ANALYSIS OF DAMAGE AND FAILURE MECHANISMS OF QUILTED STRATUM PROCESS® COMPOSITE PARTS

Y. Todeschini[1], C. Huchette[2], C. Julien[2] and D. Espinassou[2]

[1]Onera, DMSC/MC2, 29 Avenue de la division Leclerc 92320 Châtillon, France
Email: yann.todeschini@onera.fr
Email: cedric.huchette@onera.fr
Email: cedric.julien@onera.fr
[2]Cetim, IPC, Chemin du Chaffault, 44340 Bouguenais, France
Email: denis.espinassou@cetim.fr

Keywords: Discontinuous laminates, Failure Mechanisms, Delamination, Thermoplastic.

Abstract

The research work proposed here aims at studying, from the experimental and numerical standpoints, the damage and failure mechanisms of heterogeneous laminates containing discontinuous plies. To this end, a fully customizable finite element model has been developed, where bilinear cohesive zone elements are placed at the interfaces between each elementary unidirectional composite patch constituting the plies. Damage and failure mechanisms are observed by performing multi-instrumented mechanical tests (acoustic emission, edge micrographs, stereo-image correlation). Simulations and experimental studies revealed ply cuts as initiators of delamination cracks. Moreover the role of a geometric parameter (the minimum length between cuts l_s over the ply thickness t_d) on failure mode has been investigated in the simple configuration of a perfectly staggered stacking made of unidirectional cut plies. The ultimate goal of this work is to derive simple empirical design rules, based on material properties and laminate configuration that would be suitable for use in a design office.

1. Introduction

Ever more constraining regulations lead the transportation industry to make considerable efforts on reducing vehicle consumption. One solution to consume less energy is to reduce the weight of the vehicle parts either by optimizing their shapes or by using other materials. Unidirectional composite laminates have shown their excellent specific mechanical properties compared to metallic solutions. Thermoset composite laminates are developed and used in the aerospace industry for the past 30 years. Nevertheless, their long processing times, difficult formability and higher cost severely limit the scope of their application. They are specifically unsuitable for high rates parts production.

As a result, the interest for thermoplastic resins, which can be processed in several seconds, has recently been growing. Since 2013, CETIM Nantes has been working on the development of a complete industrial production line for structural thermoplastic composite parts. The so-called Quilted Stratum Process® (QSP®) consists in the stamping of an assembly of thermoplastic composite patches having unidirectional or woven reinforcement. This process offers the possibility of high speed production of parts with complex shapes, in a cost-efficient and automated way.

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

Figure 1. Presentation of QSP® (Quilted Stratum Process) line being developed at CETIM (Nantes).

Manufacturing parts by assemblies of composite patches of finite size expands the material design space and enables local tailoring of the laminate properties by changing patches sizes and reinforcement orientation [1-2]. Nevertheless, the non-homogeneous nature of the stratification introduces a lot of complexity in the design process. Indeed, it has been reported that lamination discontinuities are responsible for stress concentration effects that can be responsible for early damage of the surrounding plies (through stress transfer and delamination at the patch interfaces [3-5]). Moreover, mechanical properties of the laminate can be substantially reduced in the vicinity of the patch edges [6-7]. On the other hand, ply discontinuities can have other mechanical benefits such as crack path control [8], pseudo-ductile behaviour [9] or improved toughness [10]. Hence discontinuous stratification can, depending on the patch arrangement, exhibit low mechanical properties and early failure or exhibit controlled failure with reinforced laminate properties.

One design parameter influencing damage and failure mode is for example the distance between two discontinuities in a stack. Indeed, if several discontinuities are close to each other, the stress and strain field perturbation from each discontinuity can interact and modify the kinetics of delamination crack propagation at interfaces. This influence of discontinuity spacing on failure mode has been investigated experimentally on double lap configurations [11] and on perfectly staggered discontinuous 0° lay-up [12].

For this work, we choose to study delamination crack interaction in shear mode from the numerical and experimental standpoints. To do so, we choose to design a $[0°]_{13}$ laminate having staggered cut plies, this configuration is symmetric and thus, avoid specimen bending and allows for a close to pure mode II loading of the interfaces.

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

2. Materials

While the pultrusion line for the QSP® line was still under development, CETIM Nantes supplied an equivalent commercial raw material (T700S/PA66 from Celstran/Ticona) in roller. The material from the roller is brittle, dry and not as sticky as an epoxy prepreg. Testing samples are manufactured at Onera using a hot press and a 134x236mm metallic mould. The laminate is heated up to 290°C and pressed at 8 bars for 15 min before being unmoulded at room temperature. The combination of the consolidation pressure and the liquid state of the resin at high temperature makes the fibres susceptible to resin movement. Thus, manufacturing of discontinuous plates with geometrically controlled patch placement requires diligent work. The first samples were aimed at the characterisation of the mechanical properties of unidirectional laminate properties (Table 1).

Table 1. Elastic and strength properties of unidirectional Celstran/Ticona T700S/PA66

Ply elastic properties		Ply strength	
E_{11}(MPa)	104200	σ^t_{11}(MPa)	*1930*
E_{22} (MPa)	5450	σ^t_{22} (MPa)	*35*
G_{12} (MPa)	2022	σ^t_{12} (MPa)	*40*
ν_{12} (-)	0.34		

Longitudinal mechanical properties of unidirectional T700S/PA66 are slightly lower than those of traditional aerospace quality thermoset layers, due to its lower fibre volume fraction (~50%). Also, the ply presents relatively low transverse and shear modulus as well as low transverse strength. Those properties reflect both the influence of resin behaviour and bad resin/fibre interfaces which is an actual field of research for thermoplastic laminates [13].

For the manufacturing of controlled staggered discontinuous stratification, a chisel was used to perpendicularly cut fibres of 0° plies in order to control the spacing between cut fibres as well as their vertical alignment in the stratification (Fig. 4). The samples dimensions are 230x20x2.06mm which corresponds to 0,158mm thick plies. Eight samples were manufactured with intervals between cut ranging from 3mm to 40mm. Since resin pockets are likely to form at the ply discontinuities, we tried to limit their length to a maximum of 1mm (Fig. 4)

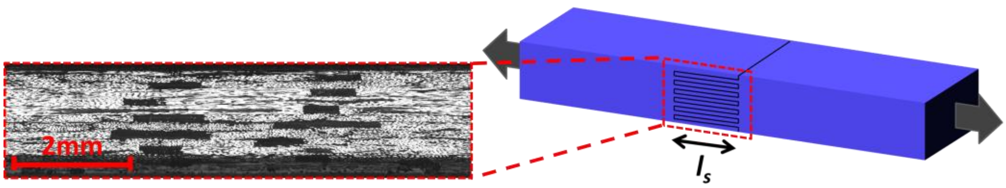


Figure 2. Representation of the discontinuous staggered laminate and edge view of a sample.

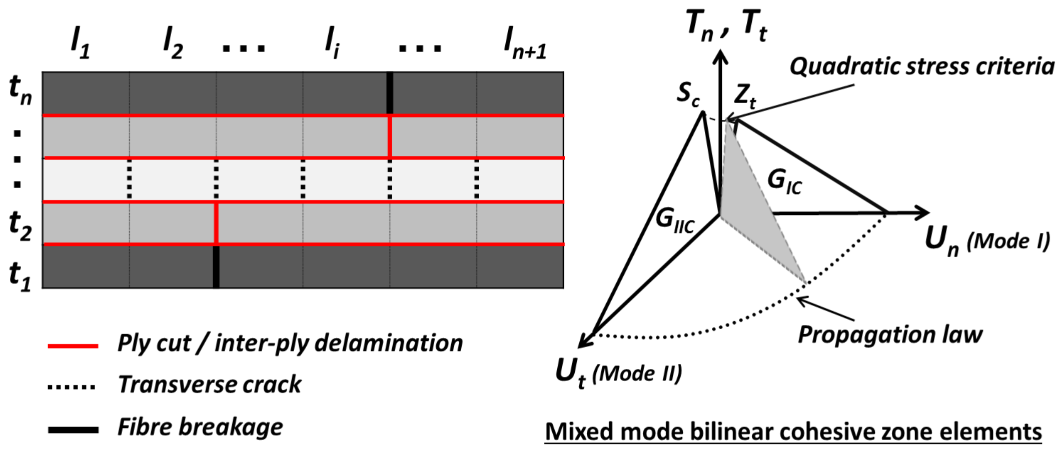
3. Numerical strategy

Numerical study of the mechanical response and damage patterns in heterogeneous composite laminates is a daunting task, since many configurations are possible. Several authors [14-16] worked on analytical models in order to predict the stress-strain response, final failure and Young's modulus of hierarchal periodic discontinuous structure (materials with nacreous architecture). Those models based on "shear-lag" considerations show good agreement with experimental results, for a limited calculation cost. Others choose to represent explicitly the discontinuous stacking, through finite element analysis (FEA) by either representing the discontinuities by a matrix pocket [7] or by inserting cohesive zone elements at the interfaces between the plies and in the discontinuous area [14]. For the

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

purpose of this work we choose to use FEA as it helps understanding the influence of the perturbation in the stress/strain fields on the damage scenarios.

The mesh construction is based on a "columns and rows" architecture and aims at representing explicitly the discontinuous stacking (Fig. 3.a). This model is fully customizable as each "brick" possess an equivalent homogenous mechanical behaviour and can be either fused or separated by cohesive zone elements with properties corresponding to either a cut, transverse crack, delamination crack or fiber rupture crack. The cohesive zone model used is bilinear [17] (Fig. 3.b) and allows description of mixed mode crack propagation. Quadratic stress criterion is used to predict initiation of a delamination crack and Benzeggagh-Kenane law [18] describes its propagation. Cohesive zones are based on linear elastic fracture mechanic considerations and their input parameters are interfacial strengths (Z_t - mode I and S_c - mode II) and toughness (G_{IC} - mode I and G_{IIC} - mode II). The principal drawbacks of this approach are *(i)* the computation time and *(ii)* the difficulty to ensure numerical convergence.



(a) (b)

Figure 3. Schematic representation of the Finite Element methodology developed.

As expected, the first numerical simulations revealed the strong stress and strain field perturbations as well as initiation and growth of delamination cracks at the discontinuities location (Fig. 4.). Experimentally, cracks appear first at fibre end before propagating at the interface between plies.

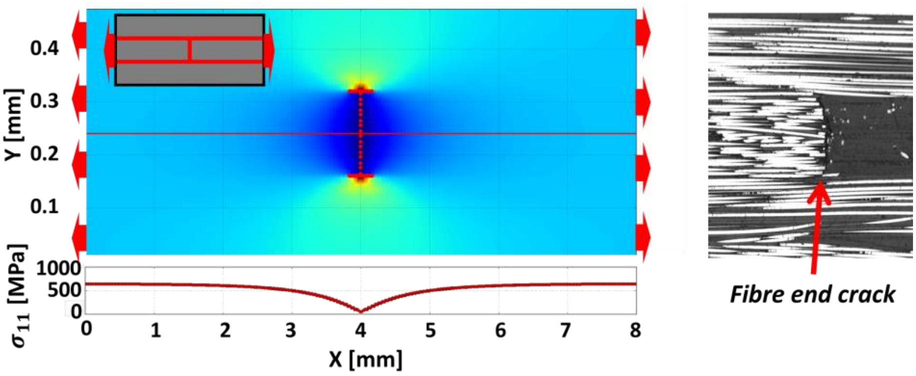


Figure 4. Stress field perturbation and damage at the interface between two patches in a $[0°]_3$ laminate having cut middle ply (damaged cohesive zones are represented in red dots).

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

4. Comparison between experimental and numerical results

In order to compare simulations to experimental results a 13 plies staggered unidirectional laminate is meshed in 2D using the developed methodology. Cohesive zone elements are placed at cut location and interface between plies but also in the continuous 0° plies to capture their failure. Characterised elastic properties given in Table 1 and properties of cohesive zone elements given in Table 2 were used for simulations. Strength of interfaces in mode II are estimated from shearing strength values of a unidirectional ply (σ^t_{12}), and longitudinal ply tenacity are also estimated for T700S carbon fibers. Tenacities in mode I and II were given by Y. Zhengrong of Imperial College who works with CETIM Nantes on the same material.

Table 2. Interface properties of Celstran/Ticona T700S/PA66 (* estimated values to evaluate).

Interface properties		Ply properties	
Z_t (MPa)	*40**	Z_t (MPa)	*1930*
S_c (MPa)	*40* - 60**	S_c (MPa)	*1930*
G_{IC} (J.m^2)	*2200*	G_{IC} (J.m^2)	*200000**
G_{IIC} (J.m^2)	*3000*	G_{IIC} (J.m^2)	*200000**

Out of eight discontinuous samples tested in tension, four had their final failure happening in the zone of interest. For each, ultimate stress of the configuration is reported as a function of the geometrical ratio δ of the distance between two cut plies (l_s) and the thickness of a ply (t_d) (Eq. 1).

$$\delta = l_s / t_d \quad (1)$$

Experimentally, for samples with small δ values, failure is caused by catastrophic delamination at ply interfaces. On the other hand, for the larger values of δ, delamination cracks cannot meet at the ply interfaces, and stress transfer through the continuous layers causes an energetic fibre failure (Fig. 5).

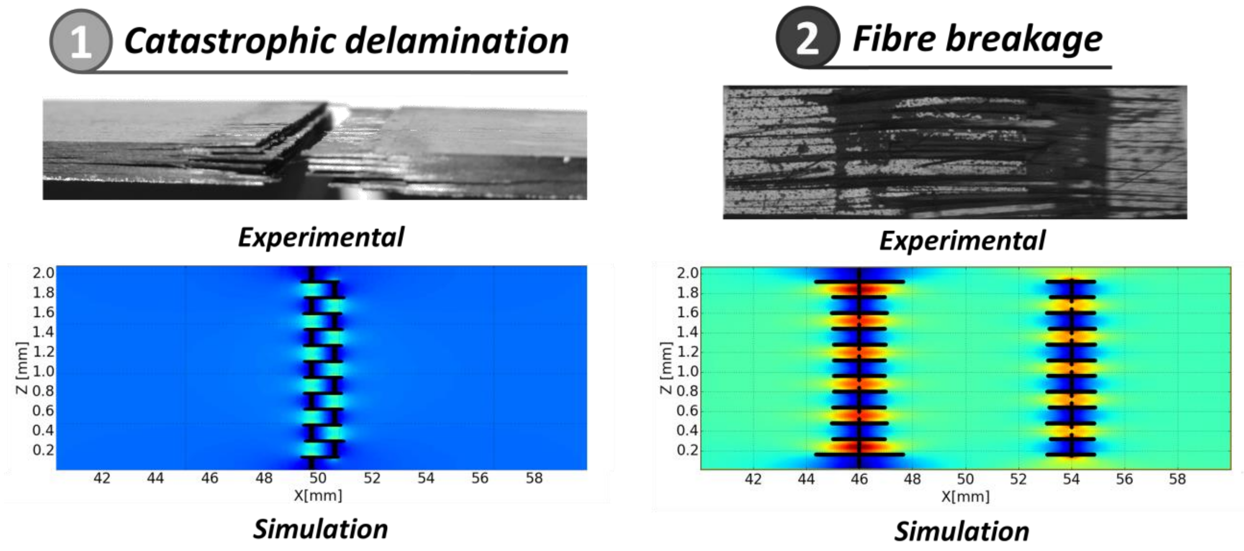


Figure 5. Experimental and numerical failure mode of staggered composite laminate for low ratio δ (1) and for higher ratio δ (2).

This failure mode and ultimate strength of samples are well captured by numerical simulations (Fig. 6). Moreover, one can see that for δ ratio higher than failure mode transition ratio δ_t the maximum admissible stress is constant and corresponds to the strength of the weakest link in the laminate.

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

Numerical simulations were run for two different values of mode II inter-ply strength (S_c). It can be seen that increasing mode II strength (S_c) of the interface increases the ultimate stress, for a small δ ratio. It also increases the threshold (δ_t) of failure modes, which is indicative of the influence on the kinetics of delamination cracks.

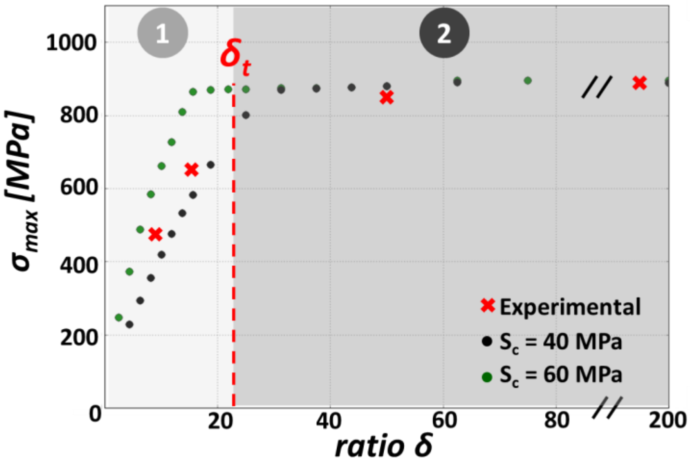


Figure 6. Maximum stress as a function of geometric ratio (distance between cut l_s / ply thickness t_d) for a $[0°]_{13}$ staggered discontinuous laminate.

These first results show that the simulation strategy is a good candidate to predict failure mode and ultimate stress at failure. Nevertheless, use of a 3 axes camera mounted on a microscope (enabling *in situ* observations of the edge of the sample) coupled to an acoustic emission acquisition chain stereo-image correlation reveals that the delamination cracks appear at higher stress and propagate less before final failure than in the experiments, in comparison with simulations. Indeed, one can see that at a stress level equivalent to 90% of the final failure stress, edge micrographs reveal initiation of cracks at the fibre ends but no delamination cracks are visible (Fig. 7-2). In addition, a change of loading velocity influences equally the energy and the number of acoustic events (Fig. 7 A-B). Finally, it can be seen that for the same loading speed (Fig. 7 B-C), acoustic emission activity increase before final failure, we suppose that it correspond to a change in failure mode, unfortunately we were unable to correlate it with edge micrographs observations.

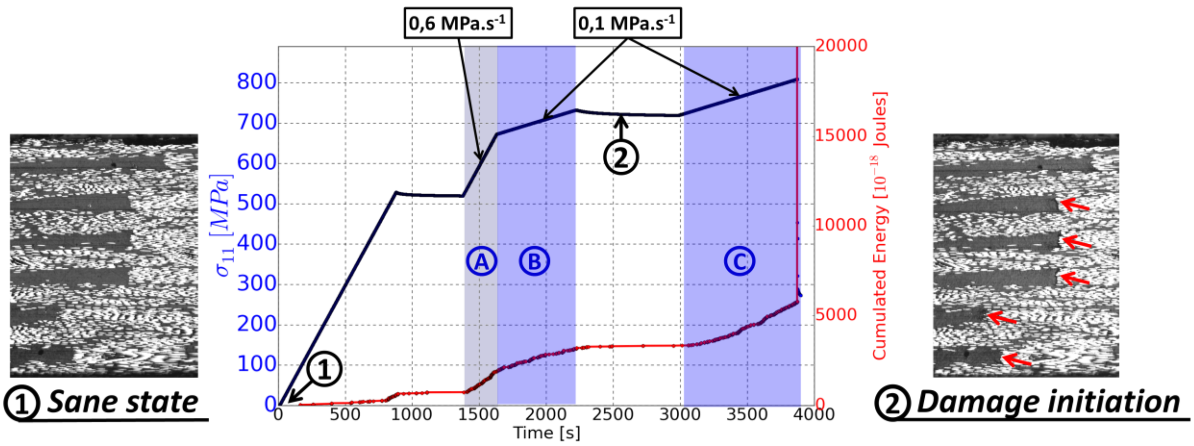


Figure 7. Comparison between applied stress and cumulated acoustic energy as a function of test time. Correlation between acoustic emission results and edge observations of the sample.

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

The observed phenomenological differences in damage mode between experiments and simulations can be due to *(i)* the imperfect experimental stratification *(ii)* no representation of the resin pocket formed at the cut locations *(iii)* bad estimation of the quadratic out of plane failure criteria *(iv)* interfaces between plies that exhibits a more ductile behaviour which is not perfectly taken into account with the cohesive zone element used. Consequently, fine interfaces strength characterization as well as explicit representation of the resin pocket should be investigated in order to see their influence on damage kinetic.

5. Conclusions

A strategy based on numerical simulations and experimental testing has been used in order to understand damage and failure mechanisms of discontinuous stratifications. The simulations strategy relies on a fully customizable mesh representing explicitly discontinuous stratification. Mixed-mode bilinear cohesive zone elements with quadratic failure criteria and Benzzegagh-Kenane propagation law are inserted at ply discontinuities and ply interfaces to represent delamination cracks. The model prediction accuracy has been studied for mode II delamination crack interaction on a staggered discontinuous $[0°]_{13}$ stratification. The role of a geometric ratio δ (minimum length between cuts l_s / ply thickness t_d) on resistances, damage interaction and failure mechanisms has been observed experimentally and numerically. The developed model shows good correlations with experimental failure mechanisms and measured resistances. Nevertheless use of multi-instrumentation during experimental testing revealed small differences between experiments and simulations on damage initiation and propagation kinetic. Hypothesis that should be investigated were made in order to justify those observations.

It is believed that the use of the developed meshing strategy together with mechanical test on chosen discontinuous stratification can in a first time increase our trust in the model and in a second time be used for virtual testing campaign to explore wider fields of variables and can then be used as an help to derive design recommendations for QSP® parts.

Acknowledgments

The authors would like to thanks CETIM of Nantes for providing raw material and Yu Zhengrong of Imperial College for sharing his thesis work results relative to the study of delamination crack propagation in mode I and mode II from which we took the tenacity values of T700S/PA66.

References

[1] F.X. Irisarri, A. Lasseigne, F.H. Leroy, R. Le Riche. Optimal design of laminated composite structures with ply drops using stacking sequence tables. *Composite Structures,* 107:559-569, 2014

[2] T. Rettenwander, M. Fischlschweiger, M. Machado, G. Steinbichler, Z. Major. Tailored patch placement on a base load carrying laminate: A computational structural optimisation with experimental validation. *Composite Structures*, 116:48-54, 2014

[3] G. Czèl, M. Jalalvand, M.R. Wisnom. Demonstration of pseudo-ductility in unidirectional hybrid composites made of discontinuous carbon/epoxy and continuous glass/epoxy plies. *Composites: Part A*, 72:75-84, 2015.

[4] M.R. Wisnom. On the Increase in Fracture Energy with Thickness in Delamination of Unidirectional Glass Fiber Epoxy with Cut Central Plies. 2:897-909, 1992.

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

[5] W. Cui, M.R. Wisnom, M. Jones, An Experimental and Analytical Study of Delamination of Unidrectionnal Specimens with Cut Central Plies", *Journal of Reinforced Plastics and Composites*, 13:722-739, 1994

[6] H. Li, W.X. Wang, Y. Takao, T. Matsubara. New designs of unidirectionally arrayed chopped strands by introducing discontinuous angled slits into prepreg. *Composites: Part A*, 45:127-133, 2013

[7] J.N Baucom, J.P Thomas, W-R Pogue, M-A Siddiq Qidwai. Tiled composite laminates. *Journal Composite Materials*, 44:3115-3132, 2010

[8] A.C. Orifici, P. Wongwichit, N.Wiwatanawongsa. Embedded flaws for crack path control in composite laminates. *Composites: Part A*, 66 :218-226, 2014

[9] G. Czél, S. Pimenta, M. Wisnom, P. Robinson Demonstration of pseudo-ductility in unidirectional discontinuous carbon fiber/epoxy prepreg composites. *Composites Science and Technology*, 106:110-119, 2015

[10] I. Taketa, N. Sato, A. Kitano, M. Nishikawa, T. Okabe. Enhancement of strength and uniformity in unidirectionally arrayed chopped strands with angled slits, *Composites: Part A*, 41:1639-1646, 2010.

[11] D. Heim, M. Hartmann, J. Neumayer, C. Klotz, O. Ahmet-Tsaous, S. Zaremba, K. Drechsler Novel method for determination of critical fiber length in short fiber carbon/carbon composites by double lap joint. *Composites: Part B*, 54:365-370, 2013.

[12] Effect of fiber length on the tensile strength of unidirectionally arrayed chopped strands. I.Taketa, A.H. Koyanagi, H. Matsutani, *Proceeding of the 20th International Conference on Composite Materials, Copenhagen, 19-24th July*

[13] A.M. Díez-Pascual, M. Naffakh, C. Marco, M.A. Gómez-Fatou, G.J. Ellis. Multiscale fiber-reinforced thermoplastic composites incorporating carbon nanotubes: A review. Current Opinion in Solid State and Materials Science, 18:62-80, 2014.

[14] S. Pimenta, P. Robinson. An analytical shear-lag model for composites with "brick and mortar" architecture considering non-linear matrix response and failure, *Composites Science and Technology*, 104:111-124, 2014.

[15] G. Liu, B. Ji, K.C. Hwang, B.C. Khoo. Analytical solutions of the displacement and stress fields of the nanocomposite structure of biological materials. *Composites Sciences and Technology*, 71:1190-1195, 2011.

[16] Hang Li, Wen, Xue Wang, Terutake Matsuba. Multiscale analysis of damage progression in newly designed UACS laminates. *Composites: Part A*, 57:108-117, 2014.

[17] P.P Camanho, C.G Dávila. Mixed mode decohesion finite elements for simulation of delamination in composite materials. *NASA/TM-2002-211737*, 2002.

[18] M.L. Benzeggagh, M. Kenane "Measurement of mixed-mode delamination fracture toughness of unidirectional glass/epoxy composites with mixed-mode bending apparatus. *Composites Science and Technology*, 56: 439-449, 1996.

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