ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

OPTIMIZATION PROCESS OF SMALL MASS IMPACT ON COMPOSITE LAMINATE USING LAMINATION PARAMETERS

Rubens Zolar Gehlen Bohrer
Sérgio Frascino Müller de Almeida
Instituto Tecnológico de Aeronáutica – ITA, Mechanical Engineering Department, 12.228-900 São José dos Campos-SP, Brazil
rubensb@ita.br, frascino@ita.br

Abstract. *The present paper presents a novel approach for laminate plates optimization subjected to small mass impact. Small mass impacts are a common issue to aeronautical projects and may be caused by dropped tools, bird strikes or runway debris, for instance. Usually composite impact simulations through commercial finite elements packages are very computational demanding. Nevertheless, it has been shown in recent literature that it is possible to predict the delamination threshold load as well as the peak load by closed forms solutions. Therefore, combining the closed form predictions to the application of lamination parameters through a databank concept it is possible to create a robust algorithm that is able to delineate, for given impact energies, feasible composite designs with a prescribed margin of safety which shall withstand small mass impacts. Moreover, laminates in the databank are penalized based on practical design rules for composite laminates. Therefore, laminates with consecutive unidirectional plies with repeated ply angles and large coupling terms in the laminate extensional and bending matrices ([A] and [D], respectively) are penalized. Hence, it is going to be demonstrated the applicability of the new approach through examples for databanks with more than 450,000 laminates. The optimization process is shown to be useful tool for designers in order to analyze composite structures under small mass impact.*

Keywords: *laminate plate optimization, small mass impact, lamination parameters*

1. INTRODUCTION

Composite structures application in aeronautical projects has been increasing over the years. This tendency may be observed in recent reports available in literature, such as the United States Government Accountability Office (Gao, 2011). Since the 1980s, composite structures have been used for some aircraft structures, primarily in control surfaces. Nevertheless, in recent years, manufacturers have expanded the use of composites to the fuselage and wings due to their unique properties of high specific stiffness, high fatigue and corrosion resistance as compared to metallic alloys (Gao, 2011).

In many applications, composites demonstrate to be a better choice compared to metals particularly when weight saving is critical, (Gyan et al., 2012). However, 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 in terms of weight and cost savings.

In aeronautical composite structures design, impact response is a major concern because it could potentially cause significant effects on the structural behavior (Olsson et al., 2006; Olsson, 2007). One of the most significant factors for this concern is due to the incapacity of detecting possible damage, such as matrix cracks and delamination onset, via visual inspection as well as the substantial stiffness reduction of the impacted composite structure, especially under compression load (Freitas et al., 2000).

Composite response under impact phenomenon changes for different types of solicitations (Olsson et al., 2006; Ferreira et al., 2011). These events are typically classified as low velocity impact and high velocity impact, though, these definitions of the impact occurrence differs among authors. On the other hand, Olsson (2000) defined that the impact response of plates is governed by the impactor/plate mass ratio, classifying the impact event as: small mass impact and large mass impact. Consequently, small mass impact occurs if the impactor/plate mass ratio (M/M_p) is less than 1/4, where M_p is the mass of the largest plate area affected by the flexural waves. Additionally, Olsson (2010) defines that small mass impact results in local response controlled by flexural waves and large mass impact results in quasi-static response, Fig. 1 (Olsson, 2010).

In order to predict the impact event and aiming at achieving good agreement with experimental results without the necessity of large computational effort, Olsson (1992) 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. This solution was reformulated and presented on subsequent publications (Olsson, 2003; Olsson et al., 2006) for the specific case of small mass impact, showing good agreement with Finite Element (FE) models and laboratory tests.

Olsson (2003) demonstrated that predictions based on closed form solutions were in good agreement with experimental results for a wide range of test cases. Olsson et al. (2006) compared the method against FE models of plates with different thickness, also showing a good agreement with experimental results. Moreover, Olsson (2007)

ISSN 2176-5480

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 practical quasi-isotropic laminates. Recently, Ferreira et al. (2011), proposed, based upon the closed form prediction, an optimization process using simulated annealing in order to minimize the total mass of impacted composite plates under small mass impact.

Therefore, combining the closed form predictions, proposed by Olsson et al. (2006), with the lamination parameters concept, it is suggested a novel approach in order to optimize composite structures behavior under small mass impact. Results are compared against experimental and theoretical results presented in recent literature and the applicability of the process is discussed. Moreover, in order to cope with the definition of feasible designs through lamination parameters, laminate databanks were created containing the stacking sequence for each lamination parameter combination as well as a penalty for repeated ply angles and elevated coupling terms.

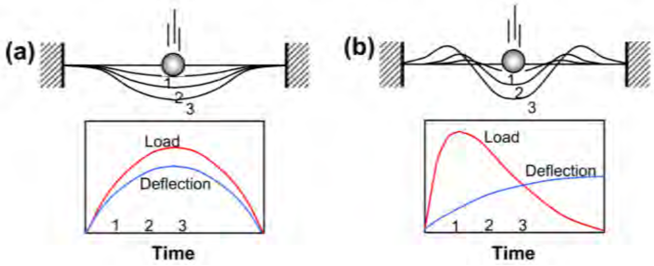

Figure 1. Large mass impact (a) and small mass impact (b) response types during impact on plates. From: Olsson (2010).

2. LAMINATION PARAMETERS

Lamination parameters are defined on the basis of the laminate thicknesses and fiber orientations (Sørensen and Kann, 2011). By definition, the lamination parameters are bounded to be $-1 \le \xi_i^{\,l} \le 1$. However, these 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 independently of the number of layers, the maximum number of parameters required to express a laminate is equal to 12 (Ghiasi et al., 2009). Nevertheless, 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, or ξ_j, j = 1, 2,.., 8, as shown in Eq. (1).

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

$$
[I_E] = \begin{bmatrix} 1 & 1 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad
[I_1] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad
[I_3] = \begin{bmatrix} 1 & -1 & 0 \\ -1 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix}
$$

$$
[I_G] = \begin{bmatrix} 0 & -2 & 0 \\ -2 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad
[I_2] = \frac{1}{2}\begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix} \quad
[I_4] = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & -1 \\ 1 & -1 & 0 \end{bmatrix}
$$

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

In Eq. (1), U_E, U_G, $U_{\Delta c}$, U_{vc}, U_{at} and $U_{\Delta t}$ are the extension and transversal stiffness invariants, respectively. Equation (2) presents the definition of the lamination parameters that express matrices [A], [D] and [A*].

$$
\begin{aligned}
\xi_{[1,2,3,4]}^A &= \xi_{[1,2,3,4]} = \frac{t_k}{T}\sum_{k=1}^{n}\left(h_k - h_{k-1}\right)\left[\cos(2\theta_k) \quad \sin(2\theta_k) \quad \cos(4\theta_k) \quad \sin(4\theta_k)\right]\\
\xi_{[1,2,3,4]}^D &= \xi_{[5,6,7,8]} = \frac{4}{T^3}\sum_{k=1}^{n}\left(h_h^3 - h_{k-1}^3\right)\left[\cos(2\theta_k) \quad \sin(2\theta_k) \quad \cos(4\theta_k) \quad \sin(4\theta_k)\right]
\end{aligned}
\tag{2}
$$

ISSN 2176-5480

where t_k and θ_k are the thickness and the orientation of the *k-th* layer, respectively, T is the laminate thickness, h_k is the position of the bottom of the *k-th* layer with respect to the mid-plane and n is the number of layers.

3. LAMINATE DATABANKS

Despite the advantages of using lamination parameters for optimization algorithms, the impossibility of defining the angles orientation from lamination parameters poses a great difficulty. Therefore, in order to cope with this problem, laminate databanks for different numbers of plies (from 3 to 40 layers) were created defining stacking sequence associated to each laminate and its lamination parameters. Consequently, any lamination parameters defined in databanks has a corresponding feasible lay-up.

Databanks were constructed varying lamination angles for each layer of the laminate as well as combining databanks in order to define a new one. These concepts result in databanks with approximately 80,000 laminates which describe the feasible regions with a satisfactory accuracy In addition, during optimization process, the laminates from databanks were rotated with respect to the transversal axis with rotations of 7.5º, 22.5º, 37.5º, 52.5º, 67.5º and 82.5º, resulting in databanks with about 450,000 laminates. These rotations were defined because in databanks creation the variation angle between plies is defined as 15º, therefore, rotations of 7.5º with 15º of interval seemed to be a good option for increasing the number of laminates in each databank.

In addition, aiming at defining a practical design, laminates are penalized based on the number of repeated ply angles as well as the influence of coupling terms in the extensional and matrices of the laminate (matrices [A] and [D], respectively). The repeated ply angle penalization weight is defined by a second order function as illustrated in Fig. 2. The penalization grade for repeated ply angles (a repeated angle is defined for a difference between two ply angles small than a tolerance defined as 45º) is multiplied by the square of the number of repeated interfaces in sequence. Then, the result penalization for repeated angles, F_{rep}, is added to the penalization due to coupling terms that is defined as the sum of the absolute values of the lamination parameters associated with the coupling terms for matrices [A] and [D], Eq. (3):

$$P_{en} = \left|\xi_2^A\right| + \left|\xi_4^A\right| + \left|\xi_2^D\right| + \left|\xi_4^D\right| + F_{rep} \tag{3}$$

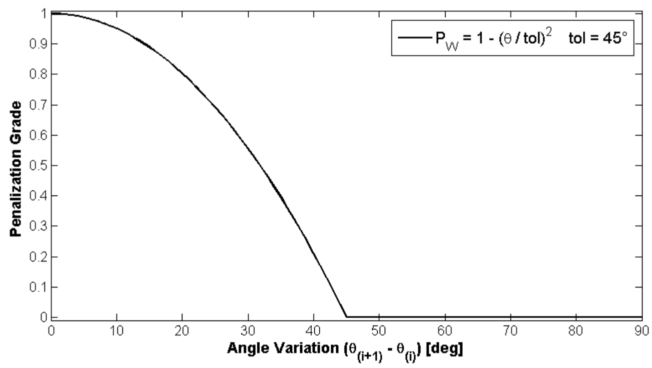

Figure 2. Penalization grade for repeated ply angles.

Therefore, through the laminate penalization, P_{en}, designers are able to evaluate results from optimization process quickly and decide among lay-ups which one is more suitable in terms of design and applicability.

4. CLOSED FORM PREDICTION THEORY

Olsson et al. (2006) proposed a closed form prediction of peak load and delamination onset under small mass impact. 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 stiffness, D^*, Eq. (4), and shear stiffness, S^*, Eq. (5), respectively.

$$D^* \approx \sqrt{\left(\frac{1+\eta}{2}\right) D_{xx} D_{yy}}, \qquad \eta = \frac{\left(D_{xy} + 2D_{ss}\right)}{\sqrt{D_{xx} D_{yy}}} \tag{4}$$

ISSN 2176-5480

$$S^* \approx \sqrt{\kappa_{xzxz}\kappa_{yzyz}A_{xzxz}A_{yzyz}} \tag{5}$$

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. (6), and the threshold delamination force F_{dl}, Eq. (7), for a given impact energy.

$$F_{peak}^{-1} \approx F_b^{-1} + F_c^{-1} + F_s^{-1} \tag{6}$$

$$F_{dl}^{dyn} = 1.213\pi\sqrt{\frac{32}{3}G_{IIc}D^*} \tag{7}$$

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

In Eq. (6) 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. (7) is determined by plate density, ρ, and laminate thickness, T, as well as the effective bending stiffness D^* and impact velocity V_0:

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

The shear force F_s is defined in Eq. (9) and depends on the impactor mass M, effective shear stiffness, S^* and initial impact velocity, V_0:

$$F_s = 2V_0\sqrt{\pi M S^*} \tag{9}$$

The expression of the contact force Fc, Eq. (10) depends on the material properties inserts on contact stiffness K_α defined in Eq. (11):

$$F_c = K_\alpha^{2/5}\left(\tfrac{5}{4}MV_0^2\right)^{3/5} \tag{10}$$

$$K_\alpha = \tfrac{4}{3}Q_\alpha\sqrt{R} \tag{11}$$

Q_α, defined in Eq. (12), is the effective contact modulus and R is the impactor radius:

$$Q_\alpha^{-1} = Q_{zp}^{-1} + Q_{zi}^{-1} \tag{12}$$

Q_{zp} and Q_{zi} are the effective contact modulus of the impactor and plate. Contact modulus Q_{zp} for a material with transverse isotropy along the loading axis z is defined by Eq. (13).

$$\begin{aligned} &Q_{zp} = 2\sqrt{G_{rz}/C_{rr}}\,(C_{rr}C_{zz} - C_{rz}^2)\Big/\sqrt{\left(\sqrt{C_{rr}C_{zz}} + G_{zr}\right)^2 - \left(C_{rz} + G_{zr}\right)^2} \\ &C_{rr} = E_r\left(1-\nu_{rz}\nu_{zr}\right)\Omega/\left(1+\nu_r\right) \qquad C_{rz} = E_r\nu_{zr}\Omega \\ &C_{zz} = E_z\left(1-\nu_r\right)\Omega \qquad \Omega = 1/\left(1-\nu_r - 2\nu_{rz}\nu_{zr}\right) \end{aligned} \tag{13}$$

Isotropic materials are a special case where the Eq. (13) simplifies to $Q_{zi} = E_i\Big/\left(1-\nu_i^2\right)$.

ISSN 2176-5480

5. ALGORITHM

From the 8 lamination parameters (ξ_i, i = 1,2,…,8), that defines each composite laminate in the databanks just four, (ξ_j, j = 1,3,5,7) are used by a Fortran code that was implemented in order to optimize the small mass impact event through the definition of the peak (F_{peak}) and delamination force (F_{dl}). Those lamination parameters are the ones involved in the formulation. The other lamination parameters, simply do not appear in the closed form equations. As design variables, the algorithm has the stacking sequence and the number of layers of the laminate. Moreover, it is worthy to mention that every laminate defined in databanks is symmetric and their lamina have the same material and thickness.

The main idea of the proposed procedure is to predict, based on the previous equations, the margin of safety that in turn is defined by the ratio between the peak impact force F_{peak} and the threshold delamination force F_{dl}. Therefore, the objective function is to maximize the ratio, *R,* Eq. (14):

$$R = F_{dl} \,/\, F_{peak} \tag{14}$$

5.1 Experimental comparison

The algorithm validation was performed comparing the results achieved through the application of the algorithm against a plenty of examples presented by Olsson (2003) and Olsson et al. (2006). Table 1 shows the material properties of impactors and laminates assumed for test cases.

Table 1. Material properties assumed for test cases. From: Olsson (2003).

Material	E_{11} [GPa]	$E_{22} = E_{33}$ [GPa]	$G_{12} = G_{13}$ [GPa]	G_{23} [b] [GPa]	$\nu_{11} = \nu_{13}$	ν_{11}	Density [kg/m³]	h_{ply} [mm]	G_{IIc}
Aluminum	71	71	27	27	0.30	0.30	7850	-	
Steel	206	206	79	79	0.30	0.30	2790	-	
XAS/914C	145	9.5	5.6	3.6	0.31	0.50[a]	1600[a]	0.125	416
T300/5208	132	10.8	5.6	4.4	0.24	0.50[a]	1600[a]	0.127	300
AS4/PEEK¹	137	10.6	5.4	3.5	0.40	0.50[a]	1600[a]	0.135	1959
AS4/PEEK²	137	10.6	5.4	3.5	0.40	0.50[a]	1600[a]	0.135	950
HTA/6376C	137	10.4	5.2	3.5	0.30	0.51	1620	0.130	600

[a] Assumed
[b] $G_{23} = E_{22}/[2(1+\nu_{23})]$

Table 2. Comparison between the predicted and observed threshold velocities

Plate material	Lay-up	T [mm]	F_{peak} [N]	F_{dl} [N]	Impactor material	R_i [mm]	M_i [g]	V_{th} [m/s]	V_{th}* [m/s]	V_{th}** [m/s]	Ref.
XAS/914C	$[0/90]_{2s}$	1.00	554	552	Steel	3.0	0.9	31.86	32.0	33.0	a
XAS/914C	$[0/90]_{8s}$	4.00	4.54	4.525	Steel	3.0	0.9	53.84	54.0	47.0	a
XAS/914C	$[0_2 / \pm 45]_{2s}$	2.00	1.469	1.431	Steel	3.0	0.9	33.18	34.0	30.0	b
T300/5208	$[0 / \pm 45 / 90]_{6s}$	6.10	7.224	7.074	Aluminum	6.4	3	37.29	38.0	38.0	c
AS4/PEEK¹	$[0_3/45_3/90_3/\text{-}45_3]_s$	3.24	6.854	6.829	Aluminum	6.4	1.9	67.76	68.0	46.0	d
AS4/PEEK²	$[0_3/45_3/90_3/\text{-}45_3]_s$	3.24	4.82	4.755	Aluminum	6.4	1.9	48.39	49.0	46.0	d
HTA/6376C	$[(0/\pm 45/90)_s/(0/\mp 45/0)_s]_3$	6.24	10.28	10.54	Aluminum	11	10.2	32.74	32.0	28.0	e

* theoretical values ** experimental values
a Olsson et al. (2006, apud Cantwell, 1988)
b Olsson et al. (2006, apud Cantwell and Morton, 1989)
c Olsson et al. (2006, apud Williams, 1984)
d Olsson et al. (2006, apud Morita et al., 1997)
e Olsson (2003)

ISSN 2176-5480

Laminates from 1.0 mm to 6.24 mm of thickness have been analyzed under small mass impact. The results are illustrated accordingly to experimental and theoretical response. The comparisons are shown in Tab. 2. For the material AS4/PEEK, two different values of G_{IIc} have been given, these values were proposed by Olsson (2003) and Olsson et al. (2006, apud Morita et al., 1997) and are a good example how the critical strain energy release rate in mode II, G_{IIc}, influences in the results of the threshold impact velocity.

As one may notice in Tab. 2, there is a significant difference between the presented values for the material AS4/PEEK. According to Olsson (2003), G_{IIc} is the key property for determining the threshold load, however a consensus about test methods for determining this property is still lacking.

5.2 Application example

As an application example laminates with 8, 16, 24, 32 and 40 layers have been analyzed in order to define not just the optimum design but feasible regions with impact velocities up to 99%, 98%, 95% and 90% of the optimum design threshold velocity. Results are presented in form of velocity curves for each databank. Materials properties used in code running are illustrated in Tab. 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_{ply} [m]
AS4/8552	135	10	4.5	3.33	0.3	0.5	1560	829	1.30×10^{-4}
Impactor	E [GPa]	ν	*Mass* [Kg]	*Radius* [m]					
Steel	210	0.3	2.1×10^{-3}	2.1×10^{-3}					

As a result, velocity curves were created for each databank showing the feasible regions defined by initial impact velocities, according to ξ_1^D and ξ_3^D (or ξ_5 and ξ_7) for different levels of impact velocities. Figures 3 to 7 show the velocity curves for 8, 16, 24, 32 and 40 layers, respectively.

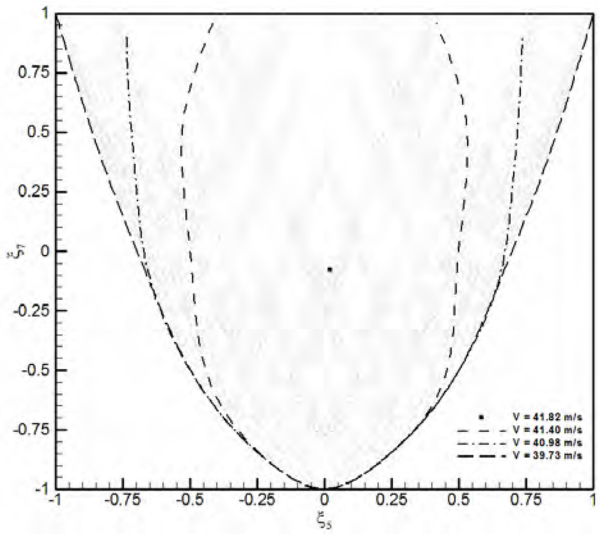

Fig. 3 – Velocity curves for 8 layers databank.

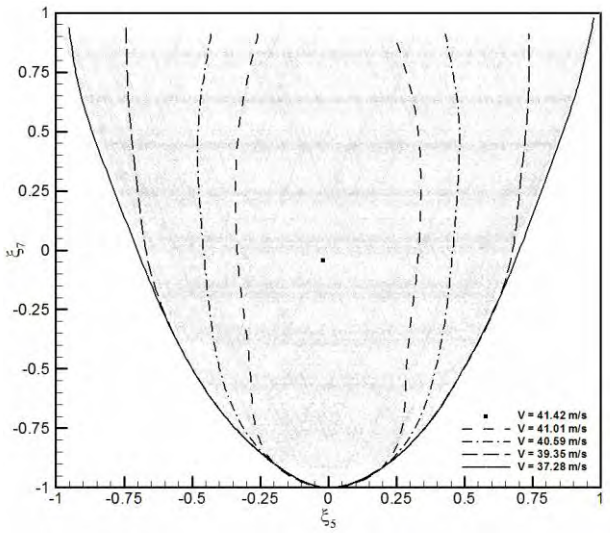

Fig. 4 – Velocity curves for 16 layers databank.

ISSN 2176-5480

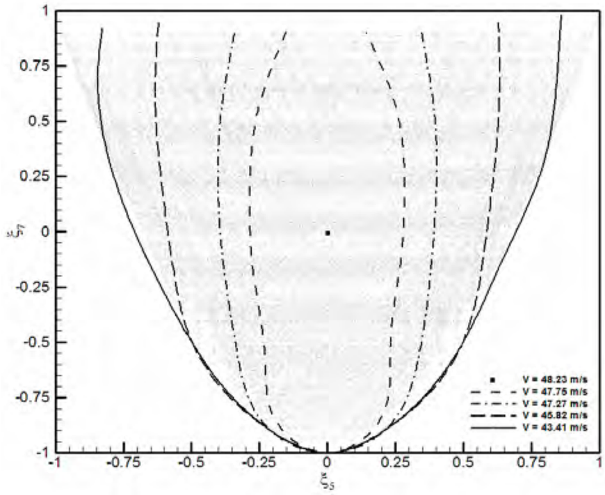

Fig. 5 – Velocity curves for 24 layers databank.

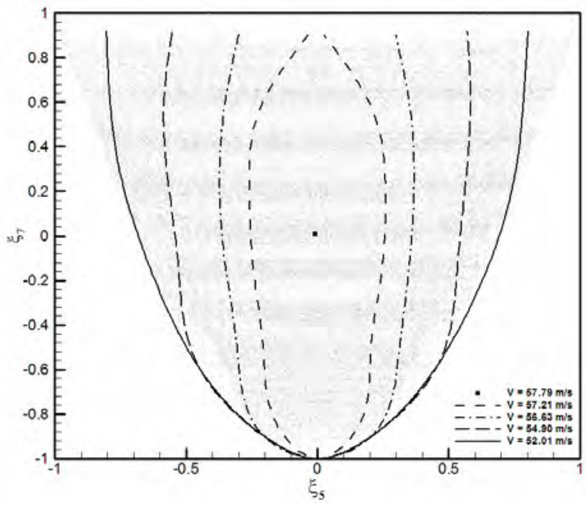

Fig. 6 – Velocity curves for 32 layers databank.

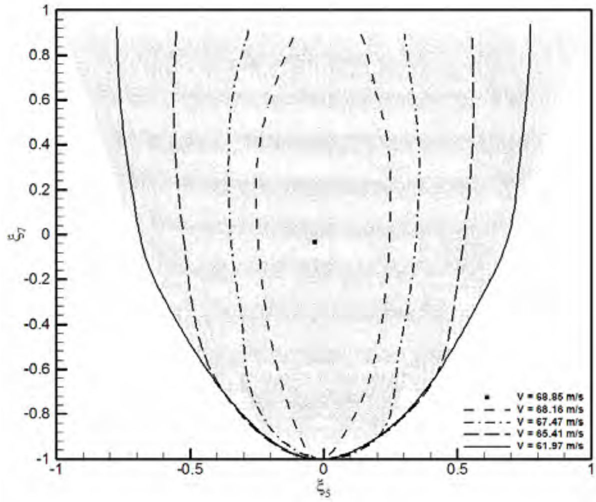

Fig. 7 – Velocity curves for 40 layers databank.

5.3 Results and discussion

Results presented in the current paper, as well as previous results discussed by Bohrer and Almeida (2013), demonstrated to be in good agreement with theoretical end experimental analyses. Validating the algorithm proposed as well as the novel approach applied during analysis.

Looking closely to the 8 layers velocity curves, for instance, Fig. 3, it is possible to verify that every laminate in the databank is capable of resisting to an initial impact velocity equal to 90% of the optimum design. On the other hand, from Figures 5 to 7 (24, 32 and 40 layers databanks, respectively) some laminates are out of the feasible region for impact velocities above 90% of the optimum design, which is represented by the dark marker at the center of each figure. The regions which are out of the feasible designs for initial velocities impact up to 90% of the optimum design are basically defined by unidirectional laminates and variations, such as $[90]_{ns}$ and $[0]_{ns}$ on the upper corner of each figure.

From Figs. 3 to 7 it is clear that the optimum design for each databank has a tendency to be such that the lamination parameters $\xi_5 = \xi_7 \approx 0$. These terms influence directly on the effective bending stiffness D^* which has an important role in the definition of the delamination force F_{dl}, and so on the delineation of the optimal design. In addition, as illustrated and discussed before, Tab. 2, the critical strain energy release rate in mode II, G_{IIc}, demonstrated to have a great impact on the threshold velocity definition.

Further analysis is still lacking concerning the capability of the presented closed form prediction theory to evaluate non quasi-isotropic laminates. Despite the fact that databanks contain in their definition non quasi-isotropic laminates a more specific study should be performed in order to evaluate the reliability of the results for this case.

Despite the fact that the closed form prediction demonstrates a good agreement with theoretical and practical results as shown by Olsson et al. (2006) as well as by Olsson (2007), the proposed examples demonstrate that the lamina orientation affects the results only about 15%. Thus, if a typical safety factor is used the dominant factor on the determination of the optimum design will be the number of layers and the laminate thickness. This discussion is supported, especially, by the results determined when applying lamination parameters as design variables. As a consequence, in practical applications, due to the flatness of the objective function, Eq. (14), the definition of an optimum design is possible but does not defines an unique design, however the procedure proposed may be used as a tool to define the number of layers for a defined composite plate under small mass impact solicitation.

6. CONCLUSIONS

Small mass impacts, such as runway debris, bird strikes and dropped tools are a constant 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 design regions for composite plate and predicted for an initial impact velocity if delamination may damage the structure or not, without the necessity of an extensive time consuming analysis, such as FE.

Nevertheless, since it is an approximate solution, based on closed form equations that involve experimentally determined factors that typically have a large scatter, such as the mode II interlaminar fracture, G_{IIc}, the closed form solution must be used carefully when defining the optimum design or even the threshold impact velocity. On the other hand, besides the capability of predicting initial delamination growth, the procedure proposed by Olsson et al. (2006), demonstrates the ability of defining feasible regions for composite plates structures design.

The application of lamination parameters, instead of lamination angles, does not bring any difference regarding the laminate analysis. But it does contribute to a better understanding of the problem as only two lamination parameters are dominant regardless the number of layers of the laminate. Moreover, databanks demonstrated to be a good manner to cope with the impossibility of defining a physical lay-up from lamination parameters.

7. ACKNOWLEDGEMENTS

The authors would like to thank the support provided by Aeronautics Institute of Technology – ITA and São Paulo Research Foundation – FAPESP. The first author thanks FAPESP by the support through process 2012/18365-2. The second author thanks to the National Council for Scientific and Technological Development, CNPq, by the support thought grant 303799/2010-2.

8. REFERENCES

Ferreira, R.T. et al., 2011. “Structural optimization of a composite plate subjected to a small mass impact”, Journal of Materials Science and Engineering B 1 (2011) 536-550.

Freitas, M. et al., 2000. “Numerical evaluation of failure mechanisms on composite specimens subjected to impact loading”. Composites: Part B 31 (2000) 199–207.

GAO, 2011. “Aviation Safety, Status of FAA’s Actions to Oversee the Safety of Composite Airplanes”. United States Government Accountability Office. Report to Congressional Requesters. 2011.

Ghiasi, H. et al., 2009. “Optimum stacking sequence design of composite materials Part I: Constant stiffness design”. Composite Structures 90 (2009) 1–11.

Gyan, S. et al., 2012. “Damage-tolerant design optimization of laminated composite structures using dispersion of ply angles by genetic algorithm”. Journal of Reinforced Plastics and Composites 2012; 31: 799 – 814.

Olsson, R., 1992. “Impact response of orthotropic composite plates predicted from a one-parameter differential equation”, AIAA Journal 30 (6) (1992) 1587-1595.

Olsson, R., 2000. “Mass criterion for wave controlled impact response of composite plates”. Composites: Part A 31 (2000) 879–887.

Olsson, R., 2003. “Closed form prediction of peak load and delamination onset under small mass impact”, Composite Structures 59 (2003) 341-349.

Olsson, R. et al., 2006. “Delamination threshold load for dynamic impact on plates”. International Journal of Solids and Structures 43 (2006) 3124-3141.

Olsson, R., 2007. “Experimental validation of delamination criterion for small mass impact”. ICCM - 16. International conference on composite materials, Kyoto, Japan, 2007.

Olsson, R., 2010. “Analytical model for delamination growth during small mass impact on plates”. International Journal of Solids and Structures 47 (2010) 2884–2892.

Sørensen, R. and Kann, J., 2011. “Optimisation of Composite Structures Using Lamination Parameters in a Finite Element Application”. Master’s thesis, Department of Mechanical & Manufacturing Engineering, Aalborg University, 117 p., 2011.

ISSN 2176-5480

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.