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Composite Plate Optimization Subjected to Small Mass Impact

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ABSTRACT

The small mass impact, such as runway debris and dropped tools, is a major issue during the design of composite plates, as it may significantly reduce the plate strength and stiffness without any visible damage. A fundamental concern in aeronautical composite structure design is the determination of the stacking sequence and thickness of a component to improve the resistance for several types of loads. In order to cope with the definition of an optimal design, this paper presents a new optimization procedure applied to composite plates subjected to small mass impact considering impact response and delamination threshold load predict by closed forms solutions. The main goal of the optimization process is to determine, not only the optimum, but a range of feasible designs with a specified number of layers which presents a predetermined margin of safety against small mass impact resulting in more flexibility and robustness to aeronautical composite structures designs. The algorithm has the stack sequence and number of layers as design variables, and predicts for known impact energy the margin safety defined by the peak impact force and the threshold delamination load. A main feature of the optimization process is its formulation based on lamination parameters which avoids large computational demands for a very complex problem. Preliminary results demonstrate that the objective function for plates with small number of layers does not vary significantly for different stacking sequences. Nevertheless, for plates with a larger number of layers, typically more than 16, the stacking sequence shows a significant influence on the objective function.

Keywords: Optimization, composite plates, small mass impact

1 INTRODUCTION

Composite structures have been playing an important role on aeronautical projects, particularly due to their unique properties of high specific stiffness and high fatigue resistance as compared to metallic alloys. Therefore, in many applications, composites are a better choice compared to metals particularly when weight saving is critical [1]. Nevertheless, an appropriate design should be developed in order to achieve the best usage of a composite structure. Otherwise metallic alloys still may be a better choice for weight saving.

In aeronautical composite structures design, impact response is a major concern because it could potentially cause significant effects on the structural behavior. In order to cope with this problem and aiming at achieving good agreement with experimental results without the necessity of large computational effort, Olsson proposed a first approach to evaluate response of small mass impact on composite structures through a model that describes the event based upon an approximate analytical solution of the governing differential equation [2]. This solution was reformulated and presented on following publications. Ref. [3] defines small mass impact for cases which the impactor mass is less than 1/4 of the mass of the largest possible area for which waves do not interfere with the boundaries.

Ref. [3] demonstrated that predictions based on closed form solutions were in good agreement with experimental results for a wide range of test cases. Ref. [4] compared the method against finite element models of plates with different thickness, also showing a good agreement with experimental results. Ref. [5] presents the comparison between experimental and predictions of impact on carbon-epoxy laminated plates. The results indicate the ability of the theory to predict delamination onset and delamination threshold velocity in real quasi-isotropic laminates. The tested plates were 100 x 100 mm and made from AS4/8552 carbon-epoxy prepreg with the layup $[(0/90/\pm45)_s/(90/0/\ 45)_s]_n$ where n = 1 or 2. The laminates were 2.1 or 4.1 mm thick and the impactor mass of 2.1 or 8.4 g. Ferreira et al. [6] combined these closed forms solutions with simulated annealing optimization algorithm in order to evaluate the applicability of an optimization scheme based on the solutions proposed in [3] validating the optimum design with finite element model analysis.

This work presents a new optimization procedure applied to composite plates subjected to small mass impact considering impact response and delamination threshold load predict by closed forms solutions proposed by Olsson [3]. The main goal of the optimization process is to determine, not only the optimum, but a range of feasible designs with a specified number of layers which presents a predetermined margin of safety against small mass impact resulting in more flexibility and robustness to aeronautical composite structures designs. As a result, the threshold velocity for different number of layers are presented as well as feasible design regions that allow more flexibility in the design of composite structures including small mass impact loads.

The main feature of the new approach of optimizing composite structures is the application of lamination parameters instead of lamination angles through the optimization process. Nevertheless, the determination of stacking sequence for a composite structure from lamination parameters is virtually impossible. Therefore, the solution adopted to cope with this problem was the creation of databanks containing the lamination parameters and stacking sequence for each angle combination.

2 LAMINATION PARAMETERS

Lamination parameters are defined on the basis of the laminate thicknesses and fiber orientations [7]. By definition, the lamination parameters are bounded to be $-1 \le \xi_i^l \le 1$. However, theses bounds do not guarantee that a given set of lamination parameters correspond to any physical lay-up.

An advantage of using lamination parameters is that the stiffness for a composite material may be expressed as linear function of the material invariants and lamination parameters, [8]. The central idea of the present approach is to use lamination parameters in order to avoid larger computational effort when optimizing composite plates subjected to small mass impact.

Only eight lamination parameters are necessary to entirely define the constitutive relations of a symmetric laminate composed by equal thickness layers of the same material. The in-plane extensional stiffness matrix [*A*], the laminate bending stiffness matrix [*D*], and the out of plane shear stiffness matrix [*A**] are fully defined by eight lamination parameters, ξ_i^A and ξ_i^D, *i* = 1, 2, 3, 4, as shown in Eq. (1).

$$\begin{aligned}
&[A]=T(U_E[I_E]+U_G[I_G]+\xi_1^A U_{\Delta c}[I_1]+\xi_2^A U_{\Delta c}[I_2]+\xi_3^A U_{\nu c}[I_3]+\xi_4^A U_{\nu c}[I_4])\\
&[D]=\frac{T^3}{12}(U_E[I_E]+U_G[I_G]+\xi_1^D U_{\Delta c}[I_1]+\xi_2^D U_{\Delta c}[I_2]+\xi_3^D U_{\nu c}[I_3]+\xi_4^D U_{\nu c}[I_4])\\
&[A^*]=T\left(U_{at}[I_t]+\xi_1^A U_{\Delta t}[I_{t1}]+\xi_2^A U_{\Delta t}[I_{t2}]\right)
\end{aligned} \tag{1}$$

where $[I_E]=\begin{bmatrix}1&1&0\\1&1&0\\0&0&0\end{bmatrix}$ $[I_G]=\begin{bmatrix}0&-2&0\\-2&0&0\\0&0&1\end{bmatrix}$ $[I_1]=\begin{bmatrix}1&0&0\\0&-1&0\\0&0&0\end{bmatrix}$ $[I_2]=\frac{1}{2}\begin{bmatrix}0&0&1\\0&0&1\\1&1&0\end{bmatrix}$

$[I_3]=\begin{bmatrix}1&-1&0\\-1&1&0\\0&0&-1\end{bmatrix}$ $[I_4]=\begin{bmatrix}0&0&1\\0&0&-1\\1&-1&0\end{bmatrix}$ $[I_t]=\begin{bmatrix}1&0\\0&1\end{bmatrix}$ $[I_{t1}]=\begin{bmatrix}1&0\\0&-1\end{bmatrix}$ $[I_{t2}]=\begin{bmatrix}0&1\\1&0\end{bmatrix}$

Despite the advantages of using lamination parameters for optimization algorithm, the impossibility of defining the angles orientation from lamination parameters poses a great difficulty. Therefore, in order to cope with this problem, databanks for different numbers of plies were created defining stacking sequence associated to each laminate and its lamination parameters. Eq. (2) presents the definition of the lamination parameters that define matrices [A], [D] and [A]*:

$$\begin{aligned}
\xi^A_{[1,2,3,4]}&=\frac{1}{T}\sum_{k=1}^{n}(h_k-h_{k-1})\left[\cos(2\theta_k)\quad \sin(2\theta_k)\quad \cos(4\theta_k)\quad \sin(4\theta_k)\right]\\
\xi^D_{[1,2,3,4]}&=\frac{4}{T^3}\sum_{k=1}^{n}(h_h^3-h_{k-1}^3)\left[\cos(2\theta_k)\quad \sin(2\theta_k)\quad \cos(4\theta_k)\quad \sin(4\theta_k)\right]
\end{aligned} \tag{2}$$

where T is the laminate thickness, h_k is the distance from the interfaces of k^{th} and k^{th+1} layers and θ_k is the lamination angle of the k^{th} layer. Due to the nature of the closed form equations, only four of these lamination parameters are actually used by the proposed optimization algorithm ($\xi^A_{[1,3]}$ and $\xi^D_{[1,3]}$).

In Eq. (1), U_E, U_G, $U_{\Delta c}$, $U_{\nu c}$, U_{at} and $U_{\Delta t}$ are the extension and transversal stiffness invariants, respectively. These invariants are defined in Eq. (3):

$$\begin{aligned}
&U_E=\frac{3Q_{11}+3Q_{22}+2Q_{12}+4Q_{66}}{8} \quad U_{\nu c}=\frac{Q_{11}+Q_{22}+2Q_{12}-4Q_{66}}{8} \quad U_{\Delta c}=\frac{Q_{11}-Q_{22}}{2}\\
&U_G=\frac{Q_{11}+Q_{22}-2Q_{12}+4Q_{66}}{8} \quad U_{at}=\frac{Q_{55}+Q_{44}}{2} \quad U_{\Delta t}=\frac{Q_{55}-Q_{44}}{2}
\end{aligned} \tag{3}$$

In Eq. (3), Q_{ij} are the components of the matrix of the stress/strain relations defined by the plate materials properties as defined in Eq. (4):

$$\begin{aligned}
&Q_{11}=\frac{E_1}{1-\nu_{12}\nu_{21}} \quad Q_{12}=\frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} \quad Q_{55}=G_{13}\\
&Q_{22}=\frac{E_2}{1-\nu_{12}\nu_{21}} \quad Q_{66}=G_{12} \quad Q_{44}=G_{23}
\end{aligned} \tag{4}$$

3 THEORY

Ref. [3] proposes a closed form prediction of peak load and delamination onset under small mass impact. The basic equation for determination of impact peak load and delamination threshold for defined impact energy are presented.

As initial assumptions, it is considered a laminate plate of thickness h and density ρ impacted by a concentrated elastic mass M with an initial velocity V_0. The impactor is considered as an isotropic sphere defined by its mechanical properties: Young modulus, E_i and Poisson ratio, ν_i.

On the other hand, laminate plate is defined by its effective bending D^* stiffness, Eq. (5), and shear stiffness, S^*, Eq. (6), respectively.

$$D^* \approx \sqrt{\left(\frac{1+\eta}{2}\right) D_{xx} D_{yy}} \qquad \eta = \frac{\left(D_{xy} + 2D_{ss}\right)}{\sqrt{D_{xx} D_{yy}}} \tag{5}$$

$$S^* \approx \sqrt{\kappa_{xzxz} \kappa_{yzyz} A_{xzxz} A_{yzyz}} \tag{6}$$

where D_{ij} and A_{ij} are the components of the bending and extension matrices of the laminate ([A] and [D] matrices, respectively). κ_{xzxz} and κ_{yzyz} are the shear correction factors assumed to be equal to 5/6.

The theory is based on the prediction of the peak force F_{peak}, Eq. (7), and the threshold delamination force F_{dl}, Eq. (8), for a given impact energy:

$$\frac{1}{F_{peak}} \approx \frac{1}{F_b} + \frac{1}{F_c} + \frac{1}{F_s} \tag{7}$$

$$F_{dl}^{dyn} = 1.213\pi \sqrt{\frac{32}{3} G_{IIc} D^*} \tag{8}$$

where G_{IIc} is the critical strain energy release rate in mode II, characteristic of the laminated material.

In Eq. (7) F_b, F_s and F_c are, respectively, the bending, shear and contact forces acting on the plate. The bending force F_b, Eq. (8) is determined by plate density, ρ, and thickness, T, as well as the effective bending stiffness D^* and impact velocity V_0.

$$F_b = 8V_0 \sqrt{\rho T D^*} \tag{9}$$

The shear force F_s is defined in Eq. (10) and depends on the impactor mass M, effective shear stiffness, S^* and initial impact velocity, V_0.

$$F_s = 2V_0 \sqrt{\pi M S^*} \tag{10}$$

The expression of the contact force *Fc*, Eq. (11) depends on the material properties inserts on contact stiffness K_α defined in Eq. (12).

$$F_c = K_\alpha^{2/5}\left(\frac{5}{4}MV_0^2\right)^{3/5} \tag{11}$$

$$K_\alpha = \frac{4}{3}Q_\alpha\sqrt{R} \tag{12}$$

Q_α, defined in Eq. (13), is the effective contact modulus and R is the impactor radius:

$$\frac{1}{Q_\alpha} = \frac{1}{Q_{zp}} + \frac{1}{Q_{zi}} \tag{13}$$

Q_{zp} and Q_{zi} are the effective contact moduli of the impactor and plate. Contact modulus Q_{zp} for a material with transverse isotropy along the loading axis z is defined by Eq. (14).

$$Q_{zp} = 2\sqrt{G_{rz}/C_{rr}}\,(C_{rr}C_{zz} - C_{rz}^2)\Big/\sqrt{\left(\sqrt{C_{rr}C_{zz}} + G_{zr}\right)^2 - \left(C_{rz} + G_{zr}\right)^2} \tag{14}$$

where

$$C_{rr} = E_r\left(1-\nu_{rz}\nu_{zr}\right)\Omega\big/\left(1+\nu_r\right) \qquad C_{rz} = E_r\nu_{zr}\Omega$$

$$C_{zz} = E_z\left(1-\nu_r\right)\Omega \qquad \Omega = 1\big/\left(1-\nu_r - 2\nu_{rz}\nu_{zr}\right)$$

Ref. [5] presented the homogenized properties of the laminate as showed in Eq. (15).

$$\nu_{rz} = \sqrt{\nu_{13}\nu_{23}} \qquad \nu_r = \sqrt{A_{xx}A_{yx}}\Big/\sqrt{A_{xx}A_{yy}}$$

$$G_{rz} = \sqrt{G_{13}G_{23}} \qquad E_r = (1-\nu_r^2)\sqrt{A_{xx}A_{yy}}\Big/T \tag{15}$$

Q_{zi} in Eq. (13) is defined by Eq. (16).

$$Q_{zi} = E_i\big/\left(1-\nu_i^2\right) \tag{16}$$

3.1 Algorithm

The optimization process was implemented in a Fortran algorithm that allows the determination not only of the optimum but a range of feasible designs for a given initial impact velocity V_0 that in turn defines the impact energy. As design variables, the algorithm has the stacking sequence and the number of layers of the laminate. The central idea is to predict, based on the previous equations, the margin safety provided by the peak impact force F_{peak} and the threshold delamination load F_{dl}.

No specific search method is used. Instead the algorithm calculates the capability of each laminate from a databank to resist to a given impact velocity. This capability is defined by the ratio $R = F_{peak} / F_{dl}$ and is used as the objective function to be maximized. It is worth mentioning that the process to define the feasible regions does not demand great computational effort and is done in less than one minute for databank with about 80,000 laminates in a personal desktop computer. As a result, feasible regions are defined for velocities of 99%, 98%, 95% and 90% of the optimum project threshold velocity and are presented in form of velocity curves for each number of layers of the laminate.

3.2 Validation

In order to validate the algorithm, the results presented in Ref. [5] were analyzed using the algorithm described previously. Table (1) presents the material properties used by [5]. Two laminates $[(0/90/\pm45)_s/(90/0/\mp45)_s]_n$ n=1 or 2 of AS4/8552 carbon-epoxy were considered. The resulting laminate thickness is 2.1 or 4.1 mm. The impactor mass was assumed to be of 2.1 g or 8.4 g (4.00 or 6.35 mm radius, respectively).

Table 1 Laminate and impactor properties

Laminate	E_{11}	E_{22} E_{33}	G_{12} G_{13}	G_{23} (GPa)	ν_{12}	ν_{23}	*Density* (Kg/m³)	G_{IIc} (J/m³)	*h* (m)
AS4/8552	135	10	4.5	3.3	0.3	0.5	1560	829	$1.30\text{x}10^{-4}$
Impactor	*E* (GPa)	ν	*Mass* (kg)	*Radius* (m)					
Steel¹	210	0.3	$2.1\text{x}10^{-3}$	$4.0\text{x}10^{-4}$					
Steel²	210	0.3	$8.4\text{x}10^{-3}$	$6.35\text{x}10^{-4}$					

The results for both laminates are compared with the threshold velocities for the optimum and worse project for 16 layers and 32 layers databanks and are presented in Table 2.

Table 2 Comparison of threshold velocities for different projects

Impactor Mass (g)	Impactor Radius (mm)	N layer / h (mm)	Ref. [5] (m/s)	Databank: Optimum project	Databank: Worse project	Databank: $V_{th,\ optimum}$ (m/s)	Databank: $V_{th,\ worse}$ (m/s)
2.1	4	16 / 2.1	40.131	$[(45)_8/0/15/\text{-}45/\text{-}60/90/\text{-}75/\mp45)_s]$	$(0)_{16}$	40.15	35.998
2.1	4	32 / 4.2	54.534	$[(50)_4/15/\text{-}90/\mp45)_s]$	$(0)_{32}$	54.556	44.854
8.4	6.35	16 / 2.1	31.685	$[(45)_8/0/15/\text{-}45/\text{-}60/90/\text{-}75/\mp45)_s]$	$(0)_{16}$	31.693	29.81
8.4	6.35	32 / 4.2	34.386	$[(50)_4/15/\text{-}90/\mp45)_s]$	$(0)_{32}$	34.396	29.884

One may notice in Fig. 1 that the layups presented in Ref. [5] ($[(0/90/\pm45)_s/(90/0/\mp45)_s]_n$ n=1 or 2) are capable of resisting to impact energies very close to the respective optimum designs found in the databanks. However, the process of finding the best layup project does not allow designers to choose a layup that might resist impact and other types of design requirements, such as buckling load and vibration.

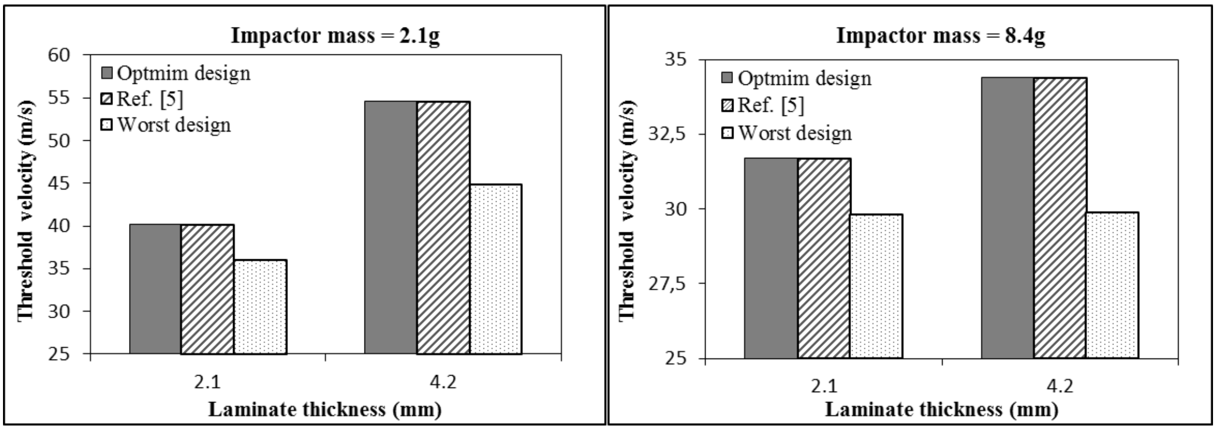

Figure 1 Threshold velocities of 2.1 mm and 4.2 mm laminates for 2.1 g and 8.4 g impactors.

On the other hand, through the proposed algorithm, one may choose among different designs capable of resisting to the same level of impact energy as analyzed in the present example. For instance, applying the proposed algorithm to a 16 layers laminate databank, more than 39,000 from approximately 84,000 laminates are able to withstand to a level of impact energy equal to 99% of the threshold velocity of the databank optimum laminate. Fig. 2 illustrates the velocity curves for 99%, 98%, 95% and 90% of the optimum project's threshold velocity for 16 and 32 layers of an AS4/8552 carbon-epoxy laminate, impacted by steel impactors of 2.1 g and with 4.0 mm radius, defined in Table 1.

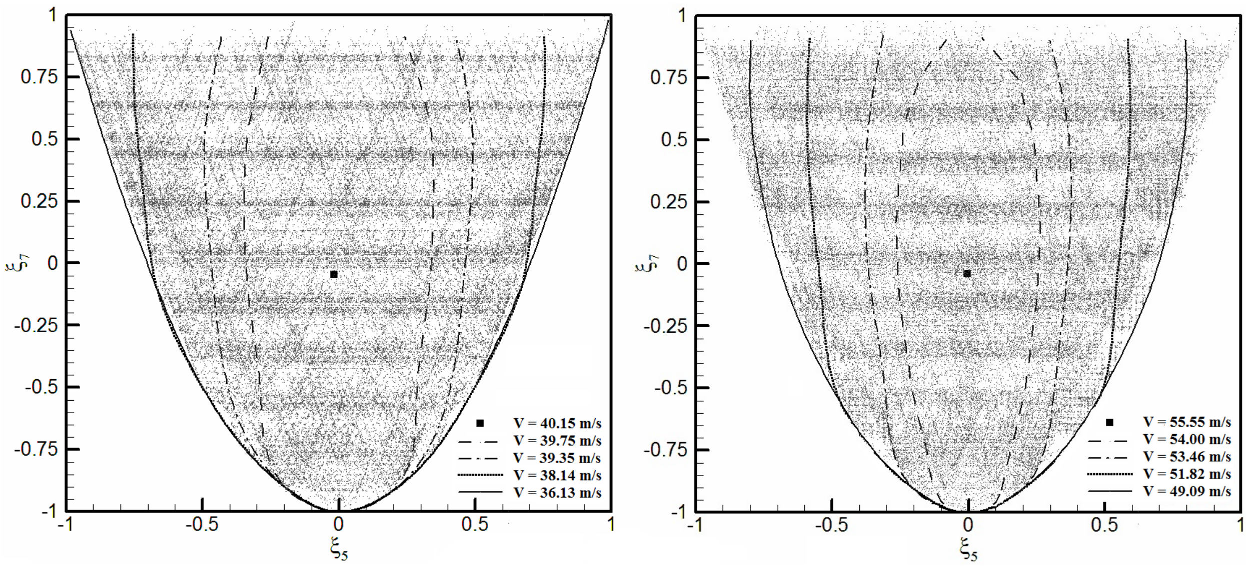

Figure 2 Velocity curves for 16 layers and 32 layers databanks
(AS4/8552 carbon-epoxy impacted by steel impactor of 2.1g of mass and 4.0mm of radius).

In Fig. 2, ξ_5 and ξ_7 are respectively the lamination parameters corresponding to matrix $[D]$ - ξ_1^D and ξ_3^D. The effective bending stiffness D^*, and so ξ_1^D and ξ_3^D, demonstrated to have a larger influence, compared to ξ_1^A and ξ_3^A, in the determination of the F_{peak} and F_{dl} forces. Therefore, the velocity curves are presented as a function of these lamination parameters.

4 APPLICATION EXAMPLES

Having the stack sequence and number of layers as design variables the applicability of the impact response theory, proposed by [2], was analyzed for 4, 8, 16, 24, 32 and 40 layers made of T300/5208 carbon-epoxy and impacted by an aluminum impactor, proposed by [6]. Composite laminate and impactor properties are shown in Table 3.

Table 3 Laminate and Impactor properties

Laminate	E_{11}	E_{22} E_{33}	G_{12} G_{13}	G_{23} (GPa)	ν_{12}	ν_{23}	*Density* (Kg/m³)	G_{IIc} (J/m³)	*h* (m)
T300/5208	132	10.8	5.6	4.4	0.24	0.5	1600	300	$1.27\text{x}10^{-4}$

Impactor	*E* (GPa)	ν	*Mass* (Kg)	*Radius* (m)
Aluminum	71	0.3	$3.0\text{x}10^{-3}$	$6.4\text{x}10^{-3}$

However, instead of evaluating only the capability of a determined lay-up to resist to a defined initial velocity, or even find the best lay-up that might resist to a defined level of impact energy, it is proposed the evaluation for a series of databanks (number of layers) the velocities to which composite laminate designs will resist without delamination growth.

As a result, velocity curves were plotted for each databank showing the feasible regions defined by initial impact velocities, in accord to ξ_1^D and ξ_3^D , for different levels of impact velocities. Figs. 3 to 8 show the velocity curves for 4, 8, 16, 24, 32 and 40 layers, respectively.

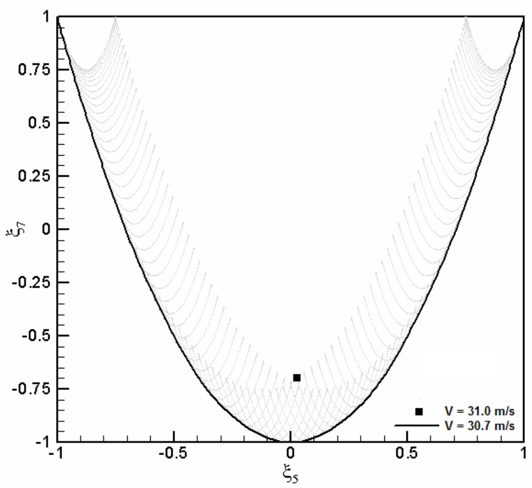

Fig. 3 Velocity curves for 4 layers databank

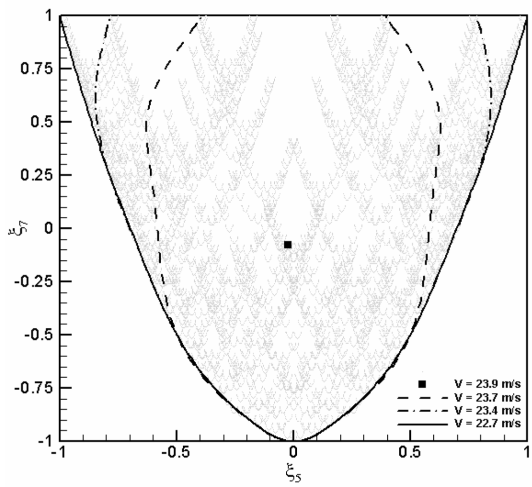

Fig. 4 Velocity curves for 8 layers databank

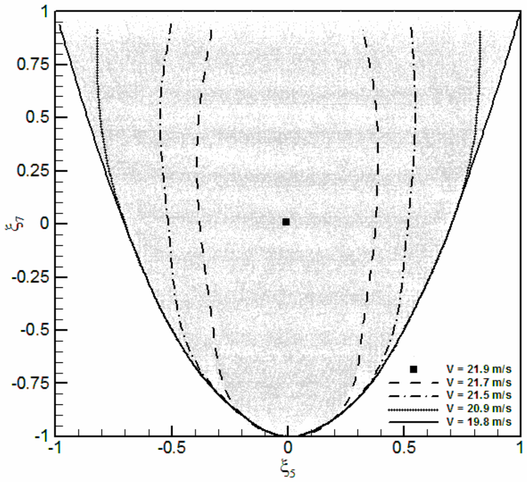

Fig. 5 Velocity curves for 16 layers databank

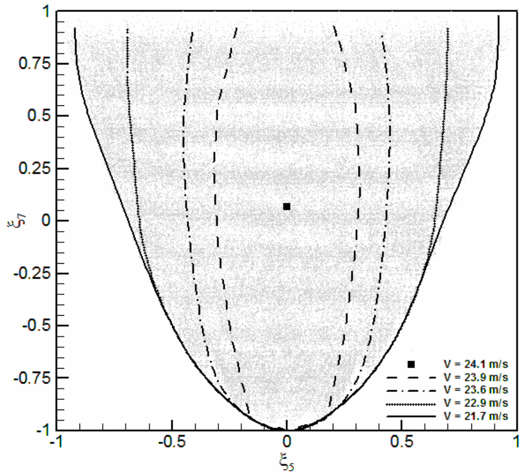

Fig. 6 Velocity curves for 24 layers databank

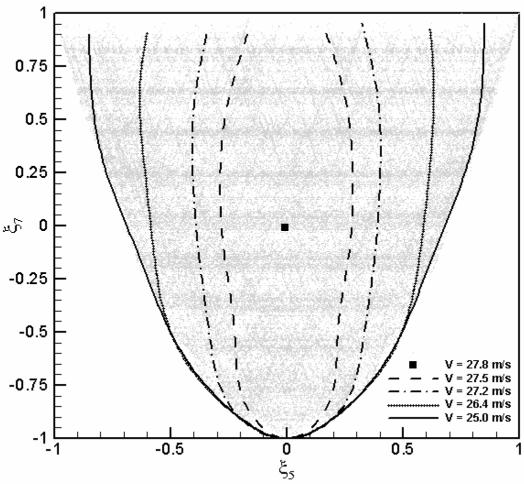

Fig. 7 Velocity curves for 32 layers databank

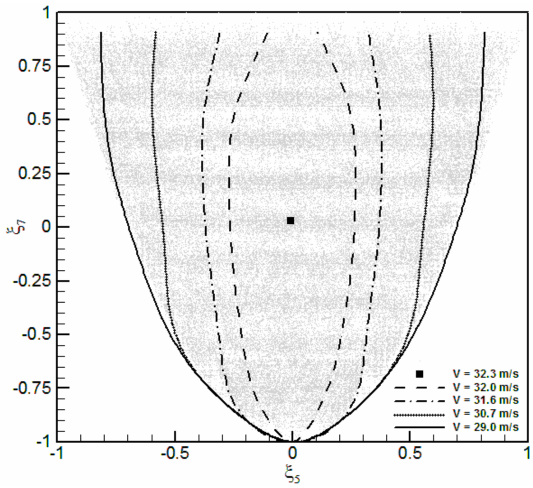

Fig. 8 Velocity curves for 40 layers databank

For laminates with 16 layers, for instance, from Fig 5 it is possible to verify that every laminate in the databank is capable of resisting to an impact velocity equal to 90% of the best laminate. On the other hand, in Fig. 8 (40 layers laminate) few laminates are out of the feasible region for impact velocities up to 90% of the best laminate, represented by the dark marker at the center.

From Figs. 3 to 8 it is clear that the best design for each databank has a tendency to be such that the lamination parameters ξ_1^D and $\xi_3^D = 0$ (this corresponds to a quasi-isotropic laminate). As mentioned before, these terms influence directly the effective bending stiffness D^* which has an important role in the delamination force F_{dl}, and so on the definition of the best design.

Laminates with few laminas present a small influence of the effective bending stiffness D^* due to the definition of terms from $[D]$ matrix and due to the large values resulting for the bending force F_b. Hence, threshold velocities for these databanks presented high threshold velocities compared to thicker laminates.

Threshold velocities for databanks other that the ones used in Figs. 3 – 8 were analyzed in order to predict for each number of layers in the laminate its feasible design regions. Fig. 9 illustrates the threshold velocities for databanks from 3 to 40 layers. The materials assumed for analysis were presented in Table 3.

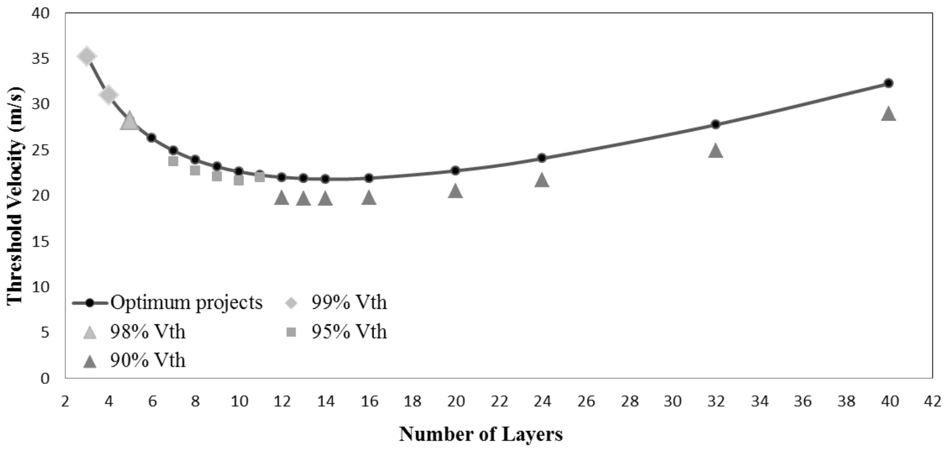

Fig 9 – Threshold velocities various laminates with different number of layers.

Fig. 9 illustrates the capability of predicting the threshold velocity for laminates with different number of layers. However, the outstanding conclusion is the small variation of threshold velocities for a large number of laminates analyzed. For example, for a laminate with 10 layers any laminate in the databank (around 59,000 projects) will withstand an impact with an initial velocity equal to 95% of the optimum design. In other words, if one considers a project safety margin of 5% for a 10 layers project, any lay-up will satisfy the safety requirement.

It must be taken into account the following facts: (a) the closed form solution is in fact an approximate solution that (b) involves experimentally determined factors that typically have a large scatter (large standard deviation). On the other hand, this paper demonstrates that the most important factor in the computation of the objective function is the laminate thickness. The lamina orientation does affect the results but only about 10%. Therefore, if a typical safety factor is used the dominant factor will be the laminate thickness. As a consequence, in practical applications, the impact of a small mass requirement defines only the number of layers of the laminate.

5 CONCLUSION

Small mass impacts, such as runway debris and dropped tools are a concern to designers of composite aeronautical structures. Despite this fact, results presented in the present paper illustrate the ability of the proposed algorithm to define feasible project regions for composite plate and predicted for an initial impact velocity if delamination may damage the structure or not. It has been shown that the predictions are in close agreement with experimental and numerical solutions as presented by [5-6] and illustrated in Fig. 1.

However, besides the capability of predicting initial delamination growth, the procedure proposed in Ref. [3], demonstrates the ability of defining feasible regions for composite plates structures design. Combined with the use of the lamination parameter approach and databank concept, the algorithm used for optimizing composite plate structures under small mass impact demonstrates an useful tool for designers to define not just the best project for a certain impact energy, but, in essence, how many layers will be necessary for standing to impact velocity defined for the design.

The use of lamination parameters does not bring any difference regarding the laminate analysis. But it does contribute to a better understanding of the as only two lamination parameters are dominant regardless the number of layers of the laminate. Therefore, the use of lamination parameters brings a new insight onto this problem.

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