DAMAGE RESISTANCE OF DISPERSED-PLY LAMINATES

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ABSTRACT

This paper presents the design procedure of a quasi-isotropic (QI) laminate employing dispersion of ply orientations. The goal is to improve damage resistance of a laminate under low velocity impact (LVI). The LVI is treated as a quasi-static loading and instead of a plate a laminated beam is considered. Therefore, this situation simplifies the problem to an interlaminar shear (ILS) test. Although the specimen might experience several failure mechanisms, only delamination which influence the load carrying capability of it drastically under compression after impact (CAI) is considered here. By studying the interlaminar shear stresses through the thickness of the laminate, initiation of crack can be inspected in every layer using a quadratic initiation criterion (QIC). Finally, employing a modified ant colony optimization (ACO) algorithm (two-pheromone ACO algorithm) a fully dispersed QI laminate is designed. The domain of the orientation angles is between -85º to 90º with a 5º interval. The results showed that the interface angles does not present a decisive influence on the crack onset. On the other hand, the dispersion tends to have as large as possible angles near the middle of the laminate to minimize the maximum value of QIC, and some small angles in the outside to provide enough bending stiffness.

1 INTRODUCTION

Nowadays, due to the high specific strength and stiffness, and high fatigue resistance, composite materials are widely used in industry, especially in commercial aircraft such as Airbus A350 XWB and Boeing 787. Most of aeronautical composite parts are made out of conventional laminates (combination of 0º, 90º, and ±45º ply angles) [1]. Composite materials are more beneficial using non-conventional laminates [2, 3] since they can be more freely tailored to a specific structural application. Dispersed laminates and variable stiffness laminates are two main types of non-conventional laminates. In variable stiffness laminates, fibres are placed with curvature based on the load path, introduced in 1989 by Hyer [4]. In dispersed-ply laminates, plies are not limited to 0º, 90º, and ±45º angles and can be in any direction limited by the manufacturing equipment (e.g. interval angle of 2º or 5º). This work focuses on the dispersed-ply laminates. Based on the loading condition, the dispersion of ply angles may improve the damage tolerance of a laminate by keeping its stiffness properties [5]. Dost et al.[6] found that compression after impact (CAI) is also strongly a function of the laminate stacking sequence. Furthermore, based on the load case the direction of the fibres can be selected such that the laminate withstands the required load with less number of plies [7].
Delamination of composite laminates is one of the most important failure mechanisms which has to be taken into account during the design. Impact of even small tool drops can result in delamination initiation that causes reduction of compression and shear strengths of the laminate [8]. Delamination behaviour is dependent on two interface properties: interface resistance and fracture toughness. Using experimental data, Strait et al. [9] showed that stacking sequence has a significant effect on the impact resistance, particularly at higher impact energies.

Low velocity impact (LVI) can often be considered as a quasi-static loading [10]. In LVI, delamination might occur such that they are not detectable; hence, this damage which can considerably influences the CAI performance needs an extra attention during design to be prevented up to Barely Visible Impact Damage (BVID). Therefore, in this work, LVI of a plate is simplified to an interlaminar shear (ILS) test. Such a test considers a laminated beam representative of only one side of a plate around the impact area. This treats impact as a 2-D case which greatly simplifies the model. Hence, the computational effort required for an analytical model is reduced drastically. In addition, a simple 2-D finite element model (FEM) can be used to verify the analytical model.

In design and optimization of laminates, different techniques such as genetic algorithm, or multi-criterion optimization, are investigated widely by different authors [11–13]. Some authors like Gyan [14], Lopes [5], and Chaperon [15] optimized a laminate composite structure using dispersion of ply angles. Ant Colony Optimization (ACO), a metaheuristic searching process introduced in the early 1990s by Dorigo et al. [16], is commonly used for this type of laminates [17, 18]. Sebaey [19] used a two-pheromone ACO algorithm to design a fully dispersed laminate in order to improve the response of laminated composite under biaxial loading, compression and tension. This paper employs this modified algorithm to consider all possible dispersion of fibres directions.

Current paper investigates the possibility to improve damage resistance of laminated beam under impact using dispersion of ply directions. Implementing a two-pheromone ACO algorithm, a set of dispersed quasi-isotropic (QI) laminates with optimum damage resistance are obtained.

2 PROBLEM DEFINITION

Interlaminar stresses in laminated composites can result in delamination between plies [20]. This work focuses on the interlaminar shear (ILS) stresses which plays the main role in triggering delamination. LVI of a plate is simplified by a quasi-static loading of a laminated beam in ILS test. 3-point bending of Short Beam (SB) test is the oldest ILS test [21] which has been made as a standard [22]. Although in this test the dominant applied load is shear, the internal stresses are more complex especially under the loading nose and the supports (see Figure 1). In these areas, other failure mechanisms than delamination might occur such as fibre breakage and matrix cracks. Hence, to study the shear stress distribution through the thickness, the mid-plane between the supports and loading nose has to be observed.

![Figure 1 Schematic view of ILS test set-up](image)

2.1 Analytical model

Since the LVI is simplified as a quasi-static loading an analytical model can be derived as follows. In order to calculate shear stress through the thickness ($\tau_{xz}$) the equilibrium equation shown below is used.
\[
\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} = 0 \tag{1}
\]

where \(\sigma_x\) is the normal stresses along the length of the beam which can be found using its relation with the strain in the same direction \((\varepsilon_x)\) as follows,

\[
\sigma_x = Q_{11}^{(k)} \varepsilon_x \tag{2}
\]

where \(Q_{11}^{(k)}\) is the stiffness related to the \(k^{th}\) fibre angle \((\theta^{(k)})\). Strain which is defined as \(\varepsilon_x = -z \frac{\partial^2 w}{\partial x^2}\) can be calculated by a simplified displacement \((w)\) equation for a beam,

\[
w = \sum \frac{2F}{l} \sin \left(\frac{m\pi}{2}\right) \sin \left(\frac{m\pi x}{l}\right) \frac{D_{11}}{\left(\frac{m\pi}{2}\right)^4} \tag{3}
\]

where \(D_{11}\) is the laminate bending stiffness. \(F\) and \(l\) represent the applied force and length of the beam, respectively. Therefore the shear stress through the thickness of each layer \((\tau_{xz}^{(k)})\) is calculated and shown in equation \((4)\).

\[
\tau_{xz}^{(k)} = -\frac{1}{2} z^2 Q_{11}^{(k)} \lambda_1 + F_0^{(k)}(x) \tag{4}
\]

where \(F_0^{(k)}(x)\) is a constant equal to the difference between the shear stresses at the top and the bottom of each layer which can be found using boundary conditions \((\tau_{xz} = 0 \text{ at } z = 0 \text{ and } z = t_{lam})\). Finally, \(\lambda_1\) is a constant defined as:

\[
\lambda_1 = \frac{2F}{l} \sum \frac{\sin \left(\frac{m\pi}{2}\right) \sin \left(\frac{m\pi x}{l}\right)}{D_{11} \left(\frac{m\pi}{2}\right)} \tag{5}
\]

### 2.2 Verification

In order to verify the results of the analytical model, a FE model is generated using Abaqus/Standard (implicit method). To capture the shear stresses between the plies, a 2-D model representing through the thickness of the laminate is modelled (see Figure 2). Since only interlaminar stresses are required here, a symmetric model can be considered.

![Figure 2 A 2-D FE model of a laminated beam.](image)

The properties of each lamina are calculated based on orthotropic materials in its local coordinates, and transformed to the global coordinate where the x-axis is parallel to the length of the beam. Therefore, the properties are defined by anisotropic material in Abaqus. Furthermore, since only the stresses through the thickness are important here, a CPE4 (A 4-node bilinear plane strain quadrilateral) element type is used. The number of elements through the thickness equals to the number of the layers (16 layers in this case). In order to have a simpler model, instead of defining the load using Hertzian contact theory, a load is distributed over the first two nodes on the top as displacement, see Figure 2.

The shear stresses through the thickness of a random symmetric laminate ([0/30/60/90/60/-60/90/-60]s) in global coordinate of the laminate and in local ply directions are plotted in Figure 3 as
calculated by equation (4) and by the FEM. Note that for the FEM, the stresses at the mid path are considered (marked in Figure 2) where the stresses are not disturbed by the applied load or the support.

Figure 3 Shear stresses through the thickness of the laminated beam using analytical and FE models.

Figure 3 shows a good correlation between the FE model at the mid path with the analytical model. The result of the FEM does not look fully symmetric which can be due to the stress concentration around the support. This analytical model can be used to study the shear stresses through the thickness caused by LVI.

2.3 Crack initiation criterion

As previously mentioned, the focus of this paper is on the interlaminar shear stress which is the dominant parameter causing a delamination onset. Since the area under the impact load is usually under compression, the assumption of considering only shear stresses is valid. In order to determine the location of crack initiation through the thickness the quadratic initiation criterion (QIC), shown in equation (6), is employed. This is the most well-known criterion for delamination initiation studied by several authors [23–25].

\[
QIC = \left( \frac{\tau_{13}}{S_{13}} \right)^2 + \left( \frac{\tau_{23}}{S_{23}} \right)^2
\]

where \( \tau \) and \( S \) represents the shear stress and strengths. Indices 1, 2, and 3 define the planes of fibre directions, transverse direction and through-thickness, respectively. This equation can be employed for every layer, and when the criterion (QIC) becomes equals to or larger than one, crack is initiated. Since the shear stress is quadratic through the thickness, it is expected to observe the delamination onset near the centreline.

3 LAMINATE OPTIMIZATION FOR INTERLAMINAR RESISTANCE

In the macro-level design of composite laminates, usually ply material is chosen based on the availability in the market and their thickness are often predetermined. Therefore, the number of the plies and their stacking sequences are the only parameters left for designing a laminate. In addition, fibre orientation are restricted to a limited number of angles based on the manufacturing constraints.

3.1 Ant Colony algorithm

The ACO algorithm is a search technique that mimics the behaviour of ants in finding the shortest path between the nest and the food source. Each ant marks the path it passed between the food and the
nest by depositing volatile chemical (pheromone) on the ground. Every time an ant passes the same path or part of the same path, more pheromone would be added to that area. In this way, the probability of choosing these paths by the other ants become higher. After a while the shortest way can be found when the amount of pheromone on a specific path is large enough [16].

In the first step when an ant leaves the nest for food (the first optimization iteration), all the paths (stacking sequences) have equal probability to be chosen by any ant. Therefore, in this step the path is picked randomly. After that, the result of every ant (the objective function) is compared with each other. The path with the shortest distance gets the highest amount of pheromone and the longest one receives the smallest amount. After the first step, ants more likely choose paths with the largest amount of pheromone. These procedure continues until all the ants choose the same path which is the shortest path (optimum solution) [26].

The detailed algorithm is explained in [26]. The probability \( P_{ij} \) of ant \( k \) to select a certain fibre angle is defined as:

\[
P_{ij}^k = \frac{\tau_{ij}}{\sum_{i=1}^{n} \tau_{ij}}
\]  

(7)

where \( \tau_{ij} \) are the components of the pheromone matrix (\( \tau \)), and \( n \) represents the number of available fibre orientations. In here, \( i \) is in the range from 1 to \( n \), and \( j \) from 1 to total number of ants. In every step, the new pheromone matrix (\( \tau^{new} \)) can be calculated as:

\[
\tau^{new} = \tau^{old} + NT \frac{f_{best}}{f_{worst}}
\]

(8)

where \( f_{best} \) and \( f_{worst} \) represent the shortest and the longest paths based on the objective function values, respectively. \( NT \) is the number of ants that selected an orientation for a specific layer.

### 3.2 Two-pheromone ACO

In this work, it is decided to design a dispersed-ply laminate including 16 plies with the fibre directions between 0° to 90° with an interval angle of 5°. In addition, the laminate is symmetric and balanced. To design a symmetric laminate, it is just enough to design half of the stacking sequence. On the other hand, designing a balanced laminate (\( A_{1w}=A_{2w}=0 \)) is more challenging since the number of unbalanced laminates is much higher than the number of balanced ones in a set of 16-layer laminates made out of fibre angles between -85° to 90° with a step of 5°.

Since finding balanced laminates needs more time, [18, 27] for every \( \theta \) fibre angle found by an ant for a specific place in the stacking sequence, they place a \( -\theta \) fibre angle next to it to obviate this problem. Since the goal of this project is to investigate the effect of fully dispersion of the fibre angles, placing plus and minus angles next to each other may not result in finding the best optimum solution. On the other hand, searching for the balanced laminates using all plus and minus angles (in total 36 fibre directions) needs more computations. Sebaey [19] used a two-pheromone ACO technique to design a fully dispersed stacking sequence without only paring \( \theta \) and \( -\theta \) fibres.

In this method, the pheromone matrix defined previously is responsible for selection of fibre orientations for every design variables which are one quarter of the total number of layers. This matrix has the dimension of \( NV \) by \( n \). Another pheromone matrix (\( \Pi \)) is responsible for shuffling of the layers. Therefore, in the first phase the fibre angles for a quarter of laminate are selected using only \( \theta \) angles and in the second phase the \( -\theta \) angles are added to the available layers and they are shuffled in different patterns. There are several shuffling forms for a set consisting of 16 layers and it is not feasible to use all of them. Hence, to investigate the effect of interface angle in a laminate, the laminates are shuffled in two ways: a) the minimum possible interface angles are placed near the middle of the stacking sequence, b) the maximum possible interface angles are located near the middle of the stacking sequence. Therefore, the top six laminates with the minimum angle difference and top six laminates with the maximum angle difference are chosen for the shuffling. As an example the top three laminates with minimum and maximum interface angles for a set of [0/5/25/80] is shown in Table 1.
= 0\).

\[ \Pi_{\text{new}} = \tau_{\text{old}} + \frac{1}{f_{\text{best}}} \] (9)

3.3 Optimization setup

The goal of this optimization is designing a 16 layers dispersed QI laminate with largest damage resistance which has bending stiffness close to a reference laminate. Hence, the objective function is minimizing the maximum value of initiation criterion \( (\text{max}(QIC)) \) through the thickness. Note that the symmetric and balance constraints are already considered in the two-pheromone ACO algorithm.

The constraints of in-plane and bending stiffness of each laminate is investigated by comparing its \( A \) and \( D \) matrices with the reference layup matrices. For this comparison a distance function as defined in equation (10) is used [28].

\[ d(A_1, A_2) = A_1^{-1} A_2 + A_1^{-1} - 6 \] (10)

where ‘:’ operator is the Frobenius inner product defined as the sum of the products of the corresponding components of two matrices with the same size (e.g. \( A: B = \sum_{i,j} A_{ij} B_{ij} \)). The distance function is defined such that when \( A_1 \) and \( A_2 \) matrices are close to each other, the distance value \( d(A_1, A_2) \) is close to zero. The order of the distance function is one and can be added to the objective function by a penalty factor \( (P \text{ and } W) \) as shown below.

\[ \text{Minimize Obj} = \text{max}(QIC) + P \ d(A_1, A_{\text{ref}}) + W \ d(D_1, D_{\text{ref}}) \] (11)

where \( A_i \) and \( D_i \) define the in-plane and bending stiffness matrices of the under investigation laminate, respectively. Subscript \( \text{ref} \) represents the reference laminate. In equation (11), the values of \( P \) and \( W \) have to be chosen delicately since assigning large values can make the \( \text{max}(QIC) \) a trivial parameter in the objective function. In this way the optimization might solve only for constrains and does not minimize the criterion.

In the ACO algorithm 10 ants are employed. Furthermore, no evaporation rate is considered \( (\rho = 0) \), and all pheromones are considered equally important \( (\alpha = 1) \). Furthermore, using trial and error the penalty values are chosen as: \( P = 10, W = 0.1 \).

4 Optimization results and discussion

In the first phase, in order to observe how the quadratic initiation criterion tends to be distributed through a laminate with minimum value of \( \text{max}(QIC) \), an optimization without any constraint is performed. The best optimum stacking sequence found is \([0/0/85/-85/90/90/90/90]_{s}\) with \( \text{max}(QIC)_{\text{NoConst.}} = 1.297 \). The shear stresses \( (\tau_{13} \text{ and } \tau_{23}) \) and the criterion \( (QIC) \) through the thickness are shown in Figure 4. It can be seen that the laminates wants to have larger fibre angles to spread the criterion away from the centre of the layup where usually the largest stresses are. This way,
QIC is distributed more uniformly through the thickness of the laminate. Note that the 0° angle fibres in the outside are to maintain some bending stiffness for the laminate.

![Image](image.png)

**Figure 4 Best laminate with no constraint**

### 4.1 Optimization with constraints

For this optimization, the laminate \([45/0/-45/90/45/0/-45/90]_s\) is chosen as a reference laminate with \(\text{max}(QIC)_{\text{ref}} = 2.11\). Now, using the method explained in the last section, the optimization considering all constraints is executed. The laminates with in-plane \((E_{11} \text{ and } E_{22})\) and bending stiffness \((E_{11b})\) values in the range of 10% of the reference layup are accepted. In Table 2 the optimum laminates with minimum values of \(\text{max}(QIC)\) with the normalized stiffness values \((E_{11\text{norm}} = E_{11}/E_{11\text{ref}}, E_{22\text{norm}} = E_{22}/E_{22\text{ref}}, \text{and } E_{11b\text{norm}} = E_{11b}/E_{11b\text{ref}})\) are shown.

<table>
<thead>
<tr>
<th>No.</th>
<th>(\text{Max}(QIC)) [-]</th>
<th>(E_{11\text{norm}}) [-]</th>
<th>(E_{22\text{norm}}) [-]</th>
<th>(E_{11b\text{norm}}) [-]</th>
<th>Laminate</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>1.477</td>
<td>1.04</td>
<td>1</td>
<td>[-5, -35, -65, -70, 70, 65, 35, 5]_s</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>1.511</td>
<td>1.02</td>
<td>0.93</td>
<td>[-10, -30, -65, -70, 70, 65, 30, 10]_s</td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>1.531</td>
<td>0.99</td>
<td>0.96</td>
<td>[-5, -45, -45, 90, 90, 45, 45, 5]_s</td>
<td></td>
</tr>
<tr>
<td>B4</td>
<td>1.626</td>
<td>0.96</td>
<td>1.01</td>
<td>[5, -70, 35, -60, 60, -35, 70, -5]_s</td>
<td></td>
</tr>
<tr>
<td>B5</td>
<td>1.639</td>
<td>0.98</td>
<td>1.02</td>
<td>[10, -75, 35, -60, 60, -35, 75, -10]_s</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Optimum laminates

In addition, to study the effect of the angles better, some of the non-optimum laminates with larger values of \(\text{max}(QCI)\) are presented in Table 3.

<table>
<thead>
<tr>
<th>No.</th>
<th>(\text{Max}(QIC)) [-]</th>
<th>(E_{11\text{norm}}) [-]</th>
<th>(E_{22\text{norm}}) [-]</th>
<th>(E_{11b\text{norm}}) [-]</th>
<th>Laminate</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>2.395</td>
<td>1.01</td>
<td>0.95</td>
<td>0.99</td>
<td>[90, 10, 90, -10, 45, -45, 40, -40]_s</td>
</tr>
<tr>
<td>W2</td>
<td>2.397</td>
<td>0.98</td>
<td>0.95</td>
<td>0.93</td>
<td>[-85, 15, 85, -15, 50, -35, 35, -50]_s</td>
</tr>
<tr>
<td>W3</td>
<td>2.429</td>
<td>1.01</td>
<td>0.95</td>
<td>1</td>
<td>[90, 10, 90, -10, 40, -40, 45, -45]_s</td>
</tr>
<tr>
<td>W4</td>
<td>2.576</td>
<td>1.05</td>
<td>1.01</td>
<td>0.9</td>
<td>[75, -10, 60, -30, 30, -60, 10, -75]_s</td>
</tr>
<tr>
<td>W5</td>
<td>2.895</td>
<td>1.08</td>
<td>0.99</td>
<td>0.92</td>
<td>[80, -80, 10, -10, 30, -30, 55, -55]_s</td>
</tr>
</tbody>
</table>

Table 3 Non-optimum laminates
Although the first three best optimum laminates in Table 2 have a small interface angles, laminate numbers B4 and B5 with large interface angles shows that the difference between fibre orientations does not have a decisive effect. Comparing the results in Table 2, one can notice that although the results tend to use larger fibre orientations in the middle of the layup, similar to the best laminate with no constraint, due to the bending stiffness constraint some of small angles are placed in the middle of the stacking sequence to maintain the required bending stiffness. On the other hand, in Table 3, the non-optimum laminates place the larger fibres in the outside and smaller ones in the middle. Smaller angles in the middle results in a larger QIC values. Figure 5, Figure 6 and Figure 7 illustrate the QIC distribution of the reference, the best optimum (B1) and the worst non-optimum laminate (W5). It can be seen that in the optimum laminate the QIC is distributed rather uniformly while in the non-optimum laminate it is concentrated in the middle of the laminate.

4.2 Verification of results

In order to verify the results of the optimization, a FE model is created explained as follows. For such a model, the configuration of SB test [22] is considered here. To investigate the delamination initiation the bond between each two layers is simulated using cohesive zone [29]. Therefore, in Abaqus the cohesive contact is defined between the bottom surface of the top layer with the top surface of the bottom layer. As it is suggested in literature [29–31] a bi-linear traction-separation law is used to observe the constitutive response of the bonds between the plies. To generate such a model four material properties are required as follows: Mode I and mode II fracture toughness values ($G_{Ic}$ and $G_{IIc}$) and the ultimate normal and shear traction values ($N$ and $S$) at which crack initiates. Since the laminate beam is under pure mode II loading, the $G_{IIc}$ is the important parameter in this model.

The previous model described in section 2.2 can be updated based on the cohesive law. As an example the force versus displacement of the beam under loading and unloading is plotted for the reference QI laminate ([45/0/-45/90/45/0/-45/90]s), see Figure 8.
In Figure 8, the load drop represents a crack initiation. As one expects, after the crack initiation, in the unloading step, the stiffness of the laminate is decreased accordingly. The maximum load triggered the delamination is marked with a red cross. The maximum load caused crack initiation \( F_{\text{max}} \) for the laminates shown in Table 2 and Table 3 are calculated using the FEM and presented in Table 4.

<table>
<thead>
<tr>
<th>No.</th>
<th>( \text{Max(QIC)} ) [-]</th>
<th>( F_{\text{max}} ) [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>1.477</td>
<td>275.05</td>
</tr>
<tr>
<td>B2</td>
<td>1.511</td>
<td>273.64</td>
</tr>
<tr>
<td>B3</td>
<td>1.531</td>
<td>283.60</td>
</tr>
<tr>
<td>B4</td>
<td>1.626</td>
<td>275.66</td>
</tr>
<tr>
<td>B5</td>
<td>1.639</td>
<td>274.94</td>
</tr>
<tr>
<td>W1</td>
<td>2.395</td>
<td>244.50</td>
</tr>
<tr>
<td>W2</td>
<td>2.397</td>
<td>247.95</td>
</tr>
<tr>
<td>W3</td>
<td>2.429</td>
<td>244.90</td>
</tr>
<tr>
<td>W4</td>
<td>2.576</td>
<td>245.35</td>
</tr>
<tr>
<td>W5</td>
<td>2.895</td>
<td>239.97</td>
</tr>
</tbody>
</table>

Table 4 Maximum force caused crack initiation for optimum and non-optimum laminates

As it was expected, Table 4 shows that the best laminates (B1, B2, etc.) have a larger maximum force compared to worse laminates (W1, W2, etc.).

5 CONCLUSION AND RECOMMENDATION

In the present study, a two-pheromone ant colony optimization (ACO) algorithm is employed to design a fully dispersed ply laminate. The impact is simplified as a quasi-static loading considering a laminated beam. Using the quadratic initiation criterion (QIC), delamination onset through the stacking sequence is studied. Applying this analytical model in the modified ACO, optimum laminates can be designed with minimizing the maximum value of QIC.

The results showed that the influence of the interface angles is not conclusive in the delamination initiation. Furthermore, it is observed that without considering any constraints the laminates tends to have large fibre angles in the middle and some small angles in the outsides to maintain the bending stiffness. This way, the QIC is distributed rather uniformly through the thickness of the laminate. On the other hand, considering the in-plane and bending stiffness constraints, some of the fibres with small fibre orientation might be placed near the middle of the layup in order to retain the bending stiffness in the range of the reference laminate.

It is recommended to investigate laminates with larger number of plies, since it might result in stacking sequences with a more conclusive pattern in the fibre angles.
ACKNOWLEDGEMENT

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