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Research Article

Finite Element Analysis and Optimization of the Composite Plate Subjected to Close-Range Explosion

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ABSTRACT

Composite materials, particularly **glass and carbon fibre composites**, are widely used in aerospace, automotive, and defence applications because of their excellent strength-to-weight ratio and superior mechanical performance. However, their structural integrity can be severely compromised when subjected to high-intensity dynamic loads such as close-range explosions.

This study presents a comprehensive finite element analysis (FEA) and optimization methodology to evaluate and improve the blast resistance of these composite plates under surface contact explosive loading. The numerical model was developed in **LS-DYNA**, where the laminates were modeled with 3D solid elements and governed by the **Tsai–Wu failure criterion** to predict ply failure behaviour. Model validation was carried out by comparing numerical predictions with experimental data from the literature, showing good agreement in terms of delamination area, perforation, and damage distribution. Following validation, a **Genetic Algorithm (GA)** implemented through **LS-OPT** was employed to optimize the laminate lay-up sequence, aiming to maximize the safety factor. The optimization yielded significant performance improvements—raising the safety factor by up to **63%** and reducing delamination damage by up to **33%**. Furthermore, the effect of explosive stand-off distance was analyzed, revealing its critical role in mitigating structural damage.

The proposed framework provides a **reliable and practical numerical tool** for designing and optimizing **blast-resistant composite structures**, offering valuable guidance for **aerospace, defence, and automotive engineers** to develop **lighter and safer structural components** capable of withstanding severe explosion environments.

1. Introduction

Finite Element Analysis (FEA) and optimization tools have become fundamental in addressing complex engineering challenges across various disciplines. When analyzing the response of composite plates subjected to close-range explosions, it becomes essential to employ precise numerical models capable of accurately capturing structural behaviour, in addition to optimizing design parameters to enhance blast resistance and ensure structural integrity[1].

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Composite plates are extensively utilized in aerospace, automotive, marine, and civil engineering sectors due to their excellent strength-to-weight ratio, corrosion resistance, and long-term durability. However, when exposed to close-proximity explosive loads, these materials may experience severe internal damage, potentially compromising the structural system and leading to critical failures.[2].This topic has gained significant attention in recent years due to the increasing demand for lightweight, high-strength materials in various industries, including defence and security. Therefore, a thorough understanding of the Behaviour of composite plates under close-range explosion, and the use of advanced modelling techniques to optimize their design, can have significant implications for improving the safety and performance of structures in these industries.[3,4]. Three main types of explosion events can be identified based on the distance between the explosive charge and the target: (1) Contact explosion – when the explosive device is in direct contact with the target surface, generating extremely high pressure and temperature;
(2) Near-contact explosion – when the explosive is placed very close to the target without direct contact, where both the blast wave and the fireball interact with the structure; (3) Stand-off (far-field) explosion – when the charge is detonated farther away, and only the blast wave reaches the target. The present study focuses on surface-contact (close-range) explosions, which represent the most critical condition due to the severe pressure and thermal loads imposed on the composite surface.

The stand-off distance is adequate to prevent interaction with the target from the fireball and detonation products [5]. High pressures and temperatures operating quickly on the target surface are what define a contact charge's blast wave. As an explosive charge detonates, a solid-to-gas reaction front moves in the direction of the charge surface at speeds that are normally between 6 and 8 km/s, though they can vary from 4 to over 10 km/s. With temperatures as high as 3000 K and pressures as high as 40 GPa, the solid explosive material is converted into a gas[5]. High temperature and pressure are produced for a surface contact charge by the extremely quick releases of thermal energy and gas produced by the explosive chemical reaction process of breakdown. Depending on the composition, form, and weight of the explosive charge, the reaction is typically 90% complete in 10^{-6} to 10^{-9} s [6,7]. As a result, the heat and pressure shock loads delivered to the target surface happen quickly (often less than a microsecond).

The behaviour of composite materials to explosive bursts has been the subject of extensive experimental and modelling studies, as reviewed by A. Gargano et al.[5] and recently by Qiang Liu et al [7]. The majority of experimental studies have investigated the blast response of composites under the far-field blast condition [8–17], and only a few studies have assessed the response of composites to near-field blast [11–15]. To analyze the deformation and damage of laminate composites subjected to far-field blast events, finite element (FE) models have been developed and solved in [9–12,18].

This work aims to present a methodology dedicated to modelling and optimization of laminated plates made of composite material (Fibre glass laminate fibre carbon) under the close-range explosion using

the finite element (FE) method. The FE model is built using Ansys LS-DYNA software, and the optimization analysis is carried out using LS-OPT

software. The optimization procedure aimed at maximizing the safety factor based on the principle of the Genetic Algorithm to find the best lay-up sequence that supports the maximum blast load possible.

2. Materials AND Methods

2.1. Model Description

The experimental work employed by A. Gargano et al.[5] was used in this study to validate our numerical model. The considered glass and carbon fibre laminate plates for the developed model were of 275 x 275 x 4.2 mm^3 dimensions, as shown in Fig. 1. This plate is composed of several glass and carbon plies of 10 and 7(hence more plies were required in the glass fibre laminate to attain the same thickness and fibre content)[5], respectively, and each has a stacking sequence of [0, 90]. It was considered that the laminate sides were initially clamped.

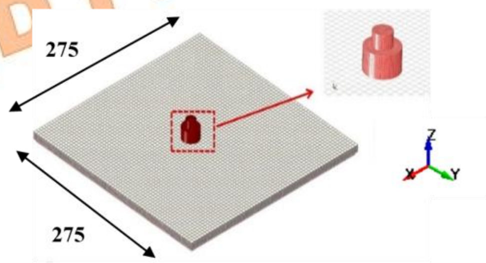


Fig. 1. Geometry of the composite plate subjected to surface-contact explosion, showing dimensions and charge position. (unit in mm)[5].

The thin and flexible primer sheet of 1000 PETN explosive material was applied to the laminate surface to create the blast tests. Table 2 lists the properties of the laminate material, and

Table 1 lists the various heights, diameters, and masses (including the detonator) of the explosive charges utilized in the experiments[5].

Table 1. Surface contact blast experimental test conditions [5].

Test Number	Charge mass (g)	Charge diameter (mm)	Charge thickness (mm)	Calculated blast impulse (N.s)
SC1	0.2	6.5	0a	0.65
SC3	*0.5*	*11.0*	*2.0*	*1.97*
SC4	1.0	11	5.0	2.43

a Represents an explosion with just the detonator and no explosive material.

Table 2. Mechanical properties of glass and carbon fibre composite plies used in the finite element model[5].

Materials property	Carbon fibre Laminate	Glass fibre Laminate
ρ (kg/m3)	1600	1900
E11, E22 (MPa)	55000	28000
E33 (MPa)	7000	7000
G12 (MPa)	4500	4500
G13, G23 (MPa)	1800	1800
υ12	0.25	0.25
XT, YT (MPa)	890	620
XC, YC (MPa)	450	360
SL (MPa)	225	180
ST (MPa)	225	120
G^c_{ft} , G^c_{fc} (kJ/m2)	45	85
G^c_{mt} , G^c_{mc} (kJ/m2)	45	85

3. Finite Element Modelling

A finite element model was built using **LS-DYNA** to simulate the response of the composite plate under surface-contact explosive loading. The plate was modeled using **3D eight-node solid elements (ELFORM = 1** Constant Stress Solid**)** as shown in Fig. *2*. Each node had three translational degrees of freedom, and a single integration point was used through the thickness of each layer. The average **element size was 2.6 mm**, which provided mesh convergence while maintaining reasonable computational efficiency. The total number of solid elements was **17,500**, with about **61,100 nodes**, and the total simulation time was **1 × 10⁻⁴ s.**

The strength of the fibre–matrix composite was governed by the **Tsai–Wu failure criterion** implemented through the *MAT054* "Composite Failure Optional" material model [19], which allows progressive damage under 3D stress states. Solid elements were selected because they can accurately capture the full three-dimensional stress distribution, especially for relatively thick composite laminates [7].

Interlaminar damage between plies was modeled using the **"CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK"** algorithm [22], which effectively simulates delamination initiation and growth. The explosive loading was defined using the built-in ***LOAD_BLAST_ENHANCED** function in LS-DYNA, based on the CONWEP formulation.

The composite plate was **fully clamped along all four edges**, preventing both translational and rotational displacements, to reproduce realistic boundary conditions under blast loading scenarios.

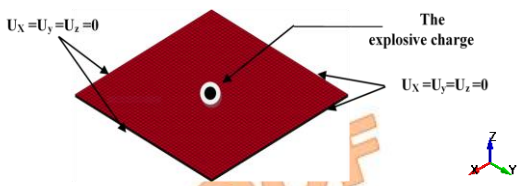


Fig. 2. FE model and boundary conditions of drilled laminate plate.

The Tsai–Wu failure criterion was selected for its superior physical accuracy in representing strength differentials and its proven capability to capture complex, interacting stress states typical of anisotropic composite laminates under blast loading. Moreover, it integrates seamlessly with the MAT054 progressive damage model in LS-DYNA, allowing consistent simulation of both intralaminar and interlaminar failure mechanisms. In addition, the linear form of the Tsai–Wu criterion facilitated the formulation of the objective function used in the optimization process, enabling an efficient coupling between the damage evaluation in LS-DYNA and the Genetic Algorithm implemented in LS-OPT. This combination provides a high-fidelity representation of the composite material response up to and including ultimate failure, ensuring the reliability and validity of the present finite element results.

3.1. FE impulse model

Explosive charges (including the detonator) determined using Eq. (1) are also provided in Table 1[5].A disc-shaped charge's overall impulse (I) can be computed using:

$$I = u_o C \mu \quad (1)$$

where u_o is the particle velocity of the detonation products, C is the charge mass and μ is the charge shape coefficient. This equation is valid for the condition $b \geq 2H$, where b is the charge diameter and H is the charge height. The charge shape coefficient for $b/H \geq 2$ is calculated using:

$$\mu = 1 - 2\frac{H}{b} + \frac{4}{3}\frac{H^2}{b^2} \quad (2)$$

The calculated impulse was then used as the loading condition on the FE model of the laminate target. The material behaviour of the explosive charge was modeled using the Jones, Wilkins and Lee (JWL) equation-of-state, which is expressed as [5]:

$$P = C_1\left(1 - \frac{\omega}{R_1 v}\right)e^{-R_1 v} + C_2\left(1 - \frac{\omega}{R_2 v}\right)e^{-R_2 v} + \frac{\omega E}{v} \quad (3)$$

4. Results and Discussion

4.1. Validation of the Model

Damage to laminates subjected to surface contact charges of various sizes could be correctly predicted using the FE impulse model. In Fig. 3, for instance, damage to the glass fibre laminates treated to two different sizes of surface charges with a diameter of 6.5 or 11 mm as shown in contour images. The perforation hole's dimensions and form, as well as any nearby delamination damage, were estimated by the model. Both types of laminates' through-thickness damage could also be accurately predicted (Fig. 4). The FE model also forecasted the areas of fibre fracture/pulverization, the distribution of through-thickness delamination cracking, the out-of-plane deformation/distortion of the plies, and the spalling of the ply at the rear surface. The FE model accurately calculated the degree of delamination damage as well as the variations in perforation size between the laminates' front and rear surfaces and even through-thickness damage. For validation purposes, the estimated damage caused by the explosive charges was evaluated using the developed FE model.

The numerical results were compared with experimental data obtained from ultrasonic testing techniques [5]. A comparison with another model developed and solved using Abaqus, excellent agreement (typically between 2-15%) was found between the measured and computed damaged delamination areas as presented in Table 3, which validates the developed FE model. The sizes and forms of the portions that were perforated and delaminated were accurately anticipated by the FE impulse model[5]. The results of FE analysis demonstrate that the carbon fibre composite suffered more delamination damage than the glass fibre laminate. The glass fibre laminate also showed better resilience to perforation caused by the blast.

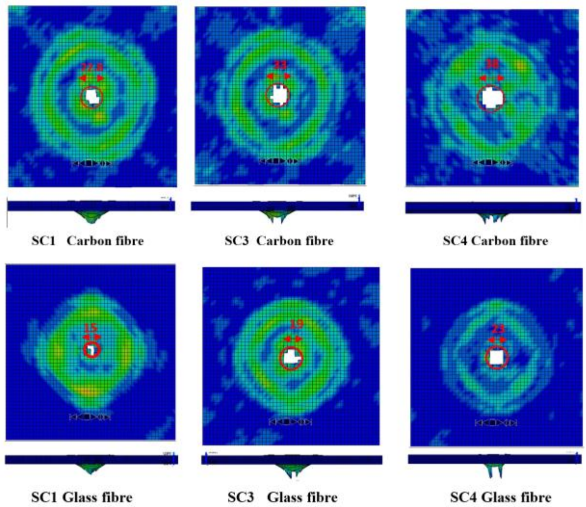
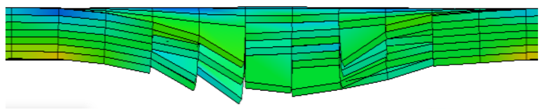
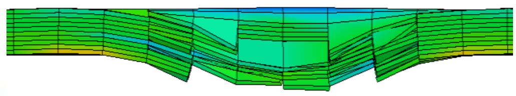


Fig. 3. Top surface and lateral surface views of the carbon and glass fibre laminate subjected to charges with diameters of 6.5 mm and 11 mm at time = 75 microseconds.



SC3 (b) Carbon fibre



SC3(a) glass fibre

Fig. 4. Comparison of through-thickness damage to the (a) glass fibre laminate and (b) carbon fibre laminate at time = 75 microseconds.

Table 3. Geometrical characteristics of the specimens.

Blast Impulse (N.s)		Glass fibre laminate				
		Delamination damage areas (mm²)				
		Experimental	FE- Abaqus	FE LS-DYNA	Difference between the Abaqus VS Experimental (%)	Difference the LS-DYNA VS Experimental (%)
SC1	0.65	1860	2200	1913	18	2.85

SC3	1.97	3190	3040	2758	4.7	13.54
SC3	2.43	2940	2850	2486	3.1	15.44
Blast Impulse (N.s)		**Carbon fibre laminate**				
		Delamination damage areas (mm²)				
		Experimental	FEAbaqus	FELS-DYNA	Difference between the Abaqus VS Experimental (%)	Difference the LS-DYNA VS Experimental (%)
SC1	0.65	2000	2010	2253	0.5	12
SC3	1.97	2450	2745	2896	12	18
SC4	2.43	3825	3840	3528	0.4	7.7

The computational model demonstrated a strong correlation with the experimental results, accurately predicting the peak load (within approximately 5%) and the dominant failure modes, such as matrix crushing and delamination near the notch region. However, a consistent slight underprediction of the overall damage area was observed, as illustrated in Fig.4 **and Table 3.**

This discrepancy can be attributed to several factors. Firstly, the inherent variability of composite materials — including micro-voids, fibre waviness, and local resin-rich zones — introduces weak regions in real specimens that are not represented in the idealized, homogeneous finite element model. These imperfections often trigger earlier damage initiation during experiments. Secondly, the MAT054 material model, although robust, employs simplified post-failure stiffness degradation laws. The fracture energy and softening parameters, calibrated from standard coupon tests, may not fully capture the complex energy dissipation mechanisms occurring in the specific structural configuration analyzed here. Finally, the sensitivity of damage evolution to element size, even after the mesh convergence study, remains a potential contributor to the slight mismatch.

Despite these minor discrepancies, the model effectively captured the global response and the critical failure mechanisms, confirming its reliability for use in parametric analyses and design optimization of composite plates subjected to close-range explosion loading.

4.2. Optimization Analysis

In order to study the optimization behaviour of plate fibre-polymer laminates subjected to surface contact explosive charges, a Genetic Algorithm (GA) was adopted, where the objective function is to maximize the safety factor by varying the fibre orientations.

4.2.4. Failure criteria of the composite plate

In the present work, the adopted failure criterion was "Tsai–Wu". This criterion is one of the most reliable and widely used to control the composite failure, which is presented in a simple expression as follows:[7,8]

$$\frac{\sigma_{11}^2}{X_t|X_c|}+\frac{\sigma_{22}^2}{Y_t|Y_c|}+\frac{\tau_{12}^2}{S^2}-\frac{\sigma_{11}\sigma_{22}}{\sqrt{X_tX_cY_tY_c}}+\left(\frac{1}{X_t}-\frac{1}{|X_c|}\right)\sigma_{11}+\left(\frac{1}{Y_t}-\frac{1}{|Y_c|}\right)\sigma_{22}<1 \quad (04)$$

where σ_{11},σ_{22} present the constraint on the axes 11; 22 _τ_{12} shear stresses_

Xt is the tension limit along the fibre.
Xc is the compression limit along the fibre.
Yt is the tension limit of the transverse fibre.
Yc is the compression limit of the transverse fibre.
S is the shear limit.

Based on the Tsai–Wu criterion, the safety factor (SF) of the kth layer, SF^k, is the multiplier of

the stress components of the layer k, 6_{ij}^k, that satisfies Eq. (4) to be equal to 1.0, Eq. (4) then can be written as:[7,19]

$$a(SF^K)^2+b(SF^K)-1=0 \quad (05)$$

where:

$$a=\frac{\sigma_{11}^2}{X_t|X_c|}+\frac{\sigma_{22}^2}{Y_t|Y_c|}+\frac{\tau_{12}^2}{S^2}-\frac{\sigma_{11}\sigma_{22}}{\sqrt{X_tX_cY_tY_c}} \quad (06)$$

$$b=\left(\frac{1}{X_t}-\frac{1}{|X_c|}\right)\sigma_{11}+\left(\frac{1}{Y_t}-\frac{1}{|Y_c|}\right)\sigma_{22} \quad (07)$$

Solving Eq. (5) to obtain the safety factor, noting 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 [7,19].

$$SF^k=\left|\frac{-b+\sqrt{b^2+4a}}{2a}\right| \quad (08)$$

4.2.2 The Objective Function

Generally, the objective function is formulated depending on the type of optimization problem and its objectives. In the first stage of this study, an improvement study was carried out by means of the genetic algorithm for the same two previous composite plates (Glass fibre and Carbone fibre) that were exposed to a contact explosion, by maximizing the safety factor associated with the Tsai–Wu criterion for each sample to raise the value of the safety coefficient associated with the optimization aims at finding the orientation of the optimum laminate that supports the maximum blasts resistance. In the second stage, the distance at which the explosive device must move away from the original plate was calculated in order to set a safety factor with a value of one.

$$SF = Max\{Min(SF^k)_{Sample}\} \qquad (09)$$

4.3. Discussion and Interpretation

The Genetic Algorithm (GA) has been used in this study to perform the optimization analysis. It is based on the principle of natural selection and the survival of the fittest. The process to produce new solutions in GA mimics nature [8]. The convergence criterion is based on either reaching the maximum number of generations or no improvement in the objective function for a set number of iterations. These values are consistent with literature practices and balance solution accuracy with computational cost. In the current study. The optimization aims at finding the best laminate orientations (lay-up sequence) that offer the best safety factor, i.e. the maximum SF subjected to a close-range explosion. At this step, the angle has nine values ±[0,30,45,60, and 90]. The design variables for the laminate stacking sequence were the fibre orientations for each ply, selected from a discrete set of angles: {0°, ±30°, ±45°, ±60°, and 90°}. This set was chosen to balance **computational efficiency, mechanical performance, and practical manufacturability**. The orientations 0°, ±45°, and 90° are fundamental for carrying **axial, shear, and transverse loads**, respectively, while the intermediate angles (±30°, ±60°) provide the optimizer with additional flexibility to fine-tune **coupling effects and stress redistribution** within the laminate. Moreover, this discrete set corresponds to **standard industry practices** for automated fibre placement and manual lay-up processes, ensuring that the optimized configurations are not only **high-performing** but also **feasible and cost-effective** to manufacture.
After finding the optimum plate (best lay-up sequence). The LS-OPT computer Programme is used to carry out the optimization calculation by linking it to LS-DYNA. Following optimizing the lay-up sequence, the distance that the explosive charge must travel so that the plate does not break is determined.

Table 4. Genetic Algorithm optimisation parameters.

Population Size	100
Number of generations	250
mutation rate	0.02
crossover rate	0.8

During the optimization process, several practical and numerical constraints were imposed to ensure manufacturable and structurally balanced laminate configurations. The stacking sequence was constrained to remain symmetric and balanced with respect to the mid-plane to avoid bending–extension coupling. Only standard ply orientations {0°, ±30°, ±45°, ±60°, 90°} were considered to reflect realistic manufacturing limitations associated with automated fibre placement and manual lay-up processes. Minimum and maximum thickness bounds were applied to preserve the overall laminate thickness of the reference design. These constraints ensured that all optimized configurations were physically feasible, mechanically stable, and manufacturable in practice.

However, the inclusion of these manufacturing restrictions necessarily limited the GA population size and the number of generations, which may have prevented full global convergence to the absolute optimum. Furthermore, the Genetic Algorithm itself is stochastic in nature and provides no formal guarantee of achieving the unique global optimum, but rather yields a highly suitable near-optimal design. Despite these limitations, the optimization results were consistent across multiple runs and demonstrated robust improvement in performance, confirming the reliability of the adopted GA-based optimization framework**[2١]**.

Table 5 presents a comparison between the actual safety factors (SF) derived from the experimental lay-up sequence and the optimized safety factors obtained through Genetic Algorithm (GA) optimization for glass fibre laminates subjected to three different explosive charges (SC1, SC3, and SC4). The actual SF values for the original lay-up configuration [00,90,00,90,00]s are 0.51, 0.46, and 0.38 for tests SC1, SC3, and SC4, respectively. All of these values fall below 1.0, indicating that the original configurations are inadequate in resisting blast-induced failure and are likely to experience significant damage or complete failure under the specified loading conditions. After optimization, the safety factors increase to 0.58, 0.59, and 0.62, with corresponding optimized stacking sequences such as [−90,45,−90,45,−90]s[-90,45,-90,45,-90]s and [−90,45,−90,45,−90]s. These improved SF values represent increases of approximately 13–24%, which significantly enhance the structural resilience of the laminate under explosive loading. Notably, the lowest-performing configuration (SC4) in the actual state achieves the greatest relative improvement in SF (from 0.38 to 0.62), underscoring the critical impact of ply orientation on failure resistance in high-intensity loading conditions. The optimized sequences incorporate angled plies (±45°, ±90°) that are better suited to distributing shear and tensile stresses, delaying the onset of damage such as fibre breakage, matrix cracking, and delamination. In summary, the results in Table 5 demonstrate the effectiveness of the Genetic Algorithm in enhancing the blast resistance of glass fibre laminates. The optimized stacking sequences significantly increase the safety factor, transforming configurations prone to failure into more robust designs. This highlights the value of computational optimization as a low-cost, high-impact strategy in the design of protective composite structures.

Table 5. Actual and optimised safety factors for glass fibre laminate under surface-contact explosion loading.

Glass fibre laminate							
Test Numbers	Charge mass (g)	Charge diameter [mm]	Lay-up sequence	SF Actual	**SF** Optimum	Lay-up sequence Optimum	SF Improvement (%)
SC1	0.2	6.5	[00,90,00,90,00]s	0.51	0.58	[-90,45,-90,45,-90]s	13.7
SC3	0.5	11	[00,90,00,90,00]s	0.46	0.59	[90,45,90,45,90]s	28.3
SC4	1.0	11	[00,90,00,90,00]s	0.38	0.62	[-90,45,-90,45,-90]s	**63.2**

Table 6 presents the actual and optimized safety factors for carbon fibre laminates subjected to surface-contact explosions. The original lay-up configuration [0°, 90°, 0°, 90°, 0°, 90°, 0°] resulted in safety factors of 0.51, 0.48, and 0.66 for SC1, SC3, and SC4, respectively—values indicating a high likelihood of structural failure under severe blast loading. Following the optimization, the safety factor values improved to 0.61, 0.57, and 0.73, with optimal stacking sequences such as [60°, −60°, −60°, −60°, 60°, −60°, 60°] and [−45°, −90°, −45°, −90°, −45°, −90°, −45°].

Table 6. Actual and optimised safety factors for carbon fibre laminates under surface-contact explosion loading.

Carbon fibre laminate							
Test Number	Charge mass (g)	Charge diameter	Lay-up sequence	SF Actual	SF Optimum	Lay-up sequence Optimum	SF Improvement (%)
SC1	0.2	6.5	[00,90,00,90,00,90,00]	0.51	0.61	[60,-60, -60,-60,60,-60,60]	19.6
SC3	0.5	11	[00,90,00,90,00,90,00]	0.48	0.57	[60,-60, -60,-60,60,-60,60]	18.7
SC4	1.0	11	[00,90,00,90,00,90,00]	0.66	0.73	[-45,-90,-45,-90,-45,-90,-45]	10.6

In the following trials, SC1, SC2, and SC3 are all levels that cause plate failure. Following the optimization computation, these values of SF are increased to 0.61, 0.57, and 0.73. The comparable optimum lay-up sequence is [60,-60,-60,-60,60,-60,60] and [-45,-90,-45,-90,-45,-90,-45]. 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. The improvement in safety factors can be physically explained by the mechanics of fibre orientation under dynamic loading. Plies oriented at ±60° and ±45° effectively redistribute in-plane shear and tensile stresses induced by close-range explosions. The ±60° layers enhance energy absorption and promote a gradual transfer of loads between longitudinal and transverse directions, thereby mitigating interlaminar stress concentrations and reducing the likelihood of delamination. Similarly, ±45° layers improve shear flexibility, allowing the laminate to deform plastically without immediate fibre rupture or matrix cracking. In contrast, the unidirectional 0°/90° lay-up tends to localize stresses along fibre paths, causing premature matrix damage. As a result, the optimized stacking sequences achieved through the Genetic Algorithm provide a more balanced stiffness distribution and superior damage tolerance, leading to enhanced overall blast resistance of the carbon fibre laminates, even under short stand-off detonation conditions.

Table 7. Comparison of experimental and calculated optimum delamination damage areas for the laminates.

Blast Impulse (N.s)		Glass fibre laminate				
		Delamination damage areas (mm^2)				
		Experimental (mm^2)	FE LS-DYNA (mm^2)	Difference the DYNA (%)	FE Optimum	Decrease in damaged (%)
SC1	0.65	1860	1913	2.85	1574	17
SC3	1.97	3190	2758	13.54	1879	31
SC3	2.43	2940	2486	15.44	2012	19
Blast Impulse (N.s)		**Carbon fibre laminate**				
		Delamination damage areas (mm^2)				
		Experimental (mm^2)	FE LS-DYNA (mm^2)	Difference the DYNA (%)	FE Optimum	Decrease in damaged (%)
SC1	0.65	2000	2253	12	1572	30
SC3	1.97	2450	2896	18	2177	24
SC4	2.43	3825	3528	7.7	2351	33

Table 7 shows the comparison of experimental [5]. and calculated optimum delamination damage areas for the laminates. The results show a significant improvement in the damaged areas, and the improvement was between 17% and 31%. In the case of the plate Glass fibre laminate, and between 24% and 33% in the case of the Carbon fibre Laminate, which is an excellent performance in the case of this type of strict load.

In the second stage, the distance at which the explosive device must move away from the plate, originally on the z-axis (the safety distance), which is calculated in order to have a safety factor equal to one value (SF = 1.0), was determined. The results are shown in Tables 8-9, respectively, for both panels Carbon fibre Laminate and Glass fibre Laminate for the initial lay-up sequence.

Table 8. The distance of the explosive mass from the plate in the z-axis for SF = 1.

Carbon fibre laminate					
Test Number	Charge mass (g)	Charge diameter	Lay-up sequence	Dimension the charge mass in the z-axis (mm)	SF
SC1	0.2	6.5	[00,90,00,90,00,90 ,00]	13.58	1.028
SC3	0.5	11	[00,90,00,90,00,90 ,00]	19.58	1.080
SC4	1.0	11	[00,90,00,90,00,90 ,00]	32.58	1.010

Table 9. The distance of the explosive mass from the plate in the z-axis for SF = 1.

Glass fibre laminate					
Test Number	Charge mass (g)	Charge diameter	Lay-up sequence	Dimension the charge mass in the z-axis (mm)	SF
SC1	0.2	6.5	[00,90,00,90,00]s	12	1.011
SC3	0.5	11	[00,90,00,90,00]s	19	1.048
SC4	1.0	11	[00,90,00,90,00]s	38	1.011

Figures 5 and 6 illustrate the evolution of the safety factor (SF) as a function of the standoff distance (Z-axis) for **glass fibre** and **carbon fibre** laminates, respectively, comparing the actual stacking sequences with the optimized configurations obtained via the Genetic Algorithm (GA). In both cases, the SF increases with the explosive charge distance from the plate, confirming the critical influence of standoff distance on mitigating blast-induced damage.

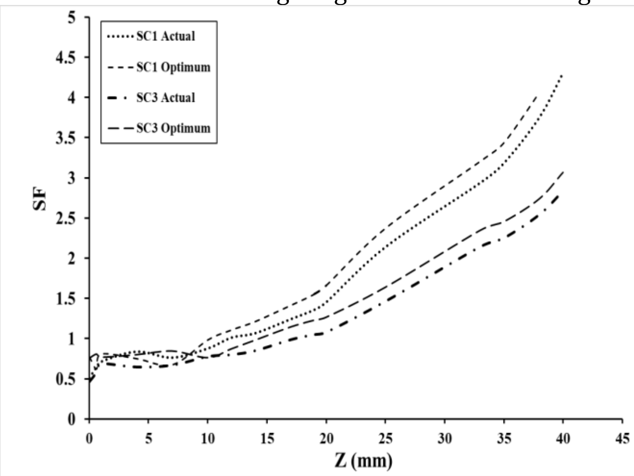


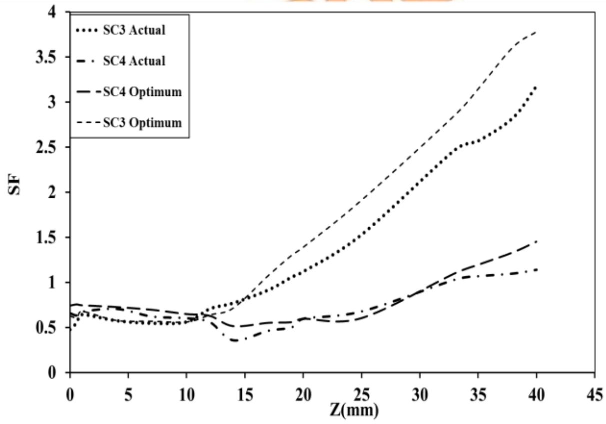
Fig. 5. Variation of safety factor (SF) with standoff distance for the glass fibre laminate: comparison between actual and optimised stacking sequences.

For the **glass fibre laminate** (Fig.5), the optimization process resulted in a significant improvement in SF, particularly at short stand-off distances where the blast intensity is highest. The optimized lay-up exhibited superior stress redistribution and delayed damage initiation due to the higher number of plies and the greater flexibility in fibre orientation. This structural adaptability enhanced energy absorption and effectively reduced the extent of delamination under severe loading.

For the **carbon fibre laminate** (Fig.6), a similar increasing trend in SF with standoff distance was observed; however, the relative improvement after optimization was smaller compared to the glass laminate. This behaviour is attributed to the inherently higher stiffness and strength of carbon fibres, which provide better baseline resistance to dynamic loading but less sensitivity to orientation adjustments.

Overall, these results confirm that both standoff distance and fibre lay-up optimization are key design parameters for improving blast resistance. While carbon fibre laminates inherently possess greater mechanical robustness, glass fibre laminates exhibit higher adaptability to optimization strategies, making them more responsive to design modifications under extreme loading conditions. Furthermore, the increase in the number of plies while maintaining the same overall laminate thickness plays a crucial role in enhancing blast resistance. This configuration allows for finer stress redistribution across more interfaces, improving energy absorption and delaying the onset of delamination and fibre–matrix separation during high-intensity impact events.

Fig. 6. Variation of safety factor (SF) with standoff distance for the carbon fibre laminate: effect of optimisation on blast performance.



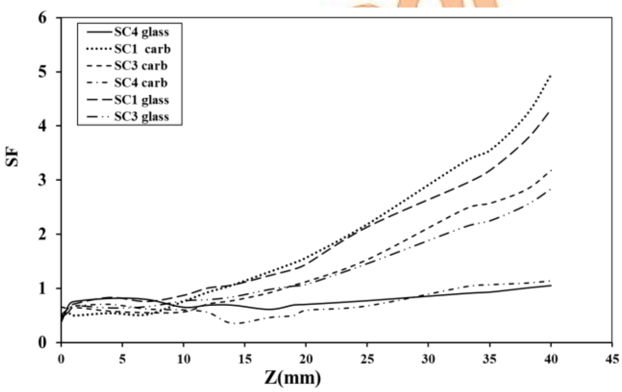


Fig. 7. SF actual Glass VS actual carbon as a function of Z.

Figure 7 provides a direct comparison between the safety factor (SF) of glass fibre and carbon fibre laminates—both using their actual (non-optimized) lay-up sequences—as a function of the standoff distance along the Z-axis. This comparative plot offers key insights into the intrinsic differences in blast performance between the two types of composite materials under identical explosive conditions. relative robustness. At greater standoff distances, the carbon fibre laminate consistently exhibits a higher safety factor than the glass fibre laminate, reflecting its superior mechanical properties, such as higher tensile strength, stiffness, and energy absorption capability. This confirms that carbon laminates are more resistant to blast-induced damage, particularly when the explosive impulse is partially dissipated before reaching the plate. However, as the explosive charge approaches the plate (i.e., at lower standoff distances), the difference in SF between the two laminates diminishes, and in some regions, the curves appear to converge. This behaviour indicates that under extreme, near-contact blast loads, both materials approach their failure thresholds, and the effect of intrinsic material properties becomes less dominant than the direct intensity of the blast impulse. This observation is logically consistent with dynamic failure mechanics: at close distances, the severity of the pressure wave overwhelms both laminates, regardless of baseline strength. Nonetheless, the carbon fibre still shows slightly better performance throughout, confirming its relative robustness.

5. Conclusion

The study demonstrated that composite laminates made of glass and carbon fibers are subject to severe and highly localized damage when exposed to surface-contact explosions. The most critical damage occurs in the immediate vicinity of the detonation point, manifesting as fiber fragmentation, matrix rupture, interlaminar delamination, and, in extreme cases, complete perforation of the laminate. Finite Element (FE) modeling using LS-DYNA was shown to accurately simulate the structural damage induced by the explosion, effectively predicting the type, extent, and spatial distribution of both intralaminar and interlaminar failure. The results indicate that the pressure impulse is the dominant factor contributing to damage, whereas thermal effects play a relatively minor role under contact charge conditions.

From an optimization perspective, the Genetic Algorithm (GA) proved to be an efficient and reliable method for identifying the optimal fiber orientation (lay-up sequence) that maximizes the safety factor. Analysis of the SF Improvement (%) clearly demonstrates that the safety factor increased across all tests, with the most substantial improvement of 63.2% observed for the SC4 Glass Fiber laminate. These findings underscore the effectiveness and robustness of the optimization strategy. Furthermore, the study highlighted the critical influence of stand-off distance; as the distance between the explosive charge and the target plate increases, the safety factor improves considerably, confirming the elevated risk associated with surface-contact blasts compared to near- or far-field explosions.

Overall, this integrated FE and optimization approach provides valuable insights into the mechanisms of damage and offers design strategies for enhancing the blast resistance of laminated composite structures, contributing to improved structural safety and performance in engineering applications.

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