Coupled Systems Mechanics, *Vol. 11, No. 4 (2022) 285-295*
https://doi.org/10.12989/csm.2022.11.4.285

Optimization of safety factor by adaptive simulated annealing of composite laminate at low-velocity impact

Lamsadfa Sidamar*[1], Zirmi Said[2a] and Mamouri Said[2b]

[1]Laboratory of Materials and Energy, University of Tamanghasset, Tamanghasset, Algeria
[2]Laboratory of Mechanics Modelisation and Experiments, University of Béchar, Béchar, Algeria

(Received September 25, 2021, Revised December 12, 2021, Accepted February 2, 2022)

Abstract. Laminated composite plates are utilized extensively in different fields of construction and industry thanks to their advantages such as high stiffness-to-weight ratio. Additionally, they are characterized by their directional properties that permit the designer to optimize their stiffness for specific applications. This paper presents a numerical analysis and optimization study of plates made of composite subjected to low velocity impact. The main aim is to identify the optimum fiber orientations of the composite plates that resist low velocity impact load. First, a three-dimensional finite element model is built using LS DYNA computer software package to perform the impact analyses. The composite plate has been modeled using solid elements. The failure criteria of Tsai-Wu's criterion have been used to control the strength of the composite material. A good agreement has been found between the predicted numerical results and experimental results in the literature which validate the finite element model. Then, an Adaptive Simulated Annealing (ASA) has been used to optimize the response of impacted composite laminate where its objective is to maximize the safety factor by varying the ply angles. The results show that the ASA is robust in the sense that it is capable of predicting the best optimal designs.

Keywords: adaptive simulated annealing, composite, delamination, failure, finite elements, impact, Mat020, Safety Factor: Mat054/55, Tsai-Wu

1. Introduction

Laminated composite materials occupy an increasing space in modern industries thanks to their good mechanical behavior, while other materials are prone to rupture, particularly the phenomenon of high stress concentration between layers i.e., delamination phenomenon. For instance, the fall of a hammer during maintenance which causes a visible impact damage. This phenomenon poses catastrophic risks to aircraft safety processes. Crash safety is very important to civil aviation industry, specifically with regard to the increasing ratio of carbon fiber reinforced plastic (CFRP) in aircraft primary structures.

In the literature, many analytical solutions as well as experimental work were carried out to

*Corresponding author, Ph.D. Student, E-mail: ammarlamsadfa@cu-tamanrasset.dz
[a]Ph.D., E-mail: zirmisaid@yahoo.fr
[b]Ph.D., E-mail: Said.mamouri@gmail.com

http://www.techno-press.org/?journal=csm&subpage=8 ISSN: 2234-2184 (Print), 2234-2192 (Online)

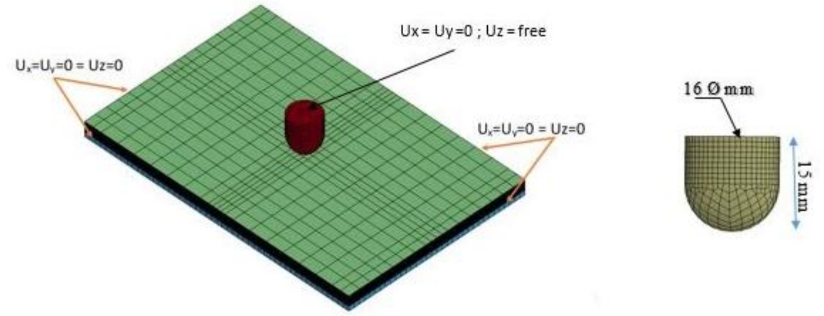


Fig. 1 FE model and boundary conditions of drilled laminate plate and impactor

analyze the behavior of different types of composite structures exposed to different types of loading (Belakhdar and Tounsi 2017, Daouadji 2017, Polatov *et al*. 2020, Abderezak *et al*. 2021). While analysis of composite structures under impact loads we can find (Zhao *et al* 2018, Santoro and Kripka 2020, Cheng *et al*. 2014, Liu *et al*. 2018, Panigrahi *et al*. 2016, Akbulut *et al.* 2011, 2020, Maamar and Zenasni 2018). Some of these pieces of research work aimed evaluating different material models such as crack models and damage models to analyze impact of composite plates (Ilyas 2010, Rizov 2017, Liu *et al.* 2018, Lavrenčiča and Brank 2018, Ghosh and Chakravorty 2018, Shyamala1*et al*. 2018, Clegg *et al*. 2019). Other pieces of research work aimed at optimizing such structures by reducing the thickness or fibers orientation in order to reduce the weight of the composite plates or to maximize their resistance (Akbulut *et al*. 2011, Maamar and Zenasni. 2018).

The aim of this work is to present a methodology dedicated to modeling and optimization of laminated plates made of composite material (carbon/epoxy T800s/M21) under an impact type loading at low velocity and high mass using finite element (FE) method. The FE model is built using LS-DYNA software and optimization analysis is carried out using LS-OPT software. The optimization procedure aimed at maximizing the safety factor based on the principle of the annealing simulate algorithm to find the best lay-up sequence that supports the maximum possible impact load.

2. Materials and methods

2.1 Model description

The experimental work done by Ilyas (2010) has been used in our study to validate our numerical model. A Graphite/epoxy T800S/M21 of epoxy matrix reinforced by carbon fibers laminate plate has the dimensions of 125×75 mm² as shown in Fig. 1. This plate is composed of 18 plies of thickness equals to h=0.45 mm each of stacking sequence [−45, 45, 0, 90, 0, 0, −45, 45, 0]s. We used an impactor (Hemispherical) with a mass of around 2368 g, the impactor (ball) with impact velocity (4.17 m/s). Shape and geometrical properties are shown in Fig. 1. The specimen is supported by a steel support plate with dimensions of 300×200 mm^2 and a thickness of 20 mm, which is bolted to a rigid frame. Tables 1 and 2 present the mechanical properties of the laminate, the impactor, and support. The plate is impacted in its center by the impactor. The latter is made of

Table 1 Material properties data for T800S/M21 simulation (Lachaud *et al.* 2015)

GPa				GPa				
E_{11}	E_{22}	E_{33}	G_{12}	G_{13}	G_{23}	v_{12}	v_{13}	v_{23}
165	7.64	7.64	5.61	5.61	2,75	0,35	0,35	0,4
GPa		GPa		GPa			Kg/m^3	
X_t	Y_t	X_c	Y_c	S		α	ρ	
2.2	0.045	1.2	0.28	0.05		0	1560	

Table 2 Material model data for impactor simulation (Lachaud *et al.* 2015)

E (GPa)	v	ρ (Kg/m^3)	Diameter (mm)	Masse (Kg)
207	0.31	7850	16	2.369

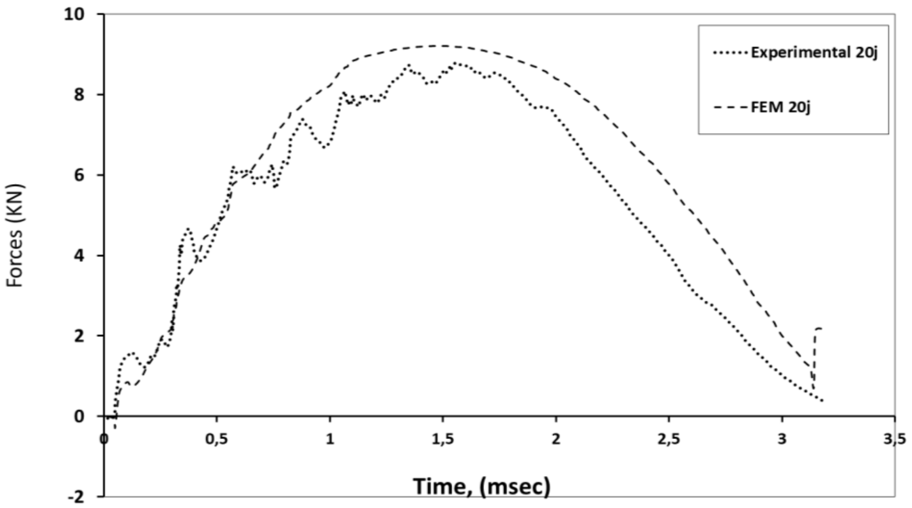


Fig. 2 Finite element Vs. experimental force history response

stainless steel. We consider that the laminate sides are initially clamped. (See Fig. 2 and Fig. 3) which represent the predicted results against the experimental test. A good agreement is found which validate the FE model.

2.2 Finite element modelling

A finite element mode is built using LS-DYNA to simulate the behavior of the composite plate under low velocity impact. The plate is modeled using 3d solid elements. The strength of the fiber-matrix composite is controlled by Tsai-Hill's law. Among the incorporated constitutive material models of lamina available in LS-DYNA (Borazjani *et al.* 2017), the "Mat Composite Failure Optional" Model (MAT054 with Solid option) (Akbulut *et al.* 2011, Yong *et al.* 2008), is adopted since it has the ability to simulate the progressive damage of the material on the basis of 3D stress-based failure criterion. The adopted MAT054 model that has been used in solid formulation is widely used and discussed in several applications and articles in the literature. The rigid body model (Mat 20 Option=Solid) is used for hemispherical head impactor as well as the supports

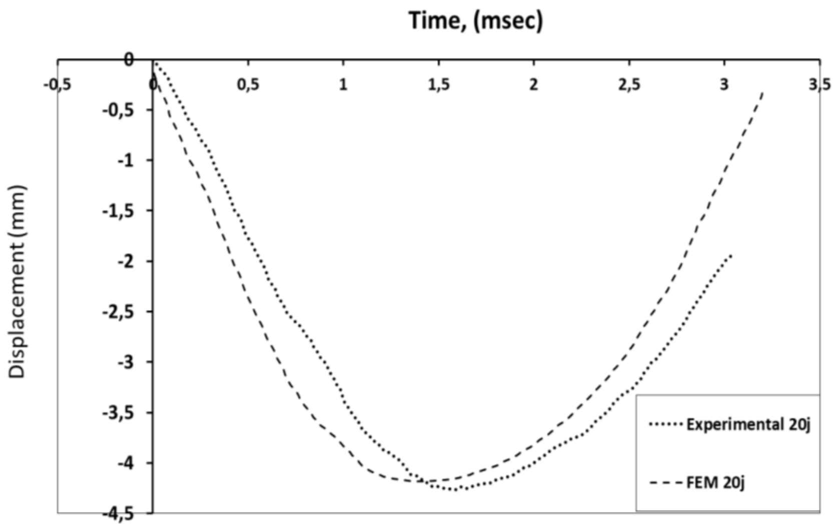


Fig. 3 Finite element Vs. experimental displacement history response shift to fit the curves

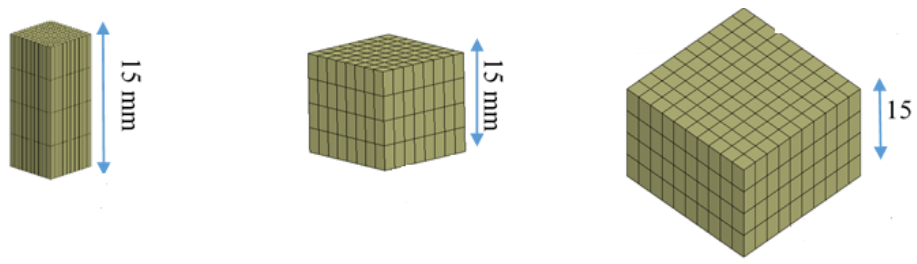
(Maamar and Zenasni 2018, Mou *et al*. 2016). Solid elements were used since they are successfully used to model thick parts because they can capture full 3D stress states (Yong *et al.* 2008). The FE element had eight nodes and one integration point through the layer thickness. Each node has three degrees of freedom. The "Automatic Surface to Surface" type of contact has been used to model the contact between the plate and the impactor while "Contact Automatic Surface to Surface Tiebreak" type of contact has been used between the plate layers (Liu *et al.* 2018). It should be noted that the total number of solid elements were 2402, while the number of nodes were about 39241 and the end time simulation is 3.5 milli seconds.

In order to study the optimization behavior of the composite laminate plate subjected to low-velocity impact, Adaptive Simulated Annealing (ASA) algorithm is adopted, where the objective function is to maximize the safety factor by varying the angles of fibers.

3. Results and discussion

3.1 Effect of contact surface:

In this section, the effect of the contact surface of the impactor on behavior of the composite plate, is studied. Fig. 4 represents three impactors having contact surface of (7×7) mm², (14×14) mm² and (28×28) mm². The reaction force and displacement in terms of time are shown on (Fig. 5 and Fig. 6), respectively. It is observed that the bigger surface is, the lower reaction force is. Additionally, the displacement time history reveals that the highest displacement occur in case of large impactor surface. It is also noted that the time of impact increases when increasing the impactor surface. This is due to the fact that when the force is transferred from the impactor to the plate through a small surface, it results in higher stress concentration within smaller area compared to large surface impactor. Therefore, smaller surface impactor highly affects a limited zone compared to large surface impactor.



a: Impactor with square surface of (7x7)mm²   b: Impactor with square surface of (14x14)mm²   c: Impactor with square surface of (28x28)mm²

Fig. 4 Impactors with different contact surface

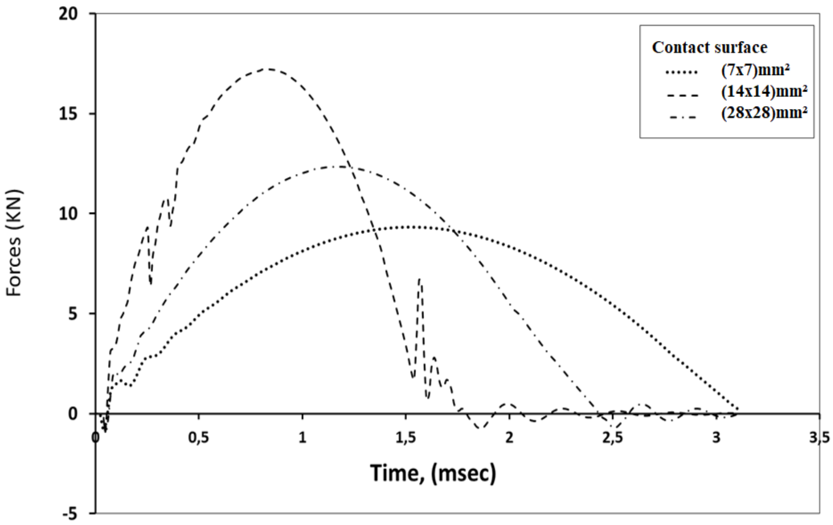


Fig. 5 Effect of the contact surface on the reaction force

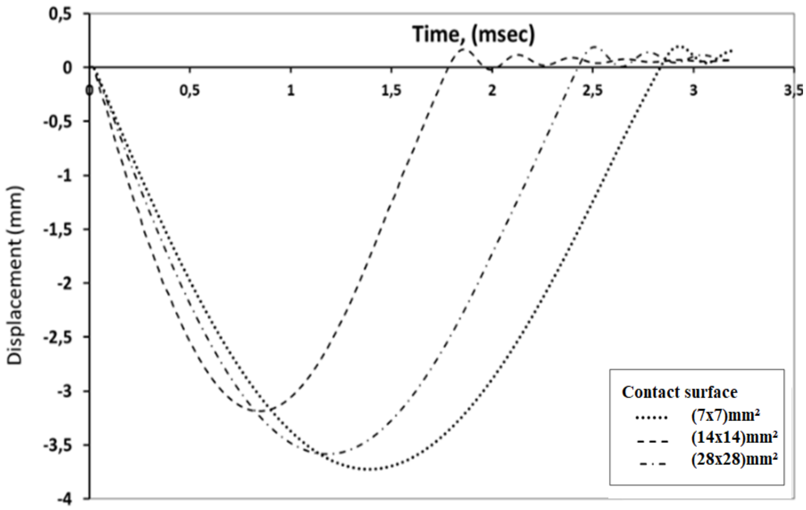


Fig. 6 Effect of the contact surface on displacement

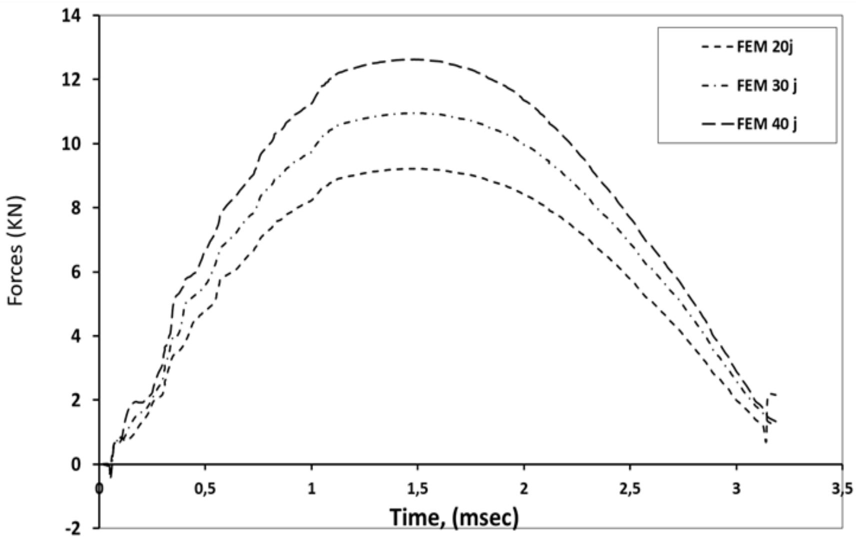


Fig. 7 Effect of the impact energy on the reaction force

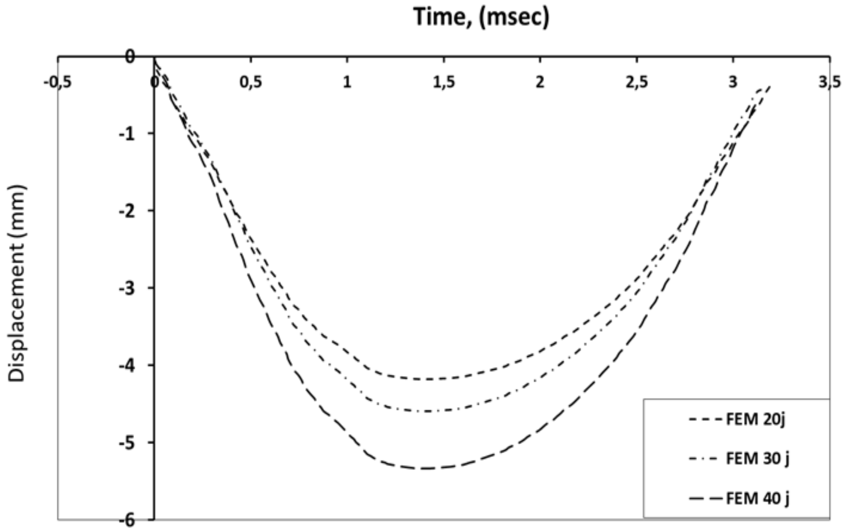


Fig. 8 Effect of the impact energy on displacement

3.2 Effect of impact energy

The energy effect is studied in this section through increasing the impactor velocity. (Fig. 7 and Fig. 8) show the force-time and displacement-time, respectively, for energy equals to 20J, 30J, and 40J. From these curves, it is clear that the more the energy is, the more the effort and the maximum displacement are. As the load increases, it is observed that the evolution of the effort has been quite disturbed (presence of oscillations). These oscillations are often attributed to the degradation of the plate under the impactor and the vibration of the plate upon impact (Maamar and Zenasni 2018).

3.3 Failure criteria of the composite plate

Minimization of weight of composite structures directly affects its strength, since when decreasing the number of plies to gain weight, the carrying capacity of the structure is decreased and may cause failure (Akbulut and Sonmez 2011). In the present work, the adopted failure criterion is "Tsai-Wu". This criterion, is one of the most reliable and widely used criterion to control the composite failure presented in a simple expression as follows (Maamar and Zenasni 2018, Almeida *et al.* 2017)

$$\frac{\sigma_{11}^2}{X_t|X_c|}+\frac{\sigma_{22}^2}{Y_t|Y_c|}-\frac{\tau_{12}^2}{S^2}\frac{\sigma_{11}\sigma_{12}}{\sqrt{X_tX_cY_t}}-\left(\frac{1}{X_t}+\frac{1}{|X_c|}\right)\sigma_{11+}\left(\frac{1}{Y}+\frac{1}{|Y_c|}\right)\sigma_{22}<1 \tag{1}$$

Based on Tsai-Wu criterion, the safety factor (SF) of kth layer, SF^k, is the multiplier of the stress components of the layer k, $б_{ij}^k$, that satisfies Eq. (1) to be equal to 1.0. Eq. (1) can be written as follows (Akbulut and Sonmez 2011, Maamar and Zenasni 2018)

$$a(SF^K)^2+b(SF^K)-1=0 \tag{2}$$

Where

$$a=\frac{\sigma_{11}^2}{X_t|X_c|}+\frac{\sigma_{22}^2}{Y_t|Y_c|}-\frac{\tau_{12}^2}{S^2}\frac{\sigma_{11}\sigma_{12}}{\sqrt{X_tX_cY_t}} \tag{3}$$

$$b=\left(\frac{1}{X_t}+\frac{1}{|X_c|}\right)\sigma_{11+}\left(\frac{1}{Y}+\frac{1}{|Y_c|}\right)\sigma_{22} \tag{4}$$

After solving Eq. (2) to obtain the safety factor, it is noted that the actual safety factor is always positive. So, the absolute value of the first root is the actual one since the negative value is physically meaningful (Akbulut and Sonmez 2011, Maamar and Zenasni 2018).

$$SF^k=\left|\frac{-b+\sqrt{b^2+4a}}{2a}\right| \tag{5}$$

3.4 The objective function

Generally, the objective function is formulated depending on the type of the optimization problem and its objectives. In this work, the SF factor derived previously is used as an objective function (extracted from Eq. (1)). The optimization aims at finding the optimum laminates orientation that supports the maximum impact resistance. That is to say maximizing the safety factor for each sample, while maintaining the same impact energy, 20 J.

The optimization function is set as follows

$$SF=\mathrm{Max}\left\{\mathrm{Min}\left(SF^k\right)_{Sample}\right\} \tag{6}$$

3.5 Optimization results and evaluation

Simulated Annealing (SA) Algorithm has been used in this study to carry out the optimization analysis. This algorithm is based on the physical process of annealing metals, where the material is initially heated then cooled slowly. Such process reduces defects. The procedure of this algorithm starts by generating randomly initial point with high temperature (Akçair *et al.* 2019, Alcantar *et* *al.* 2017). The annealing process decreases the temperature slowly the thing that helps to reduce the extent of the search to converge to a minimum. All new points having lower objective value are accepted in addition to the points with a higher objective value but with a certain probability. The substance can take some time at constant temperature. By specifying the number of iterations, each iteration has two steps: first, the solution is perturbed, then the quality of the solution is evaluated. After that, the new solution is evaluated to be accepted or rejected (Maamar and Ramdane 2016, Karakaya and Soykasap 2011). In the current study, the optimization aims at finding the best laminates orientations (lay-up sequence) that offer the best safety factor i.e., the maximum SF under constant impact energy. At this step, the angles have only three values ±[0,45,90]. After finding the optimum plate (best lay-up sequence), we evaluate the maximum impact energy that can be supported by the optimized plate. The second stage of optimization is started in order to find the maximum safety factor when including additional angles variation ±[0,5,10,20,25,30,35,40,45,50,55,60,65,70,75,80,85,90].

A graphite/epoxy laminate plate is considered with dimensions of 125×75 mm² as shown in Fig. 1, composed of 18 plies of thickness h=0.45 mm each of stacking sequence [−45, 45, 0, 90, 0, 0, -45, 45, 0]s is placed on a 125×75 mm² and support plate having 20 mm thickness made of steel bolted to a rigid frame. The Ls-Opt computer program is used to carry out the optimization calculation by linking it to LS-DYNA. The selected parameters for the optimization are listed in Table 3.

According to Table 4 which represents the optimization analysis, it should be noted that the safety factor for the laminates of the experimental study (laminates with the Actual sequence) is equal to 1.3800. This value is found to be still far from failure. After the optimization calculation, it is possible to increase this value up to 1.7157. Noting that the corresponding optimized lay-up sequence is [00, -45, -45, 00, -45, -45, 00, -45, -45]s . It should be noted also that, the optimization results are obtained after generating 23 samples. However, the optimum lay-up sequence is detected by the algorithm in four generations.

As a second stage of optimization where the optimum lay-sequence plate given in Table 4 has been tested under increasing impact energy so that it reaches SF=1. It is found that the maximum impact energy supported by this plate is 48.76 Joul (Energy Critical). Then, the same procedure of optimization described earlier is applied for this plate but with including new values of angle orientation ±[0,5,10,20,25,30,35,40,45,50,55,60,65,70,75,80,85,90] .The optimization also aims at seeking for the best lay-up sequence that maximizes the security factor. The results are shown on

Table 3 For optimization methods options

T_{min}/T_{max} (Ratio)	1e-6
Annealing Scale	1000
Cost-Parameter Anneal Ratio	1.0
Maximum Function Evaluations 10000	10000
Function Evaluations/Temp step	1

Table 4 Predicted optimized safety factor

One global optimum	Energy [J]	type	SF
[−45, 45, 00, 90, 00, 00, -45, 45, 00]s	20	Actual	1.3800
[00,-45, -45,00,-45, -45, 00,-45, -45]s	20	Optimum	1.7157

Table 5 2nd stage predicted optimized safety factor

Lay-up sequence	Energy in Joul	Type	***SF***
[00,-45, -45,00,-45, -45, 00,-45, -45]s	48.76	Actual	0.9964
[-45,-10, -25,-45,-25, -25, -45,-10, -25]s	48.76	2nd Optimum	1.2400

Table 5. It is found that the best lay-up sequence is [-45, -10, -25, -45, -25, -25, -45, -10, -25]s with security factor SF=1.24 . Here, it should be noted also that, the optimization results are obtained after generating 40 samples. However, the optimum layup sequence is detected by the algorithm in the 11^{th} the generation.

4. Conclusions

In this piece of research work, a numerical analysis and optimization study of composite plate subjected to low velocity impact are presented. The numerical impact analysis is performed by building 3D FE model using the computer program LS DYNA. “Tsai-Wu’s” failure criterion is used to control the strength of the composite laminates. It should be noted that the built finite element model is validated with experimental work from the literature where a good agreement is found. The optimization analysis is carried out to identify the optimum fiber orientations of the composite plates resisting low velocity impact load. The Adaptive Simulated Annealing (ASA) algorithm is adopted to control the optimization procedure. It should be mentioned that the objective function is set to maximize the safety factor by varying the ply angles. As a first step of the optimization procedure presented in this work, the angles are chosen as four desecrate variables $\theta=\pm[0,45,90]$. It is found that the optimum safety factor SF=1.7157 corresponding to sequence lay-up=[00, -45, -45, 00,-45, -45, 00,-45, -45]s. Noting that, the original plate has safety factor SF=1.3800 with sequence lay-up=[−45, 45, 00, 90, 00, 00, -45, 45, 00]s. As a conclusion, the safety factor is optimized to about 124% (increased by 24%). After obtaining the optimum safety factor of the first step, the optimized plate is impacted by increasing energy load up to obtaining the critical energy that leads results safety factor SF≅1. It is found that the maximum energy that the plate resists is 48.76 Joule, while the original impact energy equals 20 Joule. The second step of optimization is the same as the first one but it is done by using the lastly obtained critical energy with including other values of ply angles $\theta=\pm[0,5,10,20,25,30,35,40,45,50,55,60,65,70,75,80,85,90]$. In this step, the safety factor is increased to SF=1.24 with play-up sequence=[-45,-10,-25,-45,-25,-25,-45,-10,-25]s. Thus, the second step of optimization gives a better lay-up sequence that increases the plate resistance to impact loading to about 25% under higher impact energy (Twice higher) than the original one. As a final conclusion, the presented optimization procedure is a simple and fast procedure to find the best play angles that offer the best impact resistance.

Acknowledgement

We would like to thank the Laboratory of Materials and Energy at the University of Tamanghasset, and the Laboratory of Mechanics Modelisation and Experiments at the University of Béchar, for their support and continuous helpful guidance whenever needed.

References

Abderezak, R., Tahar, H.D., Rabia, B. and Tounsi, A. (2021), "Mechanical behavior of RC cantilever beams strengthened with FRP laminate plate", *Couple. Syst. Mech.*, **6**(3), 169-190. https://doi.org/10.12989/csm.2021.6.3.169.

Akbulut, M. and Sonmez, F.O. (2011), "Design optimization of laminated composites using a new variant of simulated annealing", *Comput. Struct.*, **89**(17-18), 1712-1724. https://doi.org/10.1016/j.compstruc.2011.04.007.

Akbulut, M., Sarac, A. and Ertas, A.H. (2020), "An investigation of non-linear optimization methods on composite structures under vibration and buckling loads", *Adv. Comput. Des.*, **5**(3), 209-231. https://doi.org/10.12989/acd.2020.5.3.209.

Akçair, M., Savran, M., Aydın, L., Ayakdaş, O., Öztürk, S. and Küçükdoğan, N. (2019), "Optimum design of anti-buckling behavior of graphite/epoxy laminated composites by differential evolution and simulated annealing method", *Res. Eng. Struct. Mater.*, **5**(2), 175-188. https://doi.org/10.17515/resm2019.66is0909.

Alcantar, V., Ledesma, S., Aceves, S.M., Ledesma, E. and Saldana, A. (2017), "Optimization of type III pressure vessels using genetic algorithm and simulated annealing", *Int. J. Hydrogen Energy*, **42**(31), 20125-20132. https://doi.org/10.1016/j.ijhydene.2017.06.146.

Almeida Jr, J.H.S., Ribeiro, M.L., Tita, V. and Amico, S.C. (2017), "Stacking sequence optimization in composite tubes under internal pressure based on genetic algorithm accounting for progressive damage", *Compos. Struct.*, **178**, 20-26. https://doi.org/10.1016/j.compstruct.2017.07.054.

Belakhdar, K. and Tounsi, A. (2017), "Finite element analysis of initially damaged beams repaired with FRP plates", *Compos. Struct.*, **134**, 429-439. https://doi.org/10.1016/j.compstruct.2015.07.124.

Borazjani, S. and Belingardi, G. (2017), "Lightweight design: Detailed comparison of roof panel solutions at crash and stiffness analyses", *Int. J. Crashworthin.*, **22**(1), 49-62. https://doi.org/10.1080/13588265.2016.1215589.

Cheng, X., Zhao, W., Liu, S., Xu, Y. and Bao, J. (2014), "Damage of scarf-repaired composite laminates subjected to low-velocity impacts", *Steel Compos. Struct.*, **17**(2), 199-213. https://doi.org/10.12989/scs.2014.17.2.199.

Clegg, H.M., Dell, G. and Partridge, I.K. (2019), "Creating damage tolerant intersections in composite structures using tufting and 3D woven connectors", *Adv. Aircraft Apacecraft Sci.*, **6**(2), 145. https://doi.org/10.12989/aas.2019.6.2.145.

Daouadji, T.H. (2017), "Analytical and numerical modeling of interfacial stresses in beams bonded with a thin plate", *Adv. Comput. Des.*, **2**(1), 57-69. https://doi.org/10.12989/acd.2017.2.1.057.

Ghosh, A. and Chakravorty, D. (2018), "Nonlinear first ply failure analysis of composite skewed hypar shells using FEM", *Struct. Eng. Mech.*, **68**(1), 81-94. https://doi.org/10.12989/sem.2018.68.1.081.

Ilyas, M. (2010), "Damage modeling of carbon epoxy laminated composites submitted to impact loading", Doctoral Dissertation.

Karakaya, Ş. and Soykasap, Ö. (2011), "Natural frequency and buckling optimization of laminated hybrid composite plates using genetic algorithm and simulated annealing", *Struct. Multidisc. Optim.*, **43**(1), 61-72. https://doi.org/10.1007/s00158-010-0538-2.

Lachaud, F., Espinosa, C., Michel, L., Rahme, P. and Piquet, R. (2015), "Modelling strategies for predicting the residual strength of impacted composite aircraft fuselages", *Appl. Compos. Mater.*, **22**(6), 599-621. https://doi.org/10.1007/s10443-014-9427-y.

Lavrenčiča, M. and Brank, B. (2018), "Failure analysis of ribbed cross-laminated timber plates", *Couple. Syst. Mech.*, **7**(1), 79-93. https://doi.org/10.12989/csm.2018.7.1.079.

Liu, H., Falzon, B.G. and Tan, W. (2018), "Experimental and numerical studies on the impact response of damage-tolerant hybrid unidirectional/woven carbon-fibre reinforced composite laminates", *Compos. Part B: Eng.*, **136**, 101-118. https://doi.org/10.1016/j.compositesb.2017.10.016.

Maamar, D.B. and Ramdane, Z. (2016), "Characterization of the mechanical behaviour of carbon fiber composite laminate under low velocity impact", *Periodica Polytechnica Mech. Eng.*, **60**(3), 142-151.

https://doi.org/10.3311/PPme.8633.
Maamar, D.B. and Zenasni, R. (2018), “Optimization of safety factor by genetic algorithm of circular notched carbon/epoxy laminate at low velocity impact”, *Periodica Polytechnica Mech. Eng.*, **62**(3), 218-225. https://doi.org/10.3311/PPme.12041.
Mou, H.L., Zou, T.C., Feng, Z.Y. and Xie, J.I.A.N.G. (2016), “Crashworthiness analysis and evaluation of fuselage section with sub-floor composite sinusoidal specimens”, *Lat. Am. J. Solid. Struct.*, **13**(6), 1186-1202. https://doi.org/10.1590/1679-78252446.
Panigrahi, S.K. and Das, K. (2016), “Ballistic impact analyses of triangular corrugated plates filled with foam core”, *Adv. Comput. Des.*, **1**(2), 139-154. https://doi.org/10.12989/acd.2016.1.2.139.
Polatov, A.M., Khaldjigitov, A.A. and Ikramov, A.M. (2020), “Algorithm of solving the problem of small elastoplastic deformation of fiber composites by FEM”, *Adv. Comput. Des.*, **5**(3), 305-321. https://doi.org/10.12989/acd.2020.5.3.305.
Rizov, V.I. (2017), “Non-linear analysis of delamination fracture in functionally graded beams”, *Couple. Syst. Mech.*, **6**(1), 97-111. https://doi.org/10.12989/csm.2017.6.1.097.
Santoro, J.F. and Kripka, M. (2020), “Minimizing environmental impact from optimized sizing of reinforced concrete elements”, *Comput. Concrete*, **25**(2), 111-118. https://doi.org/10.12989/cac.2020.25.2.111.
Shyamala, P., Mondal, S. and Chakraborty, S. (2018), “Numerical and experimental investigation for damage detection in FRP composite plates using support vector machine algorithm”, *Struct. Monit. Mainten.*, **5**(2), 243-260. https://doi.org/10.12989/smm.2018.5.2.243.
Yong, M., Falzon, B.G. and Iannucci, L. (2008), “On the application of genetic algorithms for optimizing composites against impact loading”, *Int. J. Impact Eng.*, **35**(11), 1293-1302. https://doi.org/10.1016/j.ijimpeng.2007.10.004.
Zhao, W., Guo, Q., Dou, X., Zhou, Y. and Ye, Y. (2018), “Impact response of steel-concrete composite panels: Experiments and FE analyses”, *Steel Compos. Struct.*, **26**(3), 255-263. https://doi.org/10.12989/scs.2018.26.3.255.

AI