Evaluation of laminated composites strength with different fibers direction subjected to impact load from the implicit and explicit dynamic analysis

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Abstract. The composite materials are widely used in mechanical engineering applications. Understand their behavior and how will load influence on structural elements is extremely important for technological evolution and innovation. The complexity to evaluate elements of composite materials makes the subject a fertile field for learning and new proposals. Thus, it is proposed to investigate the performance of implicit and explicit dynamic methods in the impact analysis of some composite plates. The modelling of problem consists of applying an impact load in center of the plates, which are represented by bidimensional and linear finite elements with 6 degrees of freedom per node. The influence of fiber orientation and the number of plies of the plates on their ability to resist stresses is verified. The results showed good agreement with literature and some behaviors were highlighted.

Keywords: composite, implicit method, explicit method, laminates

1 Introduction

The automotive, aeronautics and aerospace industries have evolved in technologies that improve the performance of their structures. The composite materials are part of this advance, being important allies in protecting the structural parts as well as the users. The main advantages are that they have high strength and energy absorption capacity associated with their lightness and flexibility when compared to traditional materials. However, one cannot ignore the phenomena of impact in which these structures are subject, which can lead to the compromise of their integrity and stability.

Composite materials are made of two or more materials, having mechanical properties improved when compared to the constituent materials of their composition [1]. They are used with great frequency in several industrial segments providing an excellent cost-benefit in their implementation. The classification of composite materials is conditioned on the composition of the materials that constitute its matrix and reinforcement, where for each type of composite, there is an industrial processing developed.

The impact is characterized by the performance of a load in a short period of operation, in such a way that the distribution of stresses acting on the material is non-uniform [2]. The classification of collision phenomena includes the conservation or not of kinetic energy. Elastic collision is defined by total energy conservation during the impact, while partially elastic or inelastic collisions are defined by energy losses [3]. This last behavior configures the majority of collisions, in which the separation of the bodies is observed and the final relative speed is decreased compared to the initial value [4].

The application of composite materials is observed in impact attenuating devices as demonstrated by Mohhamad [5]. On this occasion, the author explored the concepts of impact in the analysis of steel and composite safety devices on the side door of a vehicle, leading him to conclude that the composite element had better energy absorption. Barbero [6] carried out in his work the buckling process of a simply supported laminate composites and using a computational routine in the Software Ansys APDL, he performed the compression on one side of the laminate. He realized that the addition of layers gives the laminate a greater resistance to the buckling effect.

Others studies were conducted in the evaluation of the impact of laminated composites, such as those of Yehia et al [7]. They analyzed the impact of laminated composite with Aluminum fiber, using the ABAQUS computational package. Impact strength and failure modes for laminates with different fiber orientations were investigated. It was concluded that the addition of layers confers a greater energy absorption, attenuating the speed of impact. Moreover, Yehia et al [8] performed numerical simulations of ballistic impact in laminate composite plate, determining the ballistic limit velocity at the junction of the laminates through the computational package ABAQUS/explicit. There also Malekzadeh & Dehbozorgi [9], who addressed impact analysis using Newmark's implicit integration and First Order Shear Deformation Theory (FSDT) to model deflection in composite plate-nanotubes nanotubes.

The studies cited confirm the numerical solutions for the impact analysis on compositess as a tool of interest in several fields, verifying the large-scale use of the explicit integration method. However, in this study, it is proposed to evaluate the performance of both the explicit and implicit dynamic methods in the impact analysis involving laminated composite, first surrounding guarantees that determine the reliability of the analysis process. Therefore, the preliminary computational analysis is conducted in some variations of laminated composites and their results are compared with the values obtained by classical analytical theory. The behavior of different composite plates and the influence of orientation and the amount of layers on the stability of the structural element are also evaluated.

2 Methodology

It is of fundamental importance to establish the methodological conduct, in order to assure the reader, the reliability about the analysis process. Thus, this study made use of the ANSYS computational package to execute the implicit and explicit integration methods, thus enabling the assessment of the performance of these methodologies when used to evaluate the strength of composite plates subjected to a transverse impact load. According Gavin [10] and Malavolta [11], both procedures use the Central Finite Difference Method to integrate the equation of motion. The basic idea of the integration methods is to solve the dynamic equation of the problem assuming that the vectors of displacement, speed and acceleration vary within discrete intervals of time. It is noteworthy that all analyses were conducted disregarding the dissipative effects.

The use of implicit integration is recommended in the analysis of quasi-static or low-frequency problems. In highly non-linear problems, the convergence of this method is not guaranteed due to its instability, besides requiring a high computational cost for its implementation in more complex structures. Both, explicit and implicit formulation, Lagrangian multipliers are used for time increments. Advantages of the implicit method include a more complete solution due to its simplification-free structuring, as well as converging independently of the time step, Δt, adopted. Problems involving large deformations and contacts zone have a better response when simulated by the explicit dynamic method, where the method seeks to use diagonal mass and damping matrices to give more efficiency to the algorithm. Its convergence depends on the time-step size and the mesh quality [12].

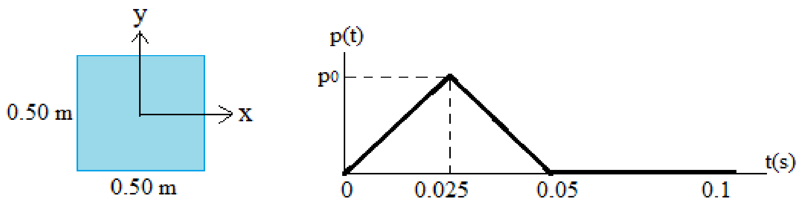
The singular stiffness matrix affects the implicit integration stability. However, this problem is overcome when diagonal mass and damping matrices are used, which result in an effective diagonal stiffness matrix. This configuration decoupled the system of equations, eliminating the need to reverse the effective stiffness matrix at each time-step [13]. The basic formulation of the implicit integration adopted by the ANSYS package is based on Newmark's integration. The equation of motion is defined as a function of α and δ, which control the stability of the method. The analytical formulation of two methods discussed here can be found in the classical works of literature, highlighting Chopra [14], Paz [15] and Clough [16].

In this work, simply supported square plates of laminated composite are evaluated when subjected to a transverse impact load applied in the center of their area. It is verified the influence of the number of layers on each composite plate, and consequently its total thickness on its ability to resist the request. Five configurations were chosen for the study, which were formed by 2, 4, 6, 8 and 10 composite layers of the same thickness and orientation. The results of this analysis are compared with those presented in the literature. Then, 6 plates formed by 10 layers were analyzed by merging the orientation of fibers. The plates that are 5 mm thick were compared with a similar thickness made of isotropic material Aluminum 2024 T851 evaluated under the same conditions, where it is expected to measure the efficiency of the composite laminates.

In the computational analysis, the laminates are modeled by a linear 2D elements, defined by 4 nodes each with 6 degrees of freedom. All laminates presented a discretization with 2500 finite elements, all with size 0.01m and mesh quality index 0.94, whose value gives an excellent conditioning with regard to the minimum presence of imperfections that can affect the efficiency and accuracy of the analysis [13]. The time increments were defined based on classical references of Chopra [14] and Clough [16] literature and limited by the capacity of the equipment. Therefore, all analysis were performed on a machine with Windows 10 Operating System, 64GB, Intel Core i7-7500U processor and 8GB RAM, which resulted in a time increment of 0.003s for implicit analysis and 10^{-12}s for explicit analysis.

3 Modeling of problem

A simply supported square plate of dimension 0.5 m x 0.5 m, as defined in Figure 1a, was evaluated. The total thickness of the laminated composite varies with the number of layers adopted. The plates are subjected to a triangular impact load that acts on its central point with a maximum intensity of 50 N and a load time, t_d, equal to 0.05 s, as shown in figure 1b. This format of load is the most suitable for modeling impact loads [16].



(a) (b)

Figure 1. (a) Cross section of each plate; (b) Impact load

The mechanical properties of each composite layers along the Cartesian x, y and z directions are the same as those adopted by Shen and Sun [17], which defined for the material density the value of 1580 kg/m^3, the longitudinal Young's modulus in the x, y and z directions equal to $E_x = 120\,GPa$, $E_y = E_z = 7.9\,GPa$, respectively, Poisson ratio of 0.3 and shear modulus equal to G = 5.5 GPa.

4 Results and discussions

The results obtained in the Finite Element simulations here were compared with those calculated by the analytical procedure described by equation (1) [14], where $A = \frac{t}{t_d}$, $B = \frac{t}{T_n}$, $S = \frac{T_n}{2\pi t_d}$, and $X = \left(t - \frac{t_d}{2}\right)$. The displacement responses depends on time load (t_d), the most relevant natural frequency of vibration (ω_n) and accordingly the natural period (T_n) and also the magnitude of the impact load (p_0), since the maximum static displacement, $(u_{st})_0$, is p_0/k, and k is the bending stiffness of the plate.

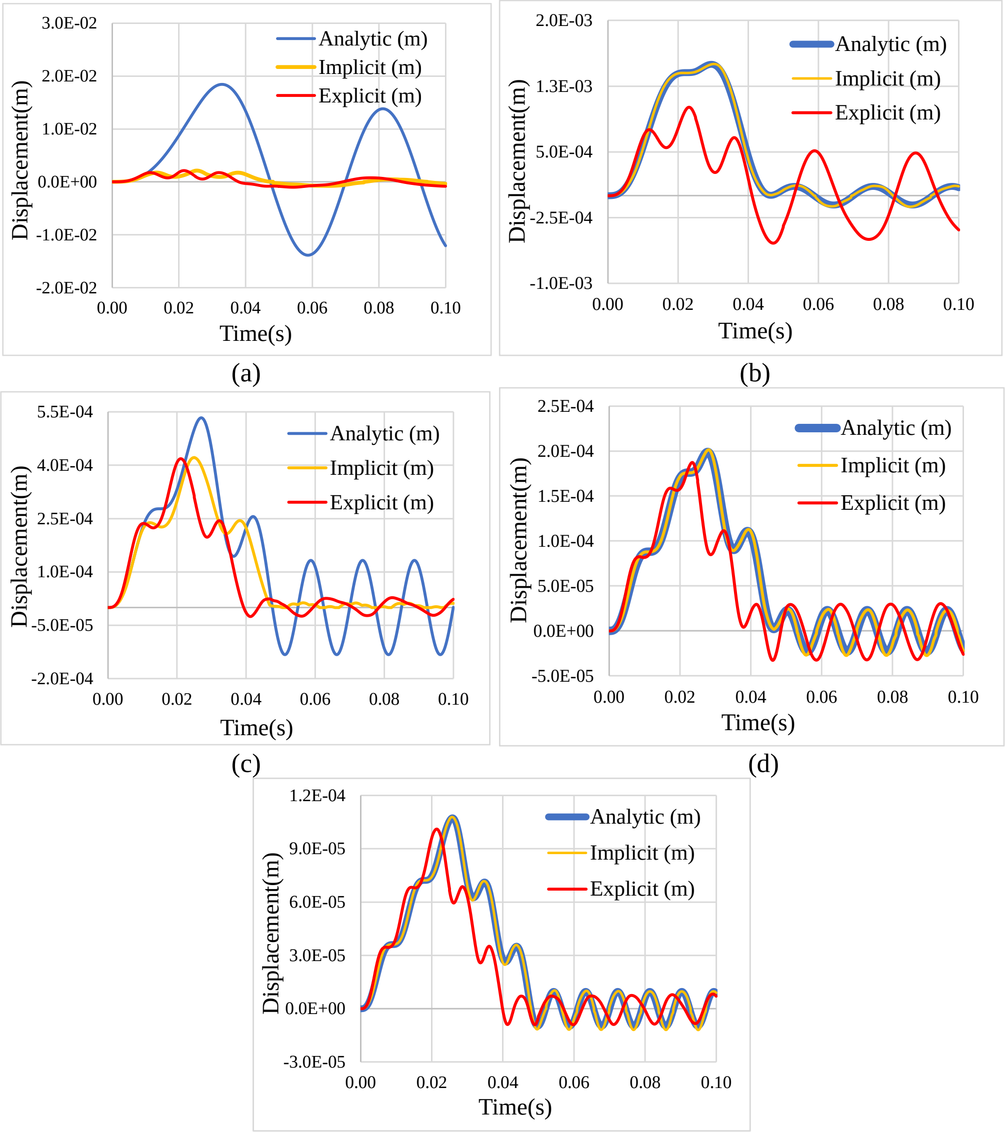
$$u(t) = \begin{cases} -2(u_{st})_0(A - S\sin(2\pi B)), \quad 0 \le t \le \frac{t_d}{2} \\ -2(u_{st})_0\left\{1 - A + S\left[2\sin\left(\frac{2\pi}{T_n}X\right) - \sin(2\pi B)\right]\right\}, \quad \frac{t_d}{2} \le t \le t_d \\ -2(u_{st})_0\left\{S\left[2\sin\left(\frac{2\pi}{T_n}X\right) - \sin\left(\frac{2\pi}{T_n}(t - t_d)\right) - \sin(2\pi B)\right]\right\}, \quad t \ge t_d \end{cases} \tag{1}$$

At first moment, it tried to observe the influence of the number of plies in laminated composites. Each ply has 0.0004 m thickness with fibers oriented at 0° degrees, as described in Table 1. The table mentioned also shows the maximum deflection results at the center of plates.

Table 1. Properties of each laminate and maximum deflections

					Maximum Deflection (10^{-3}m)		
Plate	Number of plies	Thickness of each ply (m)	Total thickness (m)	Total mass (Kg)	Method Analytical	Method Implicit	Method Explicit
I	2	0.0004	0.0008	0.316	18.4620	2.1179	2.1435
II	4	0.0004	0.0016	0.632	1.49806	1.50320	1.00920
III	6	0.0004	0.0024	0.948	0.53345	0.42133	0.41819
IV	8	0.0004	0.0032	1.264	0.19894	0.20140	0.18737
V	10	0.0004	0.0040	1.580	0.10747	0.10782	0.10107

The graphs in Figure 2 show the evolution of displacements at the central point of the plates along the time caused by impact load.



(a) (b) (c) (d) (e)

Figure 2. Evolution of displacements over time in the center of plates: (a) plate I; (b) plate II; (c) plate III; (d) plate IV; (e) plate V

It is observed that there is a greater discrepancy between the results obtained in the plates with a smaller number of plies. Differences can often be attributed to the particularities of Finite Elements available for modeling and even the boundary conditions applied when using as a comparison parameter actual values [13]. However, this justification does not apply to the problem configurated here, since Barbero [6] had already verified a similar behavior to that presented when applied an unidirectional longitudinal load on a plate of laminated composite, verifying that the convergence of results are occurred as there was an increase in the number of plies. Thus, in line with previous studies, the behavior obtained from the analyzes demonstrates that the number of plies and their thickness are convergence criteria in composite elements, where the stability of displacements values is noted when reaching a total thickness of 2.4 mm (plate III).

Also in the analysis of Figure 2, it is possible to observe that in all cases the explicit method achieved results faster than the implicit method. This convergence speed is attributed to the optimized algorithm already discussed previously and supported by literature [13], which sacrifices the accuracy of the method to obtain higher speed. Figure 3 summarizes the convergence analysis between the methodologies as there is an increase in the number of plies and, consequently, in the total thickness of the plates.

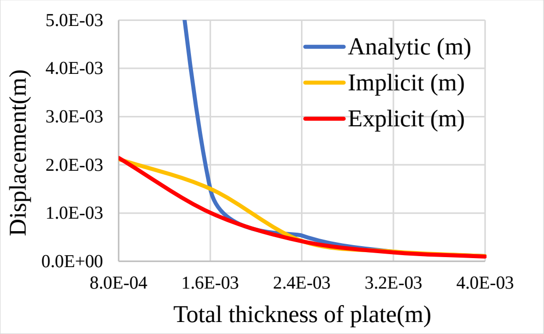


Figure 3. Convergence of methodologies

Due to the behavior observed in the previous analyzes, in which a convergence of the results was observed on plates with minimum thickness equal or greater than 2.4 mm, a new study was carried out on plates with a minimum total thickness of 3 mm. Thus, the thickness of each ply was varied, where the plates named A and B have a final thickness of 3 mm and 4 mm, respectively, and the rest of plates are 5 mm thick. Regarding fibers orientation, plates A, B and C have plies with fiber oriented at 0 degrees, while plates D and E have plies with fibers arrangements defines as [45/0/-45/0/45/0/-45/0/45/0] and [45/-45/0/90/45/-45/0/90/45/-45] degrees, respectively. The descriptions of the plates and the results obtained are shown in Table 2.

The behavior of 5 mm plates is compared with that of the same thickness and isotropic material, more specified the Aluminum 2024 T851, widely used in the aircraft industry due to its low weight and good mechanical strength. This material has density of 2780 kg/m^3, Young´s modulus equal to 72.4 GPa and Poisson ratio of 0.33.

Table 2. Properties of each laminate and maximum deflections in second analysis

					Maximum Deflection (10^{-3}m)		
Plate	N° of plies	Thickness of each ply (m)	Total thickness (m)	Total mass (Kg)	Method Analytic	Method Implicit	Method Explicit
A	10	0.0003	0.003	1.185	0.231430	0.216970	0.209680
B	10	0.0004	0.004	1.580	0.107470	0.107820	0.101070
C	10	0.0005	0.005	1.975	0.054983	0.054804	0.053238
D	10	0.0005	0.005	1.975	0.053622	0.053263	0.052044
E	10	0.0005	0.005	1.975	0.048014	0.047629	0.046738
AL	1	0.0050	0.005	3.475	0.065936	0.066013	0.063806

As observed in Table 2, the results obtained by the three methods present a good agreement with each other. The behavior of the plates can be seen in Figure 4. It is worth mentioning that Figure 4 points to a faster convergence of the explicit method, confirming what the literature already justifies for this method.

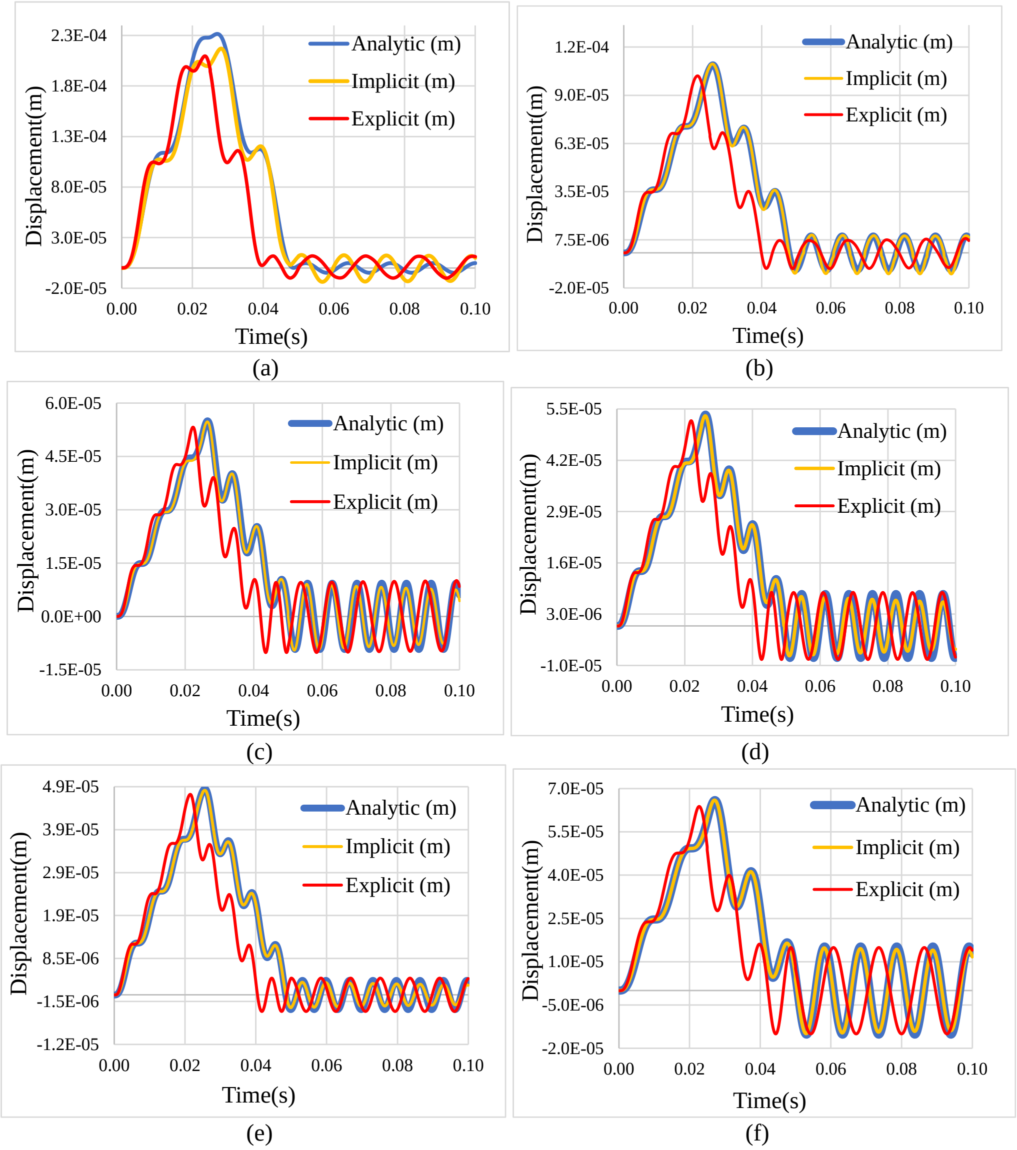


Figure 4. Evolution of displacements over time in the center of plates: (a) plate A; (b) plate B; (c) plate C; (d) plate D; (e) plate E; (f) plate AL

Little variation in computational results was observed compared to the analytical results, showing in fact that the adoption of a minimum thickness for the laminates influences the convergence of the methods, and, therefore, that the analysis was successfully conducted.

A comparative analysis between plates C, D, E and AL of the same geometry and impact load was performed. As shown in Table 2, plates C, D and E were more resistant. The plate E, which showed better performance, is 43% lighter than the AL plate and presented a displecement 26.7% lower, demonstrating the influence of fibers orientation on its load-bearing capacity.

5 Conclusions

Composite materials are great important in several engineering segments and are widely used. Understand their behavior and the ability to work with the different factors that influence their structural dynamics will always be a field of curiosity and improvement in order to achieve more daring and more efficient applications. The results of this work open up relevant opportunities in the deepening about the theme, and it is possible here to list those that materialized in a clear and satisfactory way.

The validation of the numerical procedures was naturally observed when the convergent results of the numerical simulations were in agreement with those obtained analytically through formulations of dynamic responses for short duration loads. Convergence of the deflection results in composite plates occurred as there was an increase in the number of plies, and consequently, an increase in the total thickness of the plates. The number of plies and theirs thickness were, therefore, convergence criteria in composite elements, and the stability of the displacement values was noted when a minimum total thickness of 2.4 mm was reached.

With regard to the performance of the integration methods, the explicit converged faster than the implicit one, since the latter has a more complex formulation requiring a higher computational cost.

Taking attention only to the stable composite models, a good agreement was observed with the results obtained by the three calculation methodologies. When in the comparative analysis between plates C, D, E and AL, it was possible to observe that merging the orientation of the fibers gives the composite a better structural performance, reinforcing the importance of these materials due to their high strength and low weight. In this case, composite plate E weighing about 43% less than the AL plate supported the impact with a deflection almost 29% lower than that of the Aluminum plate.

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Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors.

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