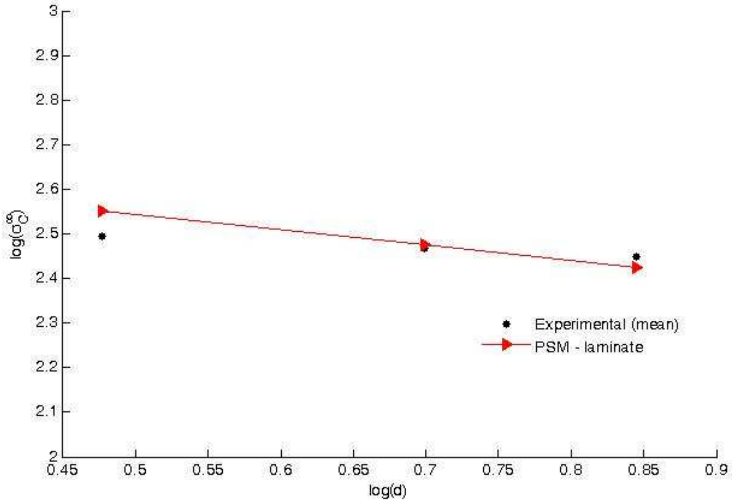

Figure 9 Point stress Model for the T800/M21 $[90_2/0_2/45_2/\text{-}45_2/90/0/45/\text{-}45]_s$ OHC Tests

5.2 Cohesive zone model: Budiansky-Fleck-Soutis (BFS) compressive criterion

The cohesive zone model is a failure prediction technique proposed by Soutis et al. [5] (Budiansky-Fleck-Soutis) to predict the failure load and critical damage length for a range of hole sizes for 0° dominated laminates. Figures 10-13 show the analytical predictions and the corresponding test results.

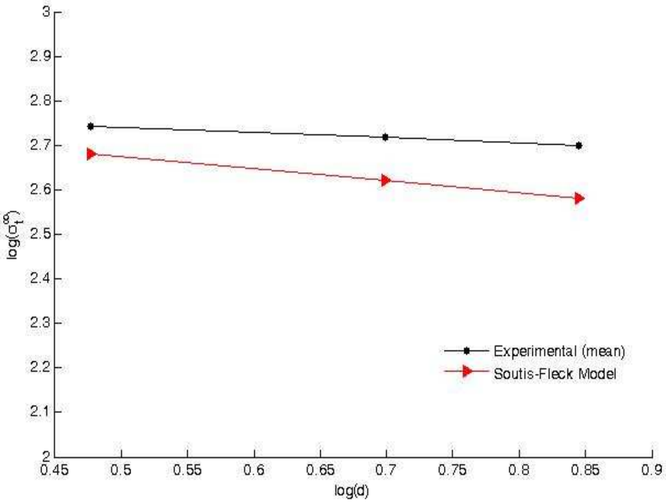

Figure 10 Cohesive Zone Model for the T800/M21 $[90/+45/0/-45]_{3s}$ OHT Tests

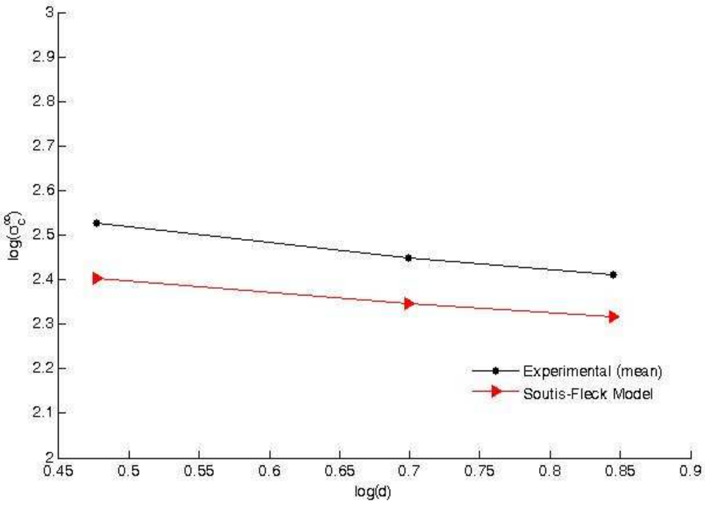

Figure 21 Cohesive Zone Model for the T800/M21 $[90/+45/0/-45]_{3s}$ OHC Tests

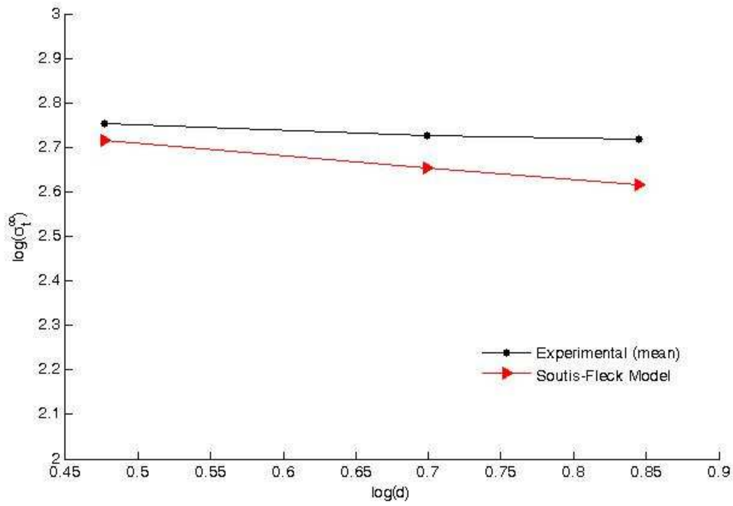

Figure 12 Cohesive Zone Model for the T800/M21 $[90_2/0_2/45_2/-45_2/90/0/45/-45]_s$ OHT Tests

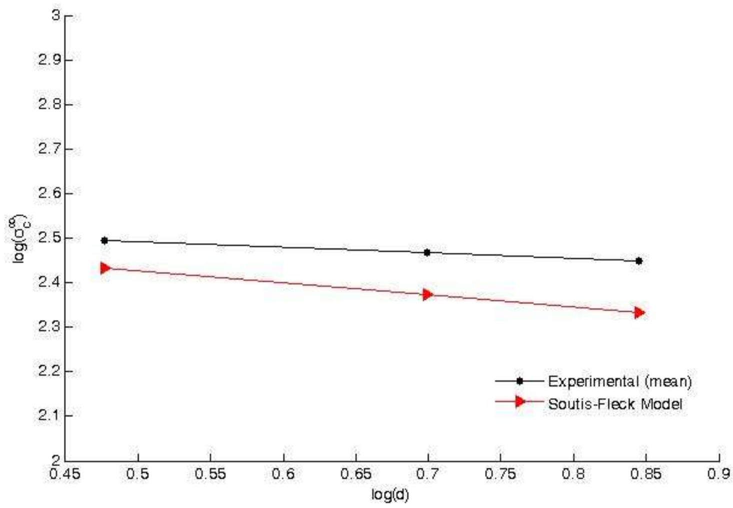

Figure 13 Cohesive Zone Model for the T800/M21 $[90_2/0_2/45_2/-45_2/90/0/45/-45]_s$ OHC Tests

6. Conclusion

In this study, open-hole tension and compression tests were performed for 2 different lay-ups and 3 different specimen geometries by using T800/-M21 material. The size effect on the material strength was observed. Strain gages and Aramis Digital Image correlation system are used for the stress-strain measurement. The Digital Image Correlation system enables the identification of the failure process of the top 90° ply. The results indicate that ply transverse cracking, both from the hole and from the free-edge, occurs well-before the final failure of the laminate. The results obtained using the Digital Image Correlation system can be used to validate in detail the analysis models (e.g. load corresponding to the onset of cracking and cracking pattern). Two parameter method using the point stress model [6] and Cohesive zone model using the Budiansky-Fleck-Soutis (BFS) compressive criterion [5] are applied for the open-hole tension and compression test specimens. The maximum errors obtained using point stress model (PSM) are 12.72% for the Laminate#1 & 2.66% for the Laminate#2 in Tension and 12.64% for the Laminate#1 & 13.47% for the Laminate#2 in Compression. The maximum errors obtained using Soutis-Fleck model (SF) are 23.9% for the Laminate#1 & 24.93% for the Laminate#2 in Tension and 21.18% for the Laminate#1 & 23.33% for the Laminate#2 in Compression.

7. Acknowledgements

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8. References

[1] S. R. Hallett, W. G. Jiang, and M. R. Wisnom, “The effect of stacking sequence on thickness scaling of tests on open hole tensile composite specimens,” 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural dynamics, and materials conference, vol. -, pp. 1–10, 2007.

[2] M. R. Wisnom, B. Green, W. G. Jiang, and S. R. Hallett, “Specimen size effects on the notched strength of composite laminates loaded in tension,” 16th International Conference on Composite Materials, Kyoto, Japan, vol. -, pp. –, 2007.

[3]C. Soutis and N. A. Fleck, “Static compression failure of carbon fibre t800/924c composite plate with a single hole,” Journal of Composite Materials, vol. 24, pp. 536–558, 1990.

[4] Open hole tensile strength of polymer composite laminates, ASTM D 5766/D 5766M-02a, American Society for Testing and Materials (ASTM), West Conshohocken, PA, U.S.A.

[5] Soutis, C., Fleck, N.A., Smith, P.A., Failure prediction technique for compression loaded carbon fibre-epoxy laminate with open holes. Journal of Composite Materials., 33:1476-98, 1991.

[6] Whitney, J.M. and Nuismer, R.J., Stress fracture criteria for laminated composites containing stress concentrations. Journal of Composite Materials. 1974; 8:253-65.

[7] Standard test method for open-hole compressive strength of polymer matrix composite laminates, ASTM D6484 / D6484M - 09, American Society for Testing and Materials (ASTM), West Conshohocken, PA, U.S.A.

[8] HexPly® M21 180°C (350°F) Curing Epoxy Matrix Product Data

[9] HexPly® UD/M21/35%/268/T800S Epoxy Matrix Product Data Sheet

[10] Bessa, M., MSc thesis, Faculty of Engineering, University of Porto, 2010.