DESIGN OF NON-CONVENTIONAL CFRP LAMINATES FOR IMPROVED DAMAGE RESISTANCE AND DAMAGE TOLERANCE

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Keywords: Non-conventional laminates, Low velocity impact, Damage resistance, Damage tolerance Mismatch angle,

Abstract

The design of stacking sequences for an improved damage resistance and damage tolerance for low velocity impact events has received a special attention from industries as well as academic research. A rational design with dispersed ply orientations is seen as a promising solution to the problem. This paper presents a new philosophy for the design of a non-conventional laminate with improved mechanical performance against impact events. The laminate is designed such that the plies at and near the top and bottom surfaces of the laminate absorb most of the impact energy and that the middle plies are left undamaged in order to carry the compressive load after impact. The results enable us to propose four non-conventional stacking sequences satisfying the constraints imposed by the conventional laminate that will be used as the baseline material in our experimental study.

1. Introduction

Composite structures may suffer severe damages under impact of an external object, causing the reduction in the residual strength and the risk of structural failure. The result from this impact event can produce matrix cracking, fibre matrix debonding, delamination or fibre breakage. Low velocity impact is considered potentially dangerous, mainly because the resulting damage can go undetected during maintenance routines. Thus, the most demanding criteria in sizing several composite structures is damage resistance and damage tolerance. The damage resistance is concerned with the creation of damage due to a specific impact event, while damage tolerance is concerned with the structural response and integrity associated with a given damage state of a structure.

In the literature, the design of lay-ups for improved damage tolerance and resistance has received a considerable attention [1, 2, 3]. Some studies have suggested that using ply clustering (ply contiguity of two or more plies with the same fibre orientation) [4, 5] and/or the mismatch angle (difference in angle between two adjacent plies) [6] may help improve damage resistance and damage tolerance.

Recent research publications report the analysis of the two effects. González et al [4] studied the effects of ply clustering in laminated composite plates under low-velocity impact loading. The authors concluded that ply clustering reduces the damage resistance of the structure, but there was no clear evidence that the damage tolerance was improved. A similar study on the effect of ply clustering by Sebaey et al. [5] using dispersed laminates (laminates using fibre orientations not limited to the conventional ply orientation angles of 0°, ±45° and 90°) demonstrates that the peak load was reduced when using dispersed lay-ups but wider delaminations were observed near the clustered plies. The study concluded that the residual compressive strength can be improved using dispersed orientations and ply clustering. The same authors [6] also studied the effect of mismatch angles of two ranges: one from 10° to 30° and the other from 55° to 80°. This study suggested that laminates with the smaller mismatch angles have better damage resistance and damage tolerance than the ones with large mismatch angles.

The aforementioned studies compare stacking sequences with equivalent in-plane/flexural stiffness in one or two laminate directions, but none of them takes into account the in-plane/flexural stiffness of the lay-up for all directions. Therefore, the aim of the current paper is to propose a non-conventional lay-up preserving the full quasi-isotropy from a baseline lay-up. The proposed stacking sequence has two different regions or sub-laminates through the laminate thickness. The idea behind this lay-up is to dissipate the impact energy during the impact test in the outer regions of the lay-up and leave an undamaged sub-laminate in the mid-plane to carry the compressive loads. The proposed laminate architecture has large mismatch angles in the outer regions and small mismatch angles in the laminate mid-plane. The Ant Colony Optimization technique [7] is used to search for non-conventional stacking sequences which satisfy all the constraints dictated by two baseline laminates that are considered for a valid, comparative analysis in our experimental study.

2. Problem statement

2.1. Baseline conventional lay-up

In order to perform a comparative study of the mechanical behaviour of the proposed non-conventional stacking sequence, two baseline conventional lay-ups are included. Both are symmetric $\pi/4$ quasi-isotropic laminates (see Table 1).

Ref.	**Stacking sequence**	**Layers (2n)**	**h** [mm]
Conv-1	$[90/-45/0/45]_{3s}$	24	4.416
Conv-2	$[90_3/-45_3/0_3/45_3]_s$	24	4.416

Table 1. Conventional baseline lay-ups

Two baseline lay-ups are proposed, one lay-up without ply clustering (*Conv-1*) and the other one with clusters of three plies (*Conv-2*). The values of the mismatch angles evaluated for the two lay-ups are given in Table 2. The mismatch angle can be calculated as the absolute value of the difference between the orientation of two consecutive plies. Note that, these interfaces represent only half of the laminate, including the interface where the symmetry condition is applied.

	Interface											
	1	2	3	4	5	6	7	8	9	10	11	12*
Conv-1	45	45	45	45	45	45	45	45	45	45	45	-
Conv-2	-	-	45	-	-	45	-	-	45	-	-	-

Table 2. Mismatch angles for baseline lay-ups (angles are expressed in degree). *Interface where symmetry is applied

Both lay-ups have the same mismatch angle through the laminate thickness and the unique difference is the number of potential interfaces for delamination (n_d): *Conv-1* has $n_d = 22$ and *Conv-2* has $n_d = 6$. The more the plies are clustered, the fewer the potential interfaces for delamination are.

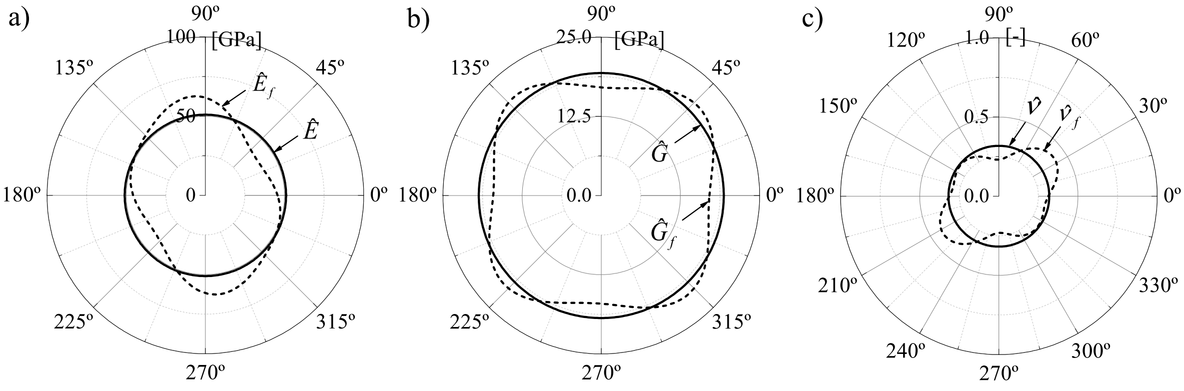

Figure 1. Laminate engineering constants for Conv-1. (a) In-plane/flexural moduli (b) In-plane/flexural shear moduli (c) In-plane/flexural Possion ratios

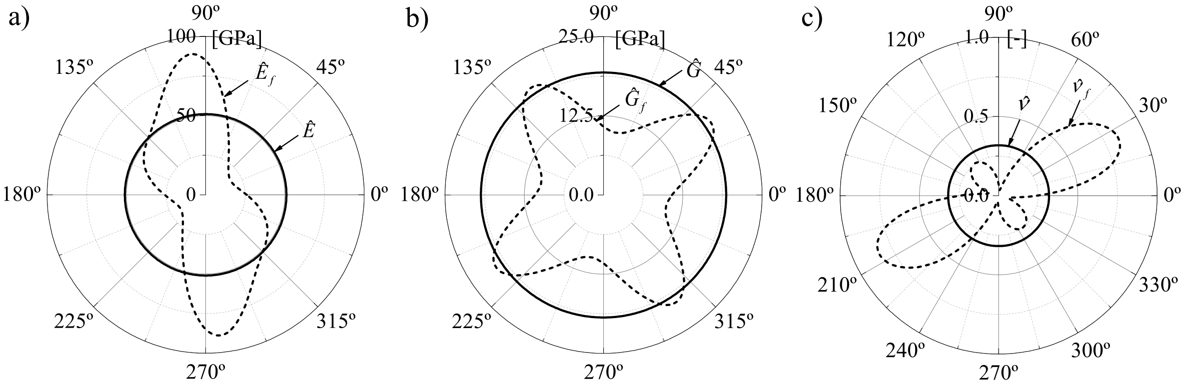

Figure 2. Laminate engineering constants for Conv-2. (a) In-plane/flexural moduli (b) In-plane/flexural shear moduli (c) In-plane/flexural Possion ratios

Using the polar method applied to the Classical Lamination Theory (CLT) [8], the engineering constants for each laminate direction can be presented in a compact way (see Figures 1 and 2). $\hat{E}$, $\hat{G}$ and $\hat{\nu}$ are the in-plane modulus, the in-plane shear modulus and the in-plane Poisson ratio respectively. $\hat{E}_f$, $\hat{G}_f$ and $\hat{\nu}_f$ are the flexural modulus, the flexural shear modulus and the flexural Poisson ratio of the laminates.

As represented in Figures 1 and 2 both lay-ups are quasi-isotropic in in-plane stiffness but not in flexural stiffness. The values of the in-plane moduli ($\hat{E}$ and $\hat{G}$) and Poisson ratio ($\hat{\nu}$) are constant for all laminate directions. On the contrary, the flexural moduli ($\hat{E}_f$ and $\hat{G}_f$) and the flexural Poisson ratio ($\hat{\nu}_f$) are not constant for all laminate directions. The material used in this analysis is T800/M21 prepeg epoxy system with the properties shown in Table 3 [9].

E_{11}[GPa]	E_{22}[GPa]	ν_{12}[-]	G_{12} [GPa]
134.7	7.7	0.369	4.2

Table 3. Material properties for T800/M21 unidirectional CFRP [9]

2.2. *Proposed non-conventional lay-up*

Experimental results reveal that laminate composites with clustered and dispersed plies have better damage resistance and tolerance than those of the conventional laminates having fibers in the plies limited to 0°, ±45° and 90°. Based on this fact and with the aim to improve the aforementioned mechanical performance we take the advantage of the design flexibility of laminated composites to perform a series of study beginning from design to experimental characterization of the laminates using plies consisting of fibre orientations not limited to the conventional ones.

In order to have a valid and comparative analysis, our design constraints are dictated by the geometry and the bulk properties of the conventional laminates. The non-conventional laminate constitutes three sub-laminates – namely top, middle and bottom sub-laminates – grouped into two regions having the same thickness. Top and bottom sub-laminates together form Region 1 of the laminate, whereas Region 2 consist of only the middle sub-laminate (see Figure 3).

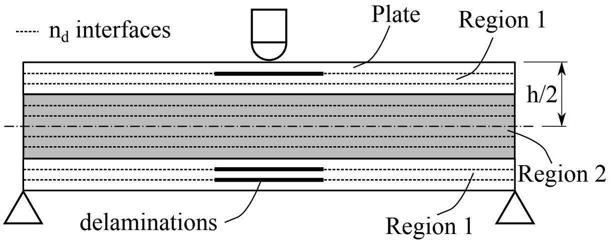

Figure 3. Definition of the laminate architecture

The proposed non-conventional laminate is designed such that Region 2 has smaller mismatch angles than Region 1. The idea behind this is to force the impact energy to dissipate in Region 1 and leave Region 2 to carry the compressive load. We design the non-conventional laminate using the Ant Colony Optimization technique (ACO) [7, 10] in order to explore stacking sequences which satisfy the design constraints.

The design constraints are: (1) Symmetric ($B_{ij} = 0$), (2) Balanced ($A_{16} = A_{26} = 0$), (3) Maximum number of clustered plies is 2, (4) First layer at 90° (first ply failure), (5) Mismatch angle allowed in Region 1 is greater than or equal to 45° and (6) Mismatch angle allowed in Region 2 is fixed to 15°. The optimization problem formulation is stated as follows:

Find a stacking sequence S such that:

$$S = \{\theta, n\}, \theta \in \{0, \pm 15, \pm 30, \pm 45, \pm 60, \pm 75, 90\}, n = 12 \tag{1}$$

and minimize the objective function f:

$$f = (A_{11} - A_{22})^2 + (A_{11} - A_{12} - 2A_{66})^2 + A_{16}^2 + A_{26}^2 + 1 \tag{2}$$

Minimizing the objective function f (Eq. 2), which is function of the terms from the in-plane stiffness matrix A, aims to find quasi-isotropic stacking sequences. When the value of the objective function is equal to 1 a quasi-isotropic lay-up is found.

3. Results

The resulting stacking sequences are presented in Table 4 using the ACO technique. It is worth noting that the problem is multi-solution thus, four $pi/12$ quasi-isotropic stacking sequences are obtained which satisfy the laminate architecture constraints. Furthermore, the value of the objective is 1, which means the quasi-isotropy is achieved for all of them.

Ref.	**Stacking sequence**	**f**
Non-conv-1	$[90/-45/75/\mp 60/-75/-30/-15/0/15/30/45]_s$	1.0
Non-conv-2	$[90/-45/75/\mp 60/-75/45/30/15/0/-15/-30]_s$	1.0
Non-conv-3	$[90/45/-75/\pm 60/75/30/15/0/-15/-30/-45]_s$	1.0
Non-conv-4	$[90/45/-75/\pm 60/75/-45/-30/-15/0/15/30]_s$	1.0

Table 4. Selected non-conventional quasi-isotropic lay-ups

The mismatch angle for each interface at both regions is shown in Table 5. Note that the maximum mismatch angle in Region 1 is 60° for all the proposed stacking sequences.

	Interfaces Region 1						**Interfaces Region 2**					
Ref.	1	2	3	4	5	6	7	8	9	10	11	12*
Non-conv-1	45	60	45	60	45	45	15	15	15	15	15	-
Non-conv-2	45	60	45	60	45	60	15	15	15	15	15	-
Non-conv-3	45	60	45	60	45	45	15	15	15	15	15	-
Non-conv-4	45	60	45	60	45	60	15	15	15	15	15	-

Table 5. Mismatch angles for non-conventional lay-ups (angles are expressed in degree). *Interface where symmetry is applied

All the laminate engineering constants for the conventional and non-conventional lay-ups are represented in Figures 4 and 5. Though all lay-ups have constant in-plane properties (see Figure 4), the flexural properties are slightly different (see Figure 5). The main emphasis, is to have equivalent in-plane properties but not necessarily equivalent flexural properties.

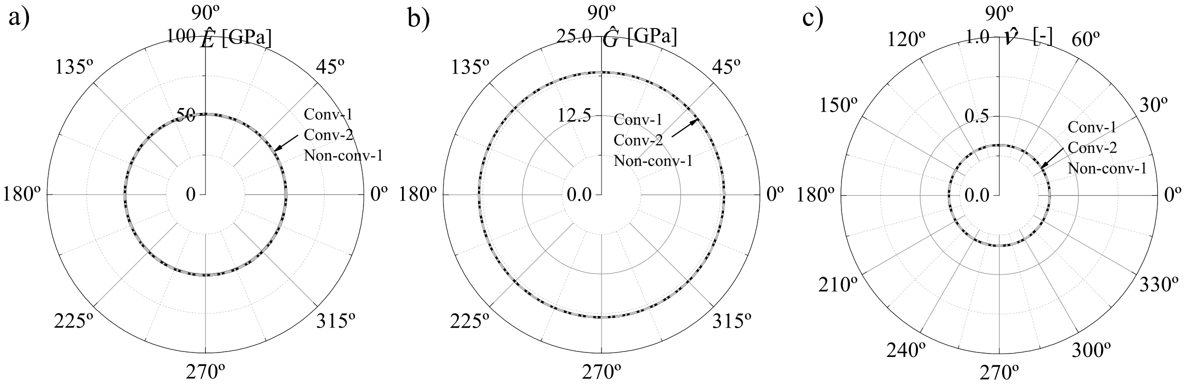

Figure 4. In-plane engineering constants for Conv-1, Conv-2 and Non-conv-1. (a) Normal modulus (b) Shear modulus (c) Poisson ratio

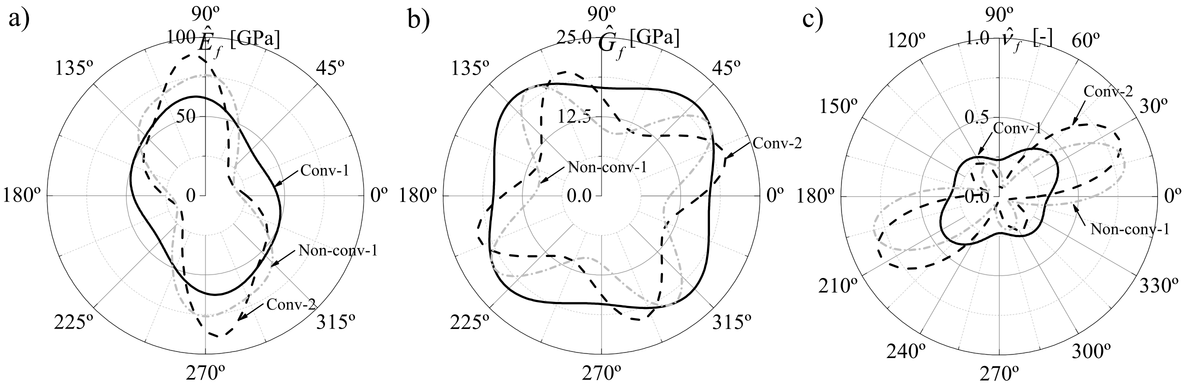

Figure 5. Flexural engineering constants for Conv-1, Conv-2 and Non-conv-1. (a) Normal modulus (b) Shear modulus (c) Poisson ratio

4. Conclusions

A methodology to define a proposed non-conventional stacking sequences for improved damage resistance and tolerance under low velocity impact is presented. The non-conventional stacking sequences satisfy all the imposed constraints dictated by the baseline lay-ups and the experimental evidences. The Ant Colony algorithm was used to generate stacking sequences able to satisfy all the design constraints imposed. The results from the searching algorithm ACO enables us to propose four non-conventional stacking sequences. All the in-plane engineering constants are preserved, while the flexural properties are slightly different from the conventional lay-ups. An on going experimental study to asses to what extent the damage tolerance and damage resistance can be improved is being performed in our group. The result will be published elsewhere in the near future.

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