Scaling effect in notched composites: the Discrete Ply Model approach

J. Serra[1], C. Bouvet[2], B. Castanié[3]and C. Petiot[4]

[1]Institut Clément Ader, MSC, ISAE, 10, Avenue Edouard Belin, 31400 Toulouse, France
Email: joel.serra81@gmail.com
[2] Institut Clément Ader, MSC, ISAE, 10, Avenue Edouard Belin, 31400 Toulouse, France
Email: christophe.bouvet@isae.fr
[3]Institut Clément Ader, MSC, INSA, 135, Avenue de Rangueil, 31400 Toulouse, France
Email: bruno.castanié@insa-toulouse.fr
[4]Airbus Group Innovations, 12, Rue Pasteur, 92152 Suresnes, France
Email: caroline.petiot@airbus.com

Keywords: Size effect, Open-hole tensile test, Discrete Ply Modelling, Experiments, Finite elements model

Abstract

Numerical and experimental investigations were carried out on the size effect in notched carbon/epoxy laminates. This paper presents a computational study of scaled open-hole tensile tests using the Discrete Ply Modeling (DPM) method, which has already proven efficient on both in-plane and out-of-plane loading cases, such as pull through, low velocity impact and compression after impact. The specificities of this finite element model are its discrete nature, the small number of parameters required and its robustness. Three different stacking sequences of thin plies coupled with three sizes of coupons having the same length to width ratio were tested. The results show that the model reflects the reduction in strength when the size of the specimen increases. Comparisons with experiments demonstrate that tensile strengths and failure scenarios and patterns are predicted with acceptable accuracy.

1. Introduction

Composite materials have now become indispensable for most transport vehicles, especially in the aerospace and astronautics sectors. The assembly of structures using such materials cannot avoid the presence of holes or cut-outs, which induce stress concentrations and reduce strength. Notched strength is hence one of the design drivers for composite structures. Moreover, holes have the particularity that they can be employed to model other complex forms of damage such as impacts or through-the-thickness cracks [1]. Scaling effects are at least as important since most tests are carried out on small coupons whereas real structures are 10 to 100 times larger. A deeper understanding of these scaling phenomena is still required in spite of the substantial amount of research devoted to it since its discovery by Leonardo da Vinci in the early 1500s.

Numerous experiments have been conducted to explore the physical causes of these phenomena [2]–[4]. As detailed in [5], size effects can occur at different levels. At the material level, an influence of the thickness has been detected, called the “in situ” effect. This phenomenon has been analyzed by Wisnom et al. on isotropic specimens in [3]. At the structural level, it has been proven that the strength of notched composite laminates decreases with increasing notch sizes when thin plies are used. It is the latter scale that is the focus of this article. The “hole size effect” is triggered by the presence of non-critical ply-level damage such as fiber fracture, fiber splitting, delamination and matrix failure in the vicinity of the hole [6], which blunts the stress concentration. The extent of this “fracture process zone” relative to the size of the specimen explains the strength difference between small and large specimens [5].

Preliminary sizing solutions were found with the point stress or the average stress models [7], [8] and all their extensions described by Awerbuch and Madhukar [9] or, more recently, with a volume

Excerpt from ISBN 978-3-00-053387-7

based criterion developed by Hochard et al. [10]. Camanho et al. then proposed an alternative method for predicting the strength of composite laminates loaded in tension and containing holes or cracks [11].

However, experimental tests revealed the substantial influence of the stacking sequence on both failure scenarios and strengths [8] . For example, the final failure of laminates manufactured with thick plies is mainly due to delamination [3]. In our study, it was experimentally determined on plain specimens that failure strength varied by thirty percent between two stacking sequences of a laminate containing the same number of plies in each direction. These fast semi-analytical and numerical methods do not take the influence of the stacking sequence into account since they consider that strain is constant within the laminate thickness [14]. This is why a more complete numerical model is needed to predict the physics associated with these failure phenomena (delamination and transverse cracks). Following the “Virtual Testing” approach, i.e. moving from numerous, expensive experimental tests towards robust, accurate numerical simulations, a large number of models have been proposed to fit experimental data.

Some of these numerical studies of size effects on open-hole tensile composite laminates have already been described by Chen et al. [15]. Delamination is often modeled using discrete elements. Pinho developed a model that predicts fiber and matrix failures using smeared crack models and delamination using cohesive interfaces [15]. ONERA developed a model composed of a multi-scale progressive failure approach to describe the softening behavior of a ply failing in fiber mode and cohesive zone elements to model delamination [16]. Similarly, a physics based, progressive damage model has also been developed by Ridha et al. to represent the different damage mechanisms. The modeling strategy [17] is based on a continuum damage mechanism for in-plane damage progression and cohesive elements for delamination.

Discrete elements may also be used to represent matrix cracks. For example, Wisnom and al. use a Weibull approach to predict fiber failure, cohesive elements between plies to model delamination, and within each ply to model potential splits initiating tangentially to the hole [25]. Recent discussions have concerned the need for discrete elements to correctly model matrix cracks and their interaction with delamination [20]. Pioneering this approach, the Discrete Ply Model (DPM) used in this paper employs cohesive interfaces to model matrix failure and delamination, and 3D volume elements to predict fiber failure. It should be noted that other researchers have simulated single matrix cracks using the cohesive zone model approach [21]–[25] but, as far as the authors know, none of them have focused on the open-hole tensile test scaling effect.

This discrete method (DPM) was initiated by Bouvet et al. for the modeling of low velocity impacts in composite panels [26] and was enhanced afterwards to capture permanent indentation [27] and to simulate compression after impact [28]. In this model, coupling between the intra- and inter-laminar damage is naturally taken into account through the use of interfaces connected by a specific mesh. This model has also been used to represent pull-through cases [29], where the effects of splitting on the load redistribution were correctly predicted. Moreover, after a modification of the hole contour mesh, the DPM has been able to predict notched strength, and failure scenarios and patterns with reasonable accuracy on different stacking sequences [30].

In this paper, open-hole tensile tests are performed and analyzed by means of the DPM method. Three different stacking sequences of thin plies coupled with three sizes of coupons with the same length to width ratio were tested. The following section gives details of the tests and samples. Then, the DPM modeling strategy is detailed and the results are compared with experimental data.

Excerpt from ISBN 978-3-00-053387-7

2. Experimental work

2.1. Material and setup

The material investigated in the present study was Hexcel's T700-M21 carbon epoxy unidirectional tape with a nominal ply thickness of 0.125 mm. Three types of stacking sequences were studied. Each laminate was symmetric and contained 13 plies, with the same number in each direction (0°, 90° and +/-45°), only the relative positions changed from one layup to another:

- C3-1 [45/-45/X/X/X/90/0/90/ X/X/X /-45/45]
- C3-2 [X/X/X/X/0/90/0/90/0/X/X/X/X]
- C3-3 [X/X/X/X/X/0/0/0/X/X/X/X/X]

The layups cannot be fully disclosed in this article. The in-plane scaled center notched specimens and plain specimens are shown diagrammatically in Figure 1. Three different sizes for the notched coupons were tested as described in Table 1. Specimens with a 1 mm diameter hole, specimens with a 3.175 mm diameter hole and specimens with a 6.35 mm diameter hole are respectively termed "Small", "Medium" and "Large" specimens hereafter.

Specimens	Hole diameter	Gauge width	Gauge length	End tab length
"Plain"	N.A.	15.00	90.00	50.00
"Small"	1.00	5.04	28.35	50.00
"Medium"	3.175	16.00	90.00	50.00
"Large"	6.35	32.00	180.00	50.00

Table 1:Dimensions of the plain and notched specimens(mm)

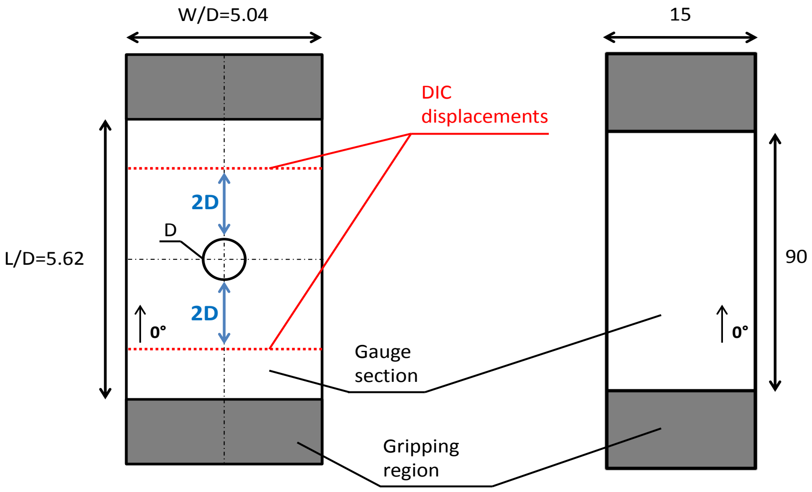

Figure 1: Open hole and plain specimen geometries (dimensions in mm)

Excerpt from ISBN 978-3-00-053387-7

Tests were performed using a 450 kN SCHENCK hydraulic driven machine for “Medium” and “Large” specimens, a 10 kN INSTRON electromechanical machine for the “Small” and a 20 kN INSTRON electromechanical machine for the “Plain” specimens, at ambient temperature and humidity. Coupons were tested under displacement control with scaled loading rates with regards to the specimen gauge lengths, the value being 0.02 mm/s for the “Large” specimens in order to obtain quasi-static loading conditions. The machines provided measurements of displacement and effort. For a more accurate value of the displacement, a linear displacement sensor (LVDT) was used.

Notched tests were also monitored by two stereocorrelation cameras on one side of the specimen and an infrared camera on the other as represented . Image analyses were performed with VIC 3D® for the stereo results and ALTAIR® for the infrared. It was, however, found after the tests that the coupons had slipped in the machine clamps. Consequently, the strain values shown in this paper come from the displacements determined using image correlation at a distance of 2D from the hole and averaged over a distance of 5D (Figure 1).

Each stacking sequence was tested to total failure with three specimens for the “Plain”, “Small” and “Medium” sizes, and two for the “Large” ones. A third coupon of the "Large" size has been tested up to various percentages of the total failure load.

2.2. Results

The test results showed little discrepancy (except for the “Small” / C3-3 combination) for the three coupon sizes combined with the three stacking sequences. Stress/strain curves of coupons n° 3, 6 and 9 of the “Small” specimens are not available because these specimens were filmed edge on, with the initial idea of detecting delamination by means of the infrared camera. Delamination damage being energetically very low and also very localized, it was not possible to record useful information about these phenomena. The only valid information was the failure strength reported in Table 2. Oriented Laminate C3-1 was the only layup for which damage recorded by the infrared camera was determined before total failure.

The experimental values presented in Table 2 clearly show a size effect: an increase in the hole diameter from 1 mm to 6.35 mm can result in a maximum decrease of 20% in strength. $\bar{\sigma}^{\infty}$ refers to the mean remote failure stress and CV to the coefficient of variation. Stress and strain values were normalized by the maximum values encountered in open-hole tests. Maximum stress was reached by coupon n°9 (C3-3, “Small”), whose stress/strain curve is not represented.

Specimens	C3-1		C3-2		C3-3	
	$\bar{\sigma}^{\infty}$ (%)	CV (%)	$\bar{\sigma}^{\infty}$ (%)	CV (%)	$\bar{\sigma}^{\infty}$ (%)	CV (%)
“Plain”	101.1	2.5	97.8	3.7	122.7	1.5
“Small”	75.8	4.4	72.1	1.6	88.4	9.4
“Medium”	69.6	1.7	66.8	4.5	82.8	0.7
“Large”	65.4	0.5	61.8	1.3	70.5	4.1

Table 2 : Results of plain and open-hole tensile tests

Consequent variations of plain failure stress were noted (Table 2) between composite laminates with the same number of plies in each orientation (only the relative positions differed). These variations were probably due to the relative influence of delamination triggered by free edge effects on

Excerpt from ISBN 978-3-00-053387-7

each of the stacking sequences studied. Mismatches in Poisson's ratios generated inter-laminar stresses [13], [31] and hence delamination. The influence of the phenomenon was confirmed by means of experimental observations and a method to predict the onset of delamination in the free edge regions of a symmetric laminate plate subjected to a uniform axial strain, such as the one exposed in the ESDU datasheet [32].

Failure patterns were all of the pull-out type, which demonstrates that some non-catastrophic damage, such as delamination and ply cracking, appeared before total failure [6].

3. Numérical analysis

3.1 Open –hole specimen mesh

The open-hole tension test was simulated using the finite element model described in [30]. The mesh was composed of specific elements, for the zone near the hole and with linear bricks near the extremities of the gauge zone (Figure 2). The latter elements, never damaged during the propagation of the crack emanating from the hole, made the calculation faster. Moreover, to further reduce the calculation cost, 2 symmetries were used (planar and circular).

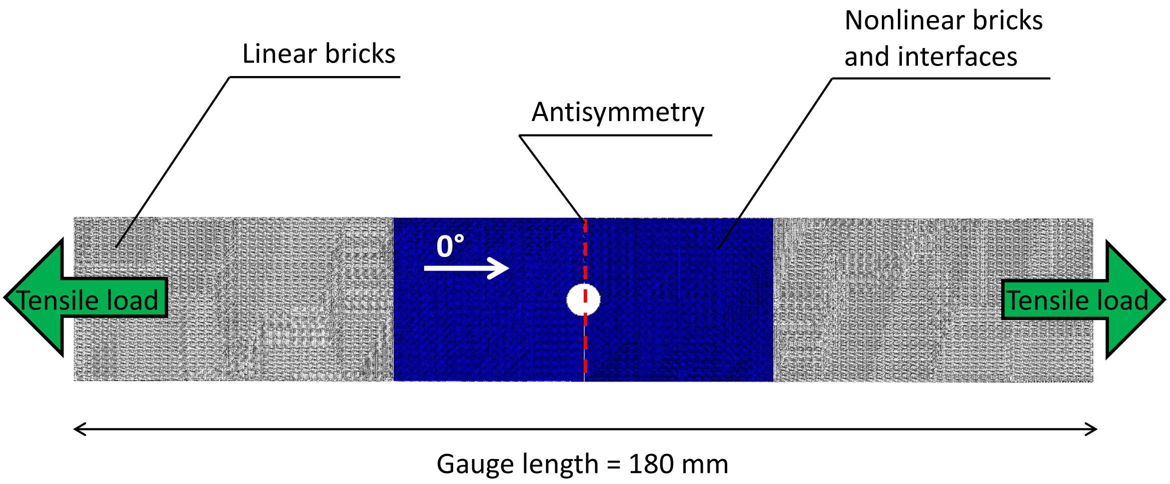

Figure 2:Numerical model of the 6.35mm diameter notched specimen under tension

3.2 C3-1 layup

Stress/strain curves obtained from numerical simulations are compared with experimental ones in Figure 3. The elastic part of the tests was very similar in simulation and experiment. It can be seen that the failure strengths are very well predicted for the three sizes.
Structural failure (B) and the other stiffness loss (C) were also determined numerically.
The only difference between experiment and simulation lay in the amplitude of the stiffness loss (C) for the "Small" specimen, which was slightly exaggerated by the model. This was probably due to the extent of the damage being too great compared with experiments.

Excerpt from ISBN 978-3-00-053387-7

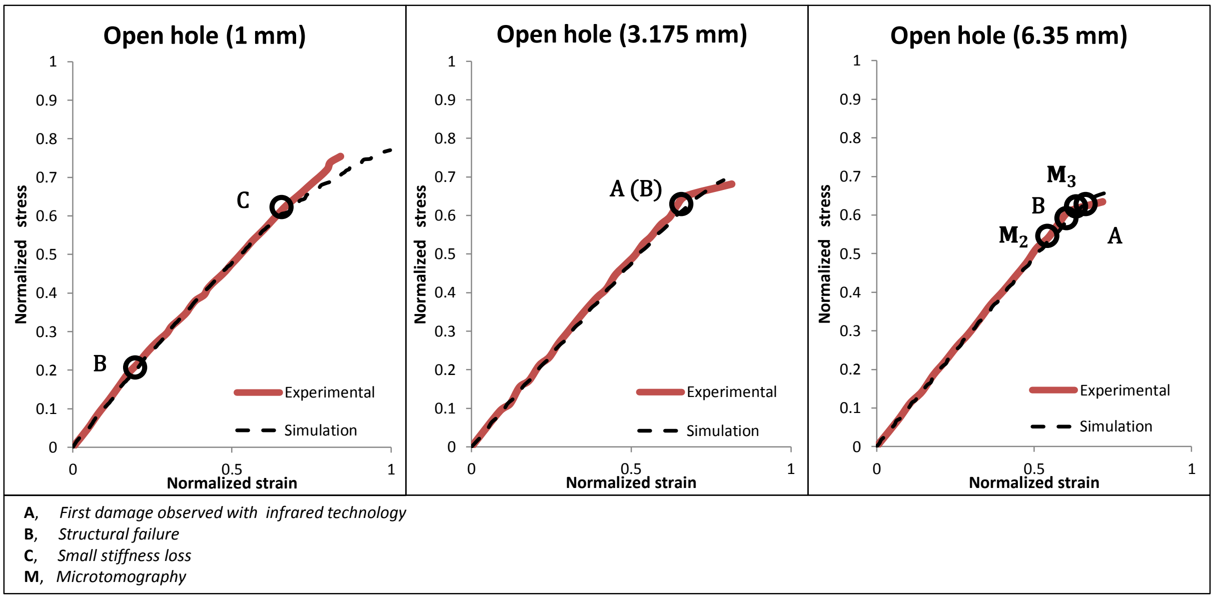

Figure 3:Stress/Strain curves of the three coupons scales (C3-1 layup) – Comparison between numerical and experimental data

3.3 Scaling effect for the three layups

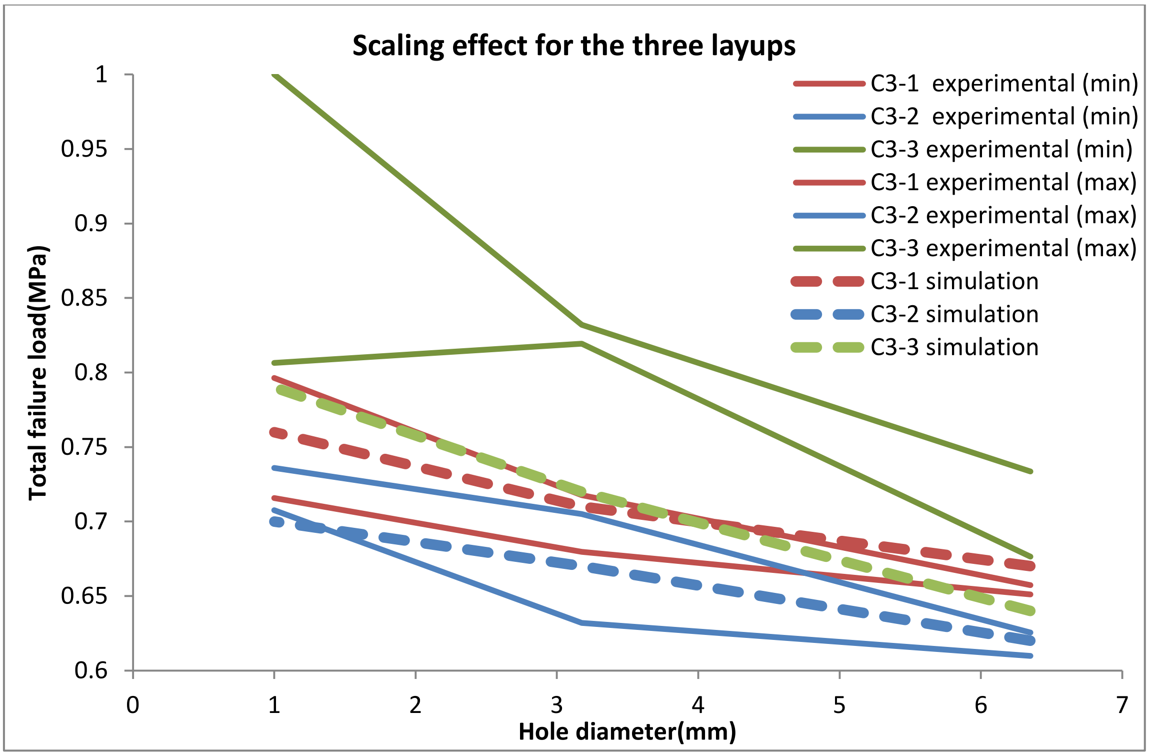

Figure 4: Scaling effect on the three different layups (C3-1, C3-2 and C3-3)

Excerpt from ISBN 978-3-00-053387-7

Numerical simulations gave excellent results for C3-1 and C3-2 layups, C3-3 simulations underpredicted the experimental results, probably because of the influence of the fiber failure fracture toughness [17], not taken into account. Maximum disparity between numerical and experimental results was 12% (C3-3, “Medium”).

4. Conclusions

Predicted notched tensile strengths of T700/M21 composite laminates decreased with specimen size for the three stacking sequences studied, as observed experimentally. The DPM approach, previously applied to open-hole tension simulation, was directly extended to represent the scaling effect through three diameter sizes here. The three most current damage types were simulated: matrix cracking, fiber failure and delamination. Stress/strain behaviors, and failure scenarios and patterns were correctly described. The influence of the layup was then simulated with reasonable accuracy via the DPM. The originality of the model comes from its discrete nature and the absence of coupling parameters.

References

[1] C. Kassapoglou, *Modeling the effect of damage in composite structures: simplified approaches*. s.l: Wiley, 2015.

[2] Z. P. Bazant, I. M. Daniel, et Z. Li, « Size effect and fracture characteristics of composite laminates », *J. Eng. Mater. Technol.*, vol. 118, n^o 3, p. 317–324, 1996.

[3] M. R. Wisnom, S. R. Hallett, et C. Soutis, « Scaling Effects in Notched Composites », *J. Compos. Mater.*, vol. 44, n^o 2, p. 195‑210, janv. 2010.

[4] X. Xu, M. R. Wisnom, Y. Mahadik, et S. R. Hallett, « An experimental investigation into size effects in quasi-isotropic carbon/epoxy laminates with sharp and blunt notches », *Compos. Sci. Technol.*, vol. 100, p. 220‑227, août 2014.

[5] P. P. Camanho, P. Maimí, et C. G. Dávila, « Prediction of size effects in notched laminates using continuum damage mechanics », *Compos. Sci. Technol.*, vol. 67, n^o 13, p. 2715‑2727, oct. 2007.

[6] S. R. Hallett, B. G. Green, W. G. Jiang, et M. R. Wisnom, « An experimental and numerical investigation into the damage mechanisms in notched composites », *Compos. Part Appl. Sci. Manuf.*, vol. 40, n^o 5, p. 613‑624, mai 2009.

[7] J. M. Whitney et R. J. Nuismer, « Stress fracture criteria for laminated composites containing stress concentrations », *J. Compos. Mater.*, vol. 8, n^o 3, p. 253–265, 1974.

[8] J. Wang, P. . Callus, et M. . Bannister, « Experimental and numerical investigation of the tension and compression strength of un-notched and notched quasi-isotropic laminates », *Compos. Struct.*, vol. 64, n^o 3‑4, p. 297‑306, juin 2004.

[9] J. Awerbuch et M. S. Madhukar, « Notched strength of composite laminates: predictions and experiments—a review », *J. Reinf. Plast. Compos.*, vol. 4, n^o 1, p. 3–159, 1985.

[10] C. Hochard, N. Lahellec, et C. Bordreuil, « A ply scale non-local fibre rupture criterion for CFRP woven ply laminated structures », *Compos. Struct.*, vol. 80, n^o 3, p. 321‑326, oct. 2007.

[11] P. P. Camanho, G. H. Erçin, G. Catalanotti, S. Mahdi, et P. Linde, « A finite fracture mechanics model for the prediction of the open-hole strength of composite laminates », *Compos. Part Appl. Sci. Manuf.*, vol. 43, n^o 8, p. 1219‑1225, août 2012.

[12] S. R. Hallett, « Experimental Investigation of Progressive Damage and the Effect of Layup in Notched Tensile Tests », *J. Compos. Mater.*, vol. 40, n^o 2, p. 119‑141, juin 2005.

[13] Z. R. Hessabi, B. Majidi, et J. Aghazadeh, « Effects of stacking sequence on fracture mechanisms in quasi-isotropic carbon/epoxy laminates under tensile loading », *Iran. Polym. J.*, vol. 14, n^o 6, p. 531, 2005.

[14] P. P. Camanho et S. R. Hallett, *Numerical Modelling of Failure in Advanced Composite Materials*. Woodhead Publishing, 2015.

[15] B. Y. Chen, T. E. Tay, P. M. Baiz, et S. T. Pinho, « Numerical analysis of size effects on open-hole tensile composite laminates », *Compos. Part Appl. Sci. Manuf.*, vol. 47, p. 52‑62, avr. 2013.

Excerpt from ISBN 978-3-00-053387-7

[16] F. Laurin, N. Carrere, C. Huchette, et J.-F. Maire, « A multiscale hybrid approach for damage and final failure predictions of composite structures », *J. Compos. Mater.*, vol. 47, n° 20‑21, p. 2713‑2747, sept. 2013.

[17] M. Ridha, C. H. Wang, B. Y. Chen, et T. E. Tay, « Modelling complex progressive failure in notched composite laminates with varying sizes and stacking sequences », *Compos. Part Appl. Sci. Manuf.*, vol. 58, p. 16‑23, mars 2014.

[18] M. R. Wisnom, « Modelling discrete failures in composites with interface elements », *Compos. Part Appl. Sci. Manuf.*, vol. 41, n° 7, p. 795‑805, juill. 2010.

[19] X. Xu, M. R. Wisnom, X. Li, et S. R. Hallett, « A numerical investigation into size effects in centre-notched quasi-isotropic carbon/epoxy laminates », *Compos. Sci. Technol.*, vol. 111, p. 32‑39, mai 2015.

[20] X. C. Sun, M. R. Wisnom, et S. R. Hallett, « Interaction of inter- and intralaminar damage in scaled quasi-static indentation tests: Part 2 – Numerical simulation », *Compos. Struct.*, vol. 136, p. 727‑742, févr. 2016.

[21] F. Aymerich, F. Dore, et P. Priolo, « Prediction of impact-induced delamination in cross-ply composite laminates using cohesive interface elements », *Compos. Sci. Technol.*, vol. 68, n° 12, p. 2383‑2390, sept. 2008.

[22] L. Lammerant, « Modelling of the interaction between matrix cracks and delaminations during impact of composite plates », *Compos. Sci. Technol.*, vol. 56, n° 10, p. 1171‑1178, 1996.

[23] M. F. S. . de Moura et J. P. . Gonçalves, « Modelling the interaction between matrix cracking and delamination in carbon–epoxy laminates under low velocity impact », *Compos. Sci. Technol.*, vol. 64, n° 7‑8, p. 1021‑1027, juin 2004.

[24] Y. Zhang, P. Zhu, et X. Lai, « Finite element analysis of low-velocity impact damage in composite laminated plates », *Mater. Des.*, vol. 27, n° 6, p. 513‑519, janv. 2006.

[25] P. H. Geubelle et J. S. Baylor, « Impact-induced delamination of composites: a 2D simulation », *Compos. Part B Eng.*, vol. 29, n° 5, p. 589–602, 1998.

[26] C. Bouvet, B. Castanié, M. Bizeul, et J.-J. Barrau, « Low velocity impact modelling in laminate composite panels with discrete interface elements », *Int. J. Solids Struct.*, vol. 46, n° 14‑15, p. 2809‑2821, juill. 2009.

[27] C. Bouvet, S. Rivallant, et J. J. Barrau, « Low velocity impact modeling in composite laminates capturing permanent indentation », *Compos. Sci. Technol.*, vol. 72, n° 16, p. 1977‑1988, nov. 2012.

[28] S. Rivallant, C. Bouvet, et N. Hongkarnjanakul, « Failure analysis of CFRP laminates subjected to compression after impact: FE simulation using discrete interface elements », *Compos. Part Appl. Sci. Manuf.*, vol. 55, p. 83‑93, déc. 2013.

[29] L. Adam, C. Bouvet, B. Castanié, A. Daidié, et E. Bonhomme, « Discrete ply model of circular pull-through test of fasteners in laminates », *Compos. Struct.*, vol. 94, n° 10, p. 3082‑3091, oct. 2012.

[30] V. Achard, C. Bouvet, B. Castanié, et C. Chirol, « Discrete ply modelling of open hole tensile tests », *Compos. Struct.*, vol. 113, p. 369‑381, juill. 2014.

[31] N. J. Pagano et R. B. Pipes, « The Influence of Stacking Sequence on Laminate Strength », in *Mechanics of Composite Materials*, Springer, 1994, p. 246–254.

[32] M. E. Grayley, « Delamination and free edge stresses in composite laminates subjected to uniform prescribed axial strain and temperature changes ». ESDU, déc-1995.

Excerpt from ISBN 978-3-00-053387-7