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Stiffened composite plates as equivalent structures for sandwich panels under low-velocity hail impact

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ABSTRACT

Despite many favorable properties of sandwich panels, moisture penetration into the core of these panels has been known to cause catastrophic failures. To address these issues, developing an alternative panel with equivalent mechanical behavior can be a viable solution. Exploring the mechanical behavior equivalency between stiffened composite plates and existing sandwich panels is advantageous due to their potential for similar applications. This study employed explicit finite element modeling using LS-DYNA package to simulate the behavior of these panels. Also, experimental investigations were conducted on stiffened composite plates to examine the effect of stiffener arrangements and impact location on their static and dynamic behaviors. The experiments highlighted the significance of stiffener arrangements in influencing the static and impact behavior of the plates. Additionally, as a case study, an optimization procedure for designing an optimal stiffened plate under ice impact was studied, utilizing the Taguchi method and analysis of variance, to identify the optimal design point. The results indicated that the stiffened plate exhibited a maximum deflection similar to that of a sandwich panel under low-velocity impact, while having a 19.3% lower von Mises stress. This means that the equivalent stiffened plate demonstrated comparable deflection while providing enhanced strength during dynamic loading. Furthermore, the analysis of the parametric study showed that the thickness of stiffeners had the most pronounced influence on the behavior of stiffened plates subjected to hail impact.

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Sandwich panel; stiffened composite plate; low-velocity impact; quasi-static indentation; hail impact

1. Introduction

Stiffened plates consist of a top face plate and several attached longitudinal (one-way) or longitudinal-transverse (two-way) stiffeners. The stiffened plates are utilized in a wide range of engineering applications, such as construction, aviation structures, and ocean engineering, owing to their notable specific stiffness and strength (Sinha et al. 2020; Zou et al. 2021). Numerous studies have explored the mechanical and thermal behavior of fiber-reinforced composite stiffened plates. These investigations demonstrate that these plates offer exceptional durability, impressive thermal characteristics, effortless production, and extended fatigue life when compared to unstiffened plates and sandwich structures of equivalent dimensions and/or weight (Gruben et al. 2017; Li and Ma 2023; Liu, Niu,

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and Jia 2021; Liu et al. 2020; Sun et al. 2018; Thinh and Quoc 2010; Yue et al. 2022). It is well known in engineering fields that sandwich panels serve similar purposes to stiffened plates and they are thus widely used in widespread utilization in various transportation and civil structures (Daniel et al. 2002; Hedayati and Sadighi 2016; Hedayati and Ziaei-Rad 2011; Hedayati, Yousefi, and Bodaghi 2022; Torkestani, Sadighi, and Hedayati 2015). However, the presence of defects and moisture penetration into the core of sandwich structures remains a significant drawback, as these defects cannot be easily detected (Avilés and Aguilar-Montero 2010; Assarar et al. 2015; Laplante et al. 2005). Over time, these defects weaken the structural integrity, leading to unexpected damage (Ramnath, Alagarraja, and Elanchezhian 2019; Wahl et al. 2014). Unlike sandwich structures, stiffened plates do not suffer from the above-mentioned drawbacks. Furthermore, the presence of visible reinforcements in stiffened plates facilitates the identification and replacement of faulty parts before they lead to catastrophic damage in structures (Gao et al. 2022; Lalisani et al. 2023; Zou et al. 2021). Moreover, in some applications, there is a limitation in physical space availability due to the considerable thickness a suitable sandwich structure might require. Exploring the feasibility of using stiffened plates as an alternative to sandwich panels seems an interesting idea. Therefore, it is essential to investigate the mechanical behavior and failure mechanisms of both structures under similar loading conditions most encountered in civil and aviation applications, particularly in scenarios involving quasi-static and low-velocity impact loads.

Another crucial aspect to explore is the behavior of stiffened plates with various configurations and under different loading conditions, aiming to determine the optimum geometries for optimal performance. Several studies have been conducted to enhance the performance of stiffened plates and develop more accurate numerical and analytical models for predicting their failure under different loading conditions. Timoshenkov and W. Krieger (1959) investigated the buckling and deflection of stiffened plates with one-way and two-way stiffeners. They analyzed the behavior of these plates using their proposed analytical models. Block, Card, and Martin (1965) employed classical plate theory to model and study the deformation of isotropic and orthotropic stiffened cylinders and plates subjected to axial and radial loadings. Liao and Reddy (1990) examined composite rectangular plates with unidirectional stiffeners to analyze their elastic behavior, buckling characteristics, and free vibrations. They considered various boundary conditions and explored different analytical approaches. Recent studies have mostly focused on predicting failure using numerical modeling (Chattopadhyay, Sinha, and Mukhopadhyay 1993; Liu et al. 2020; Sinha and Mukhopadhyay 1994; Tang et al. 2021), assessing the influence of stiffener geometry and arrangement on the behavior of stiffened plates (Chen et al. 2021; Hernandes, Almeida, and Nabarrete 2000; Wang, Hansen, and Oguamanam 2004; Zhao and Kapania 2016), and investigating the types of connections between stiffeners and plates (Chen, Wang, and Bai 2006). Furthermore, the impact behavior of stiffened plates subjected to low-velocity impact loading has also been explored in a number of studies over the past two decades (Faggiani and Falzon 2010; Gong and Lam 1999; Li, Liu, and Zhang 2014; Soto et al. 2018; Sun et al. 2018). Furthermore, numerous researchers have investigated dynamic response modeling of stiffened plates subjected to various dynamic loadings, including low-velocity impact (Peng et al. 2024; Teimouri, Faal, and Milani 2025). For instance, Hu et al. (2024) developed a multi-model to predict damage mechanisms, while Huang et al. (2024) studied a nonlinear model for debonding damage in composite stiffened structures. Localized impact response modeling was also recently studied by Yan et al. (2024), based on stress wave generation. Finally, these research endeavors have contributed significantly to the understanding and improvement of the mechanical behavior of stiffened plate structures.

In recent years, foreign object damages (FOD), particularly hail impacts, in both low- and high-velocity regimes have posed a significant concern for airborne objects and civil structures (Hedayati and Sadighi 2015; Olsson, Juntikka, and Asp 2013). Hail impacts can result in a wide range of damages, ranging from hardly noticeable surface harm to structural dents and perforations (Anghileri et al. 2005; Ganesh Ram 2021). Numerous studies have been undertaken to explore the impact resistance of metal fuselages (Cai, Zhu, and Qian 2022) and composite structures (Appleby-Thomas, Hazell, and Dahini 2011; Kim and Kedward 2000) under hail impact. Recent research works have delved into various aspects, including the influence of stacking sequence (Dolati, Fereidoon, and Sabet 2014; Tang et al. 2017), dynamic response of structures under multiple hail impacts (Sadighi et al. 2023), numerical prediction techniques (Cai et al. 2020; Kim and Kedward 2000), and simulation of ice behavior during impacts (Carney et al. 2006; Kim and Keune 2007; Tippmann, Kim, and Rhymer 2013). These investigations have significantly contributed to the understanding and mitigation of the effects caused by hail impacts.

In recent years, several studies have been undertaken to investigate the experimental and numerical analysis of hail impact on stiffened plates (Lalisani et al. 2023; Song et al. 2018). The primary aim of these research efforts was to gain a deeper understanding of how these structures respond when subjected to hail impacts. In addition, the load-bearing capacity and failure modes of stiffened plates after being impacted at different positions have been studied in (Cui et al. 2023; Sharif-Khodaei, Ghajari, and Aliabadi 2012).

As mentioned, the biggest challenge in utilizing sandwich panels is the presence of invisible defects and moisture penetration into their core, which can compromise structural integrity over time. The present study aims to address these challenges by exploring the feasibility of composite stiffened panels as a possible alternative. While previous studies have extensively examined the mechanical response of stiffened plates and sandwich panels under various loading scenarios, the direct comparison of their performance in terms of failure modes and load-bearing capacities under quasi-static and low-velocity impact loads remains limited. In particular, the influence of stiffener spacing and arrangement (one-way vs. two-way) on the mechanical behavior of stiffened plates has not been systematically investigated. This study contributes to the field by experimentally analyzing these parameters in detail and introducing novel experimental methodologies and optimization techniques to enhance the impact resistance of stiffened plates, particularly against hail impacts in aviation and civil applications. Furthermore, a review of existing experimental and numerical studies highlights an unexplored gap in modeling hail impacts and conducting optimization design analysis, which this research seeks to bridge through a comprehensive experimental investigation.

2. Materials and methods

2.1. Experimental set-up

In the present study, the stiffened composite plates consisted of two parts: (1) 4-layer composite face sheet laminate, and (2) 24-layer composite stiffener laminate. Both laminates consisted of plain woven glass fiber, 205 gr/m^2 in areal weight, and ML-506 epoxy resin, and were fabricated by the VARTM (Vacuum-Assisted Resin Transfer Molding) method. The lay-up of the face sheet was $[0/90]_4$, and the lay-up of the stiffener was $[0/90]_{24}$.

The face sheet was manufactured with a $[0/90]_4$ lay-up as a one-piece sheet and was then cut into the required specimen sizes. The cutting was performed using a cold water-jetting process, ensuring minimal impact on the composite material, with no heat damage and with high precision. Similarly, the stiffener part, with a $[0/90]_{24}$ lay-up, was produced as a one-piece using the VARTM method and was subsequently cut into the desired shapes and forms, as shown in Fig. 1. The cutting process was carried out using cold water-jetting to prevent damage and achieve high dimensional accuracy. Subsequently, the hand lay-up method was employed to attach the face sheets and stiffeners. This process involved manually applying the epoxy resin to ensure proper adhesion and structural integrity. Following the completion of the hand lay-up procedure, the

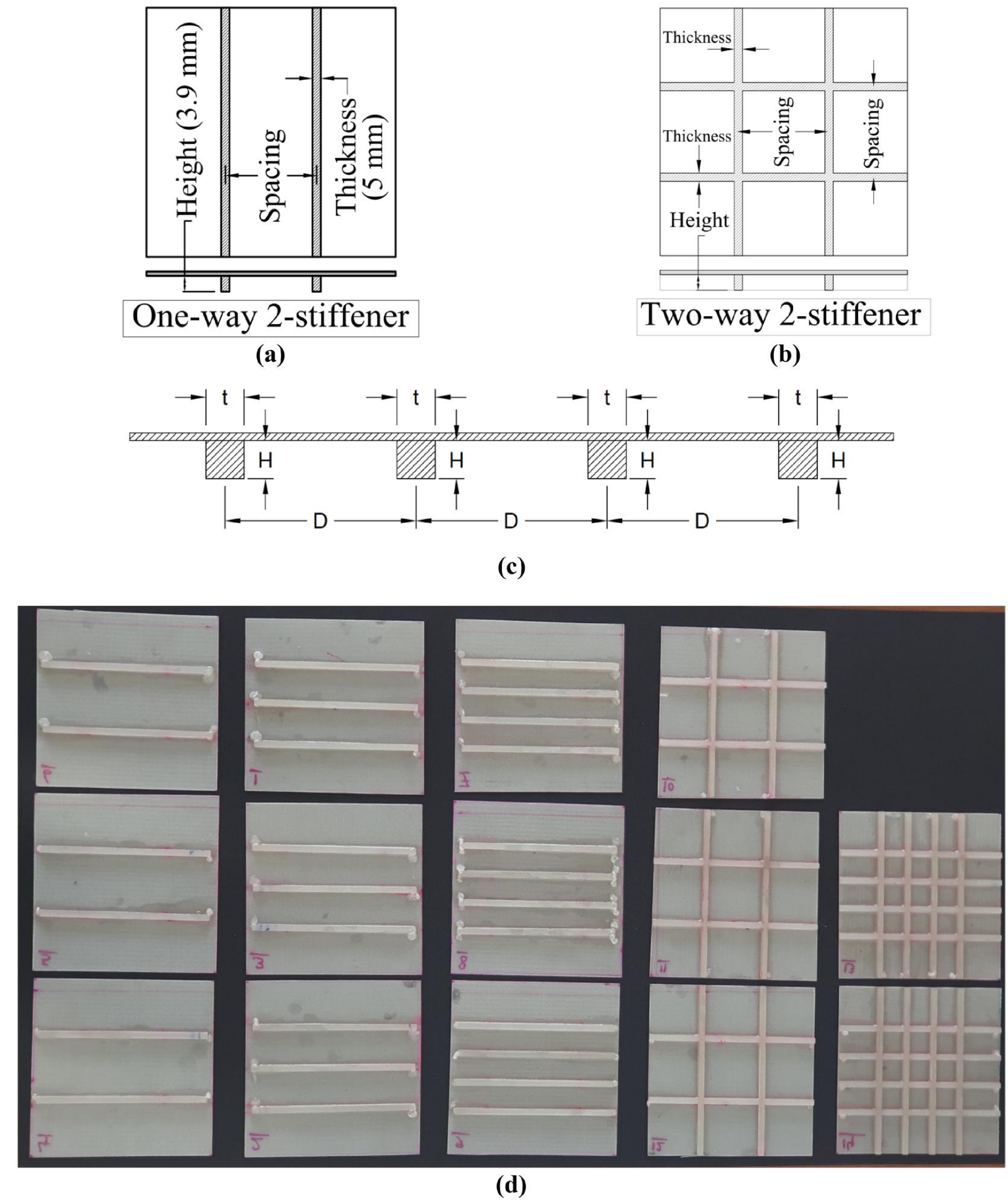


Figure 1. (a) & (b) The schematic view of the studied one-way and two-way specimens, (c) the geometrical parameters, and (d) the manufactured specimens before mechanical tests.

fabricated panels were subjected to a uniform pressure of 1.5 bar to eliminate voids and to enhance bonding quality. The panels were then left to cure for a duration of one week, allowing sufficient time for the resin to fully harden and achieve the desired mechanical properties. The entire production process was carried out at room temperature.

The final manufactured specimens featured a 150×150 mm face sheet with stiffeners measuring 5 mm in thickness and 3.9 mm in height, as depicted in Fig. 1. Additionally, the spacing

Table 1. The test matrix of experimental investigation.

Loading type	Stiffener spacing	No. of stiffeners	Stiffener arrangement	Purpose of experiment	Results section
Quasi-static	50 mm	2	One-way	Effect of spacing	3.1.1
	30 mm	3	One-way	Effect of spacing	3.1.1
	20 mm	4	One-way	Effect of spacing	3.1.1
	50 mm	2	Two-way	Effect of arrangement/spacing	3.1.1
	20 mm	4	Two-way	Effect of arrangement/spacing	3.1.1
Low-velocity impact	50 mm	2	One-way	Effect of spacing	3.1.2
	30 mm	3	One-way	Effect of spacing	3.1.2
	20 mm	4	One-way	Effect of spacing	3.1.2
	50 mm	2	Two-way	Effect of arrangement/spacing	3.1.3
	20 mm	4	Two-way	Effect of arrangement/spacing	3.1.3
	30 mm	3	One-way	Effect of impact location	3.1.4

between stiffeners is listed in Table 1. Figure 1 presents the schematic views of the specimens considered for the study, as well as the corresponding manufactured samples.

Two types of mechanical testing, namely quasi-static indentation and low-velocity impact tests were carried out. The quasi-static loading was applied using a universal testing machine (Zwick 50Tons, Germany), and the low-velocity behavior of specimens was experimentally investigated using a drop-weight apparatus (Figs. 2a and 2b). The indenters of both tests were spherical-ended cylinders with a 12.7 mm diameter (Fig. 2c). The target panels were clamped in a square fixture with internal dimensions of $100 \times 100\,\text{mm}^2$ (Fig. 2d). Furthermore, it is worth noting that in most drop-weight tests, the impactor was captured after the first impact on the specimens. In some specimens, to investigate the rebounding phenomenon (the results of which can be found in Section 3.1.3), the impactor was not captured after the first impact.

As shown in Fig. 2(d), the specimens are clamped by sandwiching them between two thick steel plates with square openings. Bolts are used to prevent the in-plane movement of the specimen within the fixture. The top plate and stiffeners were fully put in direct contact with the clamps to ensure prevention of in-plane movement. To further ensure this, the specimens were marked along the opening edges and checked after loading to confirm the prevention of in-plane movement. The primary output of the low-velocity impact test is the acceleration-time response. To measure this data, a piezoelectric accelerometer is securely mounted on the impactor, and the acceleration signal is recorded at a sampling rate of 96 kHz. The deflection history of the specimen is determined by applying the principle of energy conservation throughout the impact. This is achieved by numerically integrating the recorded acceleration data twice over time while considering the initial velocity of the impactor. Additionally, the absorbed energy history—representing the amount of energy transferred from the impactor to the specimen—is calculated by performing a further integration of the impact load with respect to the measured deflection.

To investigate the effect of geometrical parameters on the mechanical behavior of stiffened composite panels, stiffened panels with different spacings between stiffeners (two stiffeners with 50 mm spacing, three stiffeners with 30 mm spacing, and four stiffeners with 20 mm spacing) and different arrangements (one-way and two-way) were manufactured. The information regarding the experimental test matrix and the number of sections where the results were studied can be found in Table 1.

2.2. Numerical modeling

Numerical modeling was carried out using the double precision mode of the commercial finite element (FE) program LS-DYNA. The finite element mode builder (FEMB) was used to generate the models and nonlinear dynamic analysis was carried out using LS-DYNA solver.

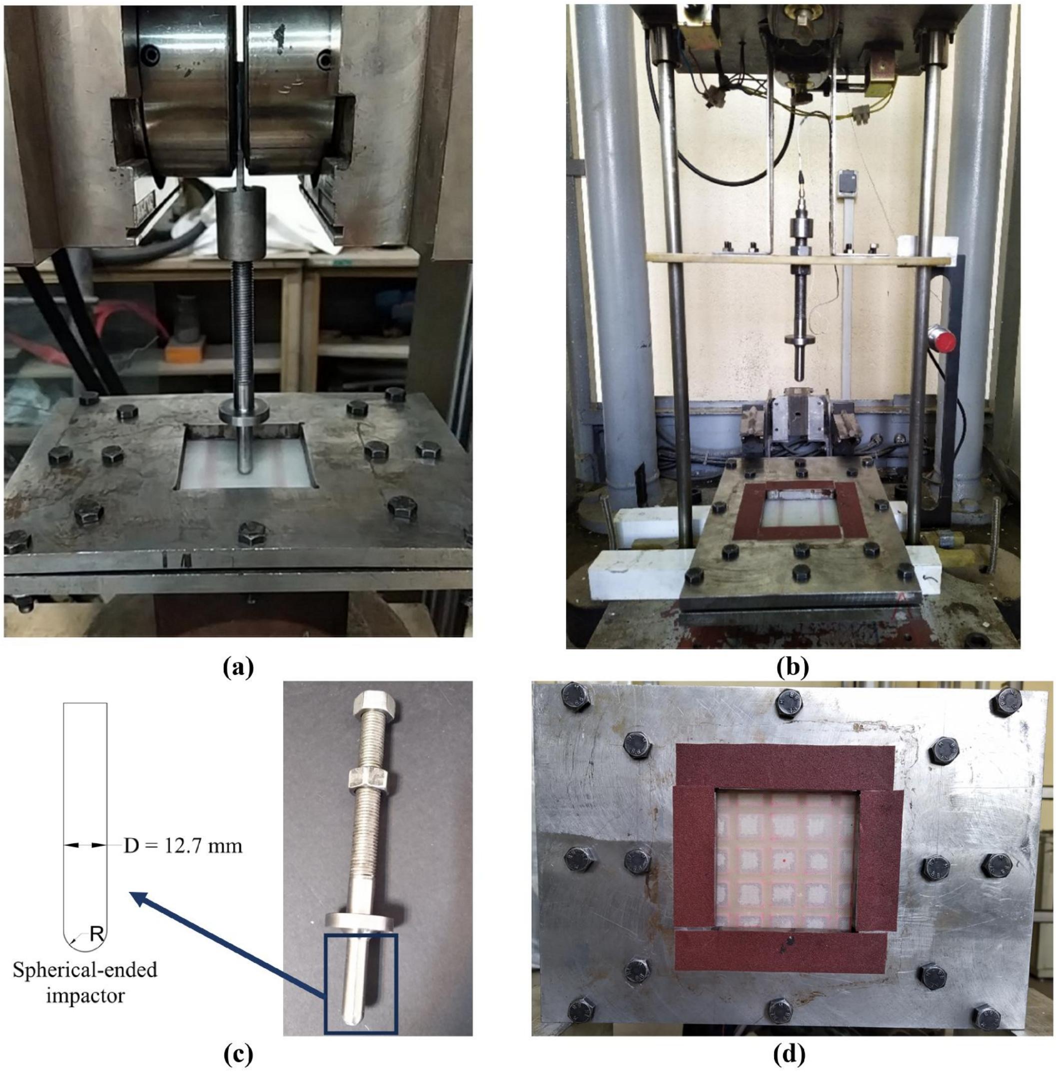


Figure 2. (a) Quasi-static test setup, (b) low-velocity impact test setup, (c) the indenter, and (d) the clamping fixture. The bolts do not penetrate the specimens, and the stiffeners run into the clamps.

In addition to modeling the stiffened plates, some sandwich panels were also modeled for the stiffened plate/sandwich structure equivalency study of this research (the results of which can be found in Section 3.3), and which will be referred to equivalency study in the remainder of this paper.

For the equivalency study, symmetrical sandwich panels featuring orthotropic composite face sheets and cores made of polyvinyl chloride (PVC) foam were modeled. The dimensions of the glass fiber reinforced epoxy panels used in the face sheets were $80 \times 80 \times 1\,\text{mm}^3$, their layup sequence was [0°/90°/0°/90°], and a 10-mm-thick high temperature resistant polyvinyl chloride foam core (Divinycell® PVC HT-110) was used for the purpose of comparison with the available literature (Shokrieh and Fakhar 2012). The size and layup of the face sheets in the equivalent stiffened plates were kept the same as those in the sandwich panel (i.e., $80 \times 80\,\text{mm}^2$ in-plane dimension).

The material model MAT_ENHANCED_COMPOSITE_DAMAGE was used to model the mechanical behavior of the composite in the stiffened plates as well as the face sheets of the

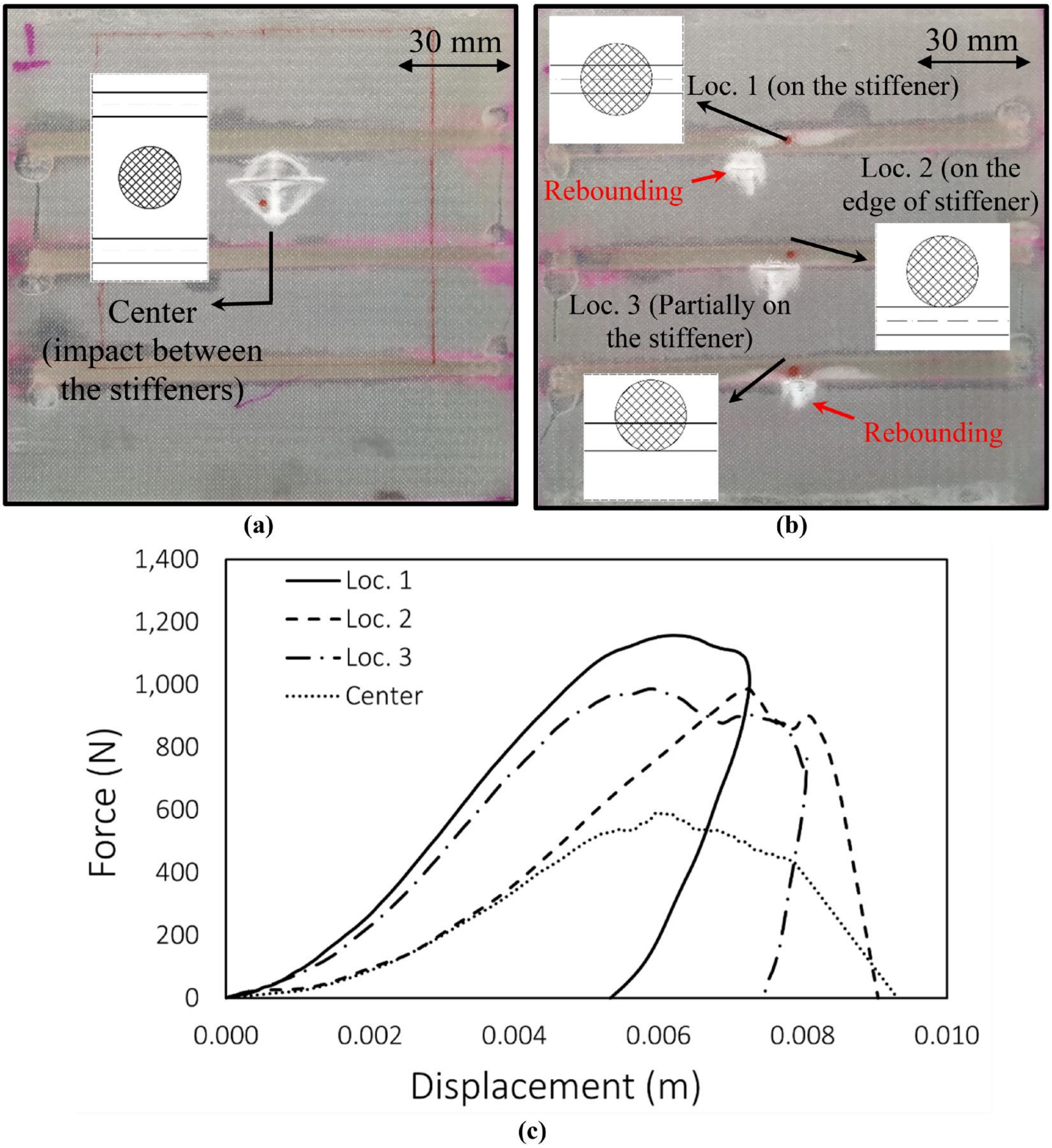


Figure 8. The location of impactors on the stiffened plate: (a) between the stiffeners, (b) directly on or near to the stiffeners, and (c) the force-deflection curves of the stiffened plate with different impactor location under low-velocity impact. The areas outside of the red marked contour in (a) were clamped.

sandwich panel. This model was chosen due to its enhanced capability to model fibrous composites, providing more accurate damage predictions based on the literature (Dhakal et al. 2019; Liu, Zhang, and Ye 2017; Sadighi et al. 2023). The concept of this material model is a set of stress-based failure criteria for the fiber and matrix under tensile, compressive, and/or in-plane shear loadings. The failure behavior of the composite plates was described by the Chang-Chang damage model (Dhakal et al. 2019; Liu, Zhang, and Ye 2017; Shokrieh and Fakhar 2012). This material model exhibits linear elastic behavior until the elements reach their yield strengths. In addition to tensile and compressive fiber failure, the matrix failure mode is also considered. Failure occurs when any of the following criteria are satisfied.

Fiber failure occurs when:

$$e_f^2 = \left(\frac{\sigma_{11}}{S_{XL}}\right)^2 + \beta\left(\frac{\sigma_{12}}{S_c}\right) - 1 \geq 0 \tag{1}$$

The matrix fails under tensile stress when:

$$e_m^2 = \left(\frac{\sigma_{11}}{Y_t}\right)^2 + \left(\frac{\sigma_{12}}{S_c}\right)^2 - 1 \geq 0 \tag{2}$$

and fails in compression when:

$$e_d^2 = \left(\frac{\sigma_{22}}{2S_c}\right)^2 + \left[\left(\frac{Y_c}{2S_c}\right)^2 - 1\right]\frac{\sigma_{22}}{Y_c} + \left(\frac{\sigma_{12}}{S_c}\right)^2 - 1 \geq 0 \tag{3}$$

In the above equations, σ_{11} and σ_{12} are the normal and shear stresses, S_{XL} is the longitudinal strength ($S_{XL} = X_t$ in tension and $S_{XL} = X_c$ in compression), S_c is the shear strength, and β is the weighting factor for shear term in tensile fiber mode. And Y_t is the transverse tensile strength and Y_c is the transverse compressive strength.

The crushing behavior of the foam core was represented by the material model MAT_CRUSHABLE_FOAM. This model requires the main material characteristics as well as the experimental stress-strain curve in compression as input which were obtained by data sheets provided by Divinycell® (Rajaneesh, Sridhar, and Rajendran 2014). It should be noted that the impactor used for the validation and equivalency study simulations were steel hemispherical-ended cylinders. The material model MAT_RIGID was used to model the behavior of the steel impactor and the material properties were derived from literature (Bayat, Mashhadi, and Rahmani 2018; Shokrieh and Fakhar 2012).

However, another main goal of this study was the response of stiffened plates to ice impactors for which ice sphere was used as impactors in parametric studies. Smoothed particle hydrodynamics (SPH) method was used to model the ice impactor, and the constants of the equation of state (EOS) were taken from the work by Carney et al.'s (2006). Instead of a mesh system, the SPH method makes use of particles alongside a smooth weighting function (kernel) to calculate variable gradients for parameters (Wu et al. 2021; Hedayati and Ziaei-Rad 2014). The value of an arbitrary function A for a particle i can be approximated by

$$\langle A_i \rangle = \sum_j V_j A_j W_{ij} \tag{4}$$

where $V_j = \frac{m_j}{\rho_j}$ is each particle's set fluid volume, $W_{ij} = W_h(r_i - r_j, h)$ is a smooth kernel function, and h is the smoothing length, which determines the influence region of W (Sadighi et al. 2023). As it can be seen in Fig. 3, the value of a property at the point of interest is calculated by integrating the values of the property of the nearby particles, which are weighted by the kernel function. The SPH method offers several advantages over conventional numerical approaches for fluid flow modeling, such as the Lagrangian and Arbitrary Lagrangian-Eulerian (ALE) methods. First, because the material is not discretized using continuous elements, issues like element distortions (mesh tangling) are eliminated, thereby avoiding associated solution problems. Second, unlike the ALE method, which requires a large number of parameters to achieve satisfactory results, the SPH method involves a more limited set of influencing parameters, simplifying the modeling process.

The SPH ice impactor used in this study consisted of 2,176 particles with a 1.88 mm spacing between them. The PLASTICITY_COMPRESSION_TENSION material model and TABULATED_COMPACTION EOS were employed to simulate the behavior of the ice impactor. Table 2 lists the values of the material constants used for each component.

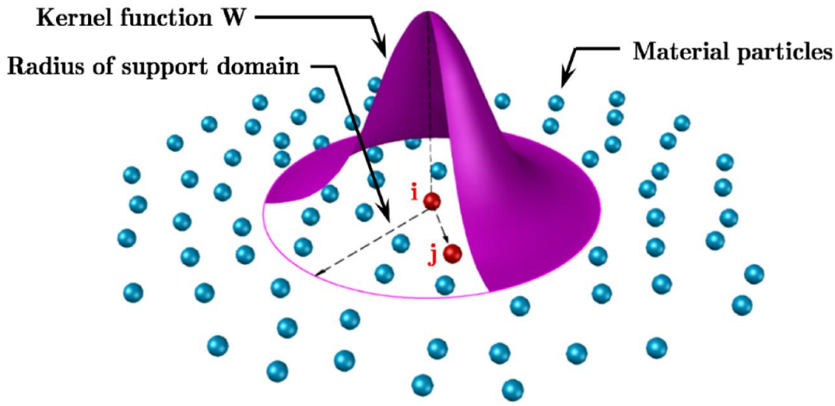


Figure 3. The SPH method definition (Sadighi et al. 2023).

Table 2. The material properties used in the FE model.

Material	Value
Composite face (Shokrieh and Fakhar 2012)	$\rho = 1700\,kg/m^{3,}$ $E_{11} = 17\,GPa$, $E_{22} = 17\,GPa$, $E_{13} = 4\,GPa$, $E_{23} = 4\,GPa$ $\nu_{12} = \nu_{21} = 0.046$, $\nu_{23} = 0.2$ $X_T = 250\,MPa$, $X_C = 250\,MPa$, $Y_T = 204\,MPa$, $Y_C = 204\,MPa$ $S_{xy} = 250\,MPa$, $S_{xz} = 250\,MPa$, $S_{yz} = 250\,$ Mpa
PVC foam (Shokrieh and Fakhar 2012)	$\rho = 110\,kg/m^3$ $E_c = 180\,GPa$, $G_c = 50$ Gpa, $\nu_c = 0.021$ $q_c = 2.1\,MPa$, $\tau_c = 1.6$ Mpa
Ice impactor (Sadighi et al. 2023)	$\rho = 897\,kg/m^3$, $E = 9.31\,GPa$, $\nu = 0.33$, $P_{cut-off,tensile} = 0.433\,MPa$ $P_{cut-off,compression} = 4.93\,MPa$
Steel impactor (Shokrieh and Fakhar 2012)	$\rho = 7850\,kg/m^3$, $E = 210\ GPa$, $\nu = 0.3$

It should be noted that in this study, we investigated the quasi-static and low-velocity regimes of the composite material, and the effect of the strain rate on the material's response was not taken into account due to the low loading rate of the quasi-static test (Fathi, Liaghat, and Sabouri 2021) and the low level of impact energy in the low-velocity test (Fathi, Liaghat, and Sabouri 2021; Zhu and Yu 2023). Therefore, we did not consider the strain rate effect on the composite material's behavior in this study. On the other hand, our previous study showed that the behaviour of ice impactors is dependent on the strain rate even in the low-velocity regime. Therefore, we incorporated the strain rate in the ice model based on the strain rate properties reported in (Sadighi et al. 2023).

3. Results

3.1. Experimental results

Quasi-static indentation loading exhibits similarities to low-velocity impacts (Fathi, Liaghat, and Sabouri 2021; Fathi et al. 2021). Hence, the quasi-static and low-velocity behavior of stiffened plates are presented and discussed in the following sections.

3.1.1. Quasi-static indentation of stiffened plates

To gain insight about the energy absorption characteristics of the specimens and to determine energy levels for impact testing, the stiffened panels were subjected to a quasi-static indentation test prior to the impact tests. This test involved applying a loading rate of 3 mm/min. It should be noted that the panels used in the low-velocity impact tests had the same material and dimensional configurations (similar length and width, and also identical clamp) as those used in the quasi-static loading tests. Figure 4 shows the schematic force-displacement curve (a) and the results of the one-way (b) and two-ways stiffened plates (c) under quasi-static indentation loading. Upon closer look at the load-displacement curves, it is evident that the overall shapes of the curves are analogous, indicating similarities in the failure modes.

Figure 4(a) depicts that the load-displacement curves can be divided into four regions. The mechanical behavior of the stiffened plates when subjected to quasi-static test, as well as the failure modes and damage mechanisms in each zone, are described here. In the first region, the indenter makes its initial contact with the panel. The small fluctuations in this region can be attributed to micro-fiber breakages and micro-cracks due to the indentation of the indenter. The second region starts after the load shows a slight decrease in its value, indicating the onset of delamination. In the third region, the compressive load applied by the indenter reaches its peak. Once the load reaches its maximum value, failure occurs in the specimen, accompanied by the initiation of indenter perforation. During the fourth region, the formation of petal-like patterns becomes evident, which is followed by complete perforation of the indenter through the panels. Notably, shear mode is the dominant failure mechanism in this region. As the indenter penetrates through the specimens, the strength of the panels gradually diminishes, leading to a sudden drop in the applied load, ultimately reaching the endpoint of the curve.

As it can be seen in Figs. 5(a)–5(e), the stiffeners have prevented the growth of cracks and have increased the strength and stiffness of the panel. By comparing the behavior of one-way stiffened plates under quasi-static load in Fig. 4(a), it can be said that by increasing the number of stiffeners, the maximum load and stiffness increased, and the maximum deflection and damage

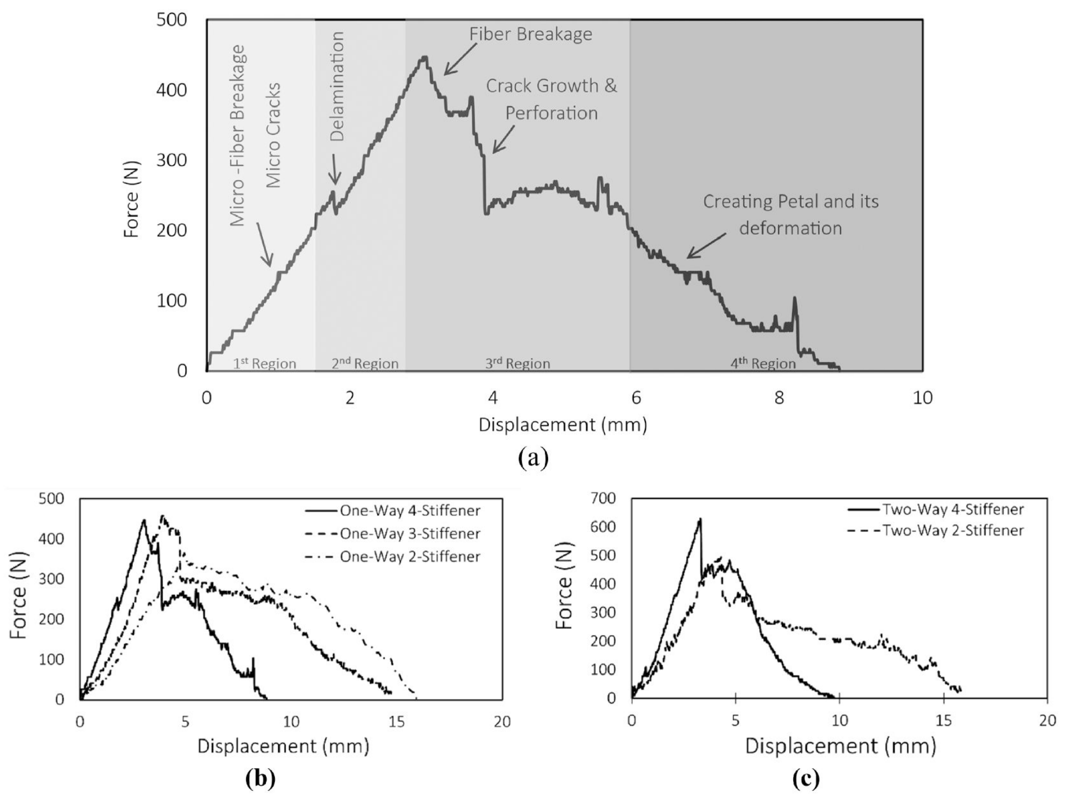


Figure 4. (a) Classification of quasi-static indentation behavior of stiffened plates, (b) force-displacement curves of quasi-static indentation tests for one-way stiffened plates, and (c) two-way stiffened plates.

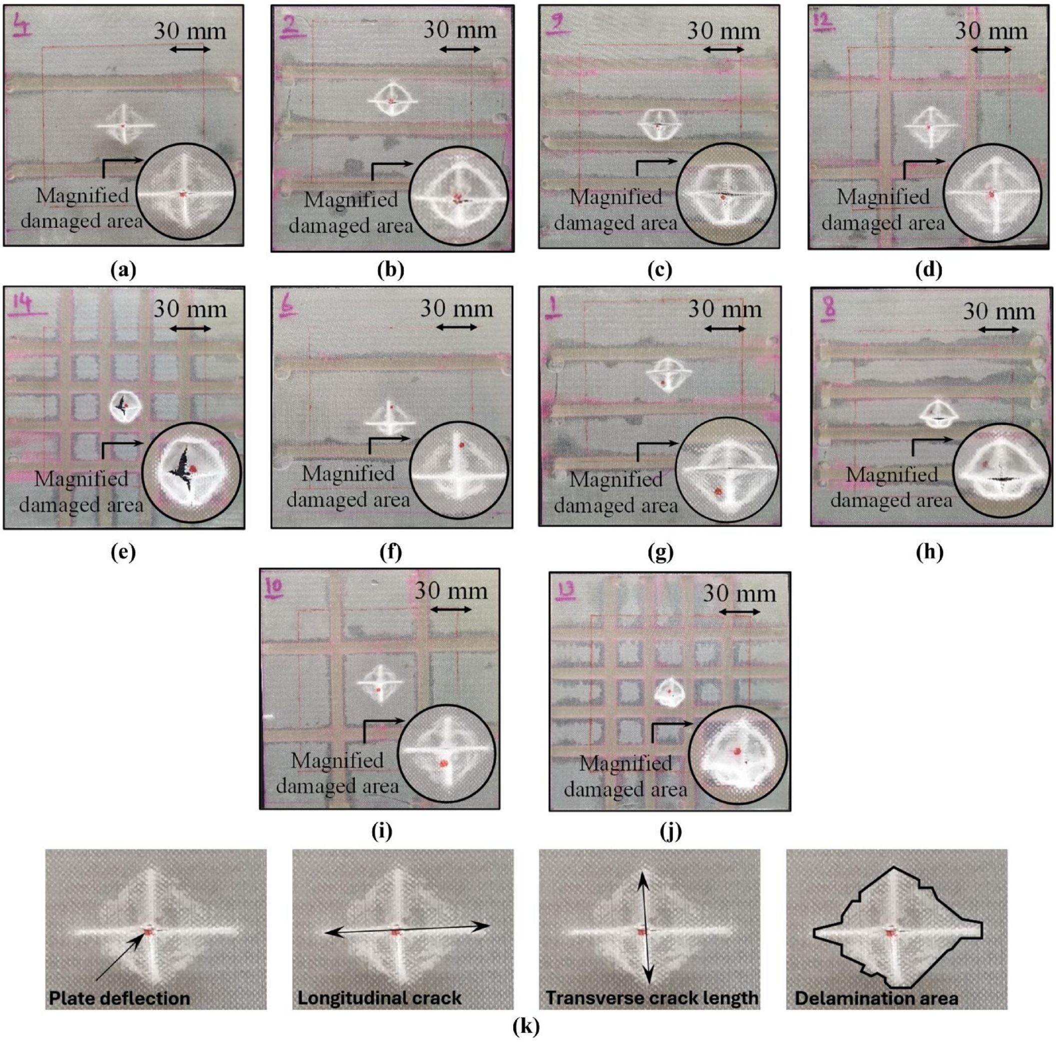


Figure 5. Damage morphologies of (a) quasi-static indentation of one-way 2-stiffener, (b) quasi-static indentation of one-way 3-stiffener, (c) quasi-static indentation of one-way 4-stiffener, (d) quasi-static indentation of two-way 2-stiffener, (e) quasi-static indentation of two-way 4-stiffener, (f) low-velocity impact of one-way 2-stiffener, (g) low-velocity impact of one-way 3-stiffener, (h) low-velocity impact of one-way 4-stiffener, (i) low-velocity impact of two-way 2-stiffener, (j) low-velocity impact of two-way 4-stiffener panels. (k) The fracture parameters: transverse deflection (not visible from this direction), longitudinal crack length, transverse crack length, and delamination area.

area decreased. For instance, by increasing the number of stiffeners from 2 to 3 in one-way stiffened samples, the damage area decreased by 19.5% (Figs. 5b and 5c) and the maximum tolerable load is increased by 26.9% (Fig. 4(b)). This improvement can be attributed to the additional support provided by the stiffeners, which helps distribute the applied load more evenly and restricts the growth of cracks. In addition, by changing the arrangement of the stiffeners from one-way to two-way, the damage area and the propagation of delamination were significantly reduced. The two-way arrangement offers a more uniform distribution of stiffness, which effectively constrains the crack propagation in multiple directions. Figures 5(d) and 5(e) illustrate that the damage areas in the two-way stiffened plates were smaller compared to one-way plates due to the additional restrictions they put on crack growth paths. This indicates that the two-way stiffened plates are more effective in mitigating damage and enhancing the structural integrity of the panels. It should be mentioned that, in all tested samples, no visible debonding between stiffeners and the plate occurred.

3.1.2. Low-velocity impact test of stiffened plates

The specimens were subjected to a low-velocity impact with an energy level of 4.7 J. As suggested by other works (Fathi, Liaghat, and Sabouri 2021; Fathi et al. 2021), to ensure that perforation would occur in all specimens, we used an impact energy 2.5 times higher than the maximum indentation energy required in the quasi-static loading. The damage morphologies of specimens are shown in Figs. 5(f)–5(j). Figure 6 compares force-deflection curves of the considered one-way and two-way stiffened plates. In addition, the absorbed energy, maximum load, and maximum deflections are reported in Figs. 7(a)–7(c). It is worth noting that the maximum deflections were recorded where the load reached its maximum value.

Based on the results, several conclusions can be made. Increasing the number of stiffeners and reducing the spacing between them had positive effects on the plate's performance. Specifically, reducing the distance from 50 mm (i.e., 2 stiffeners) to 30 mm (i.e., 3 stiffeners) in one-way stiffened plates resulted in a 10% increase in the maximum tolerable load (Fig. 7c) and a 31% improvement in energy absorption capability (Fig. 7a). Moreover, the maximum displacement

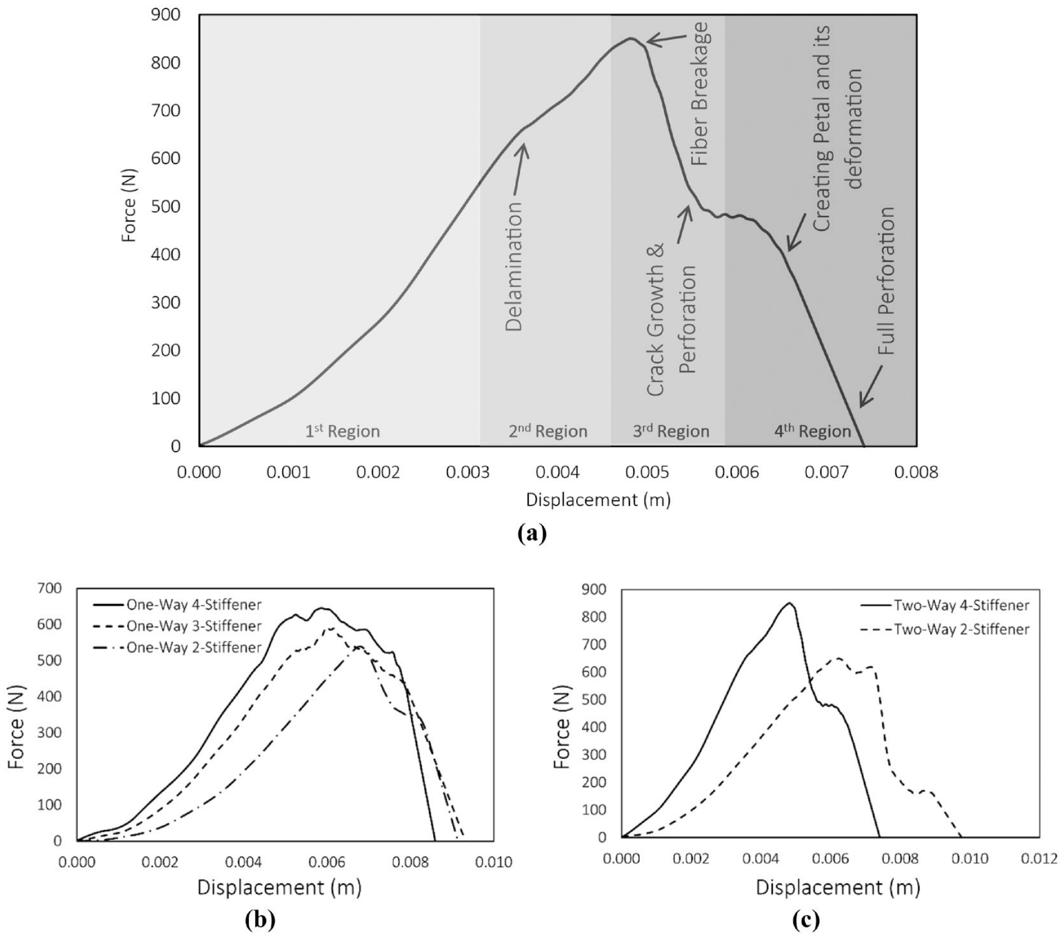


Figure 6. (a) Classification of low-velocity impact behavior of stiffened plates, (b) force-displacement curves of low-velocity impact tests for one-way stiffened plates, and (c) two-way stiffened plates.

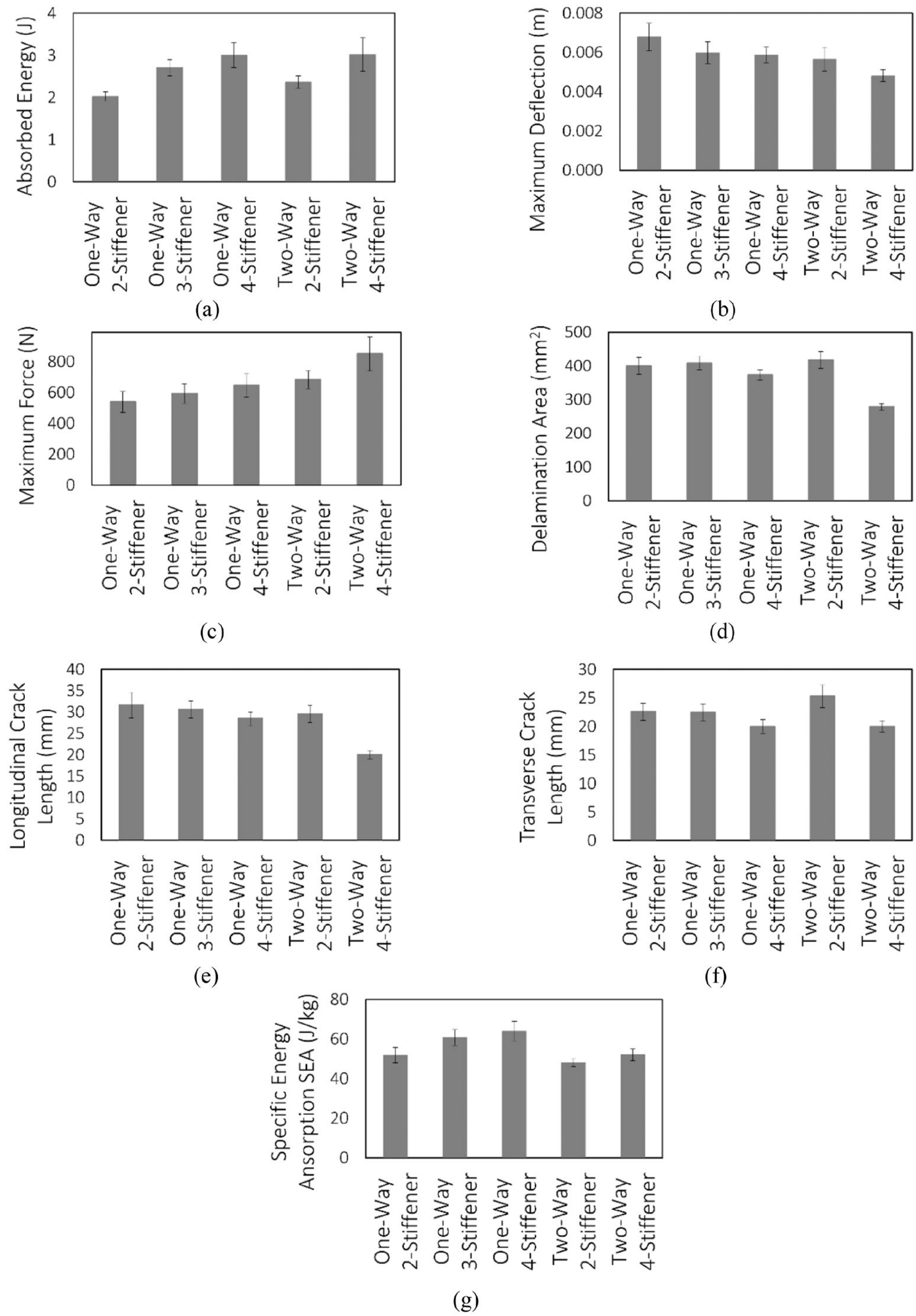


Figure 7. The failure parameters analysis of one-way and two-way stiffened plates under low-velocity impact test: (a) absorbed energy, (b) maximum deflection, (c) maximum force, (d) delamination area, (e) longitudinal crack length, (f) transverse crack length, and (g) specific energy absorption.

decreased by 13% (Fig. 7b). Similar trends were observed when increasing the number of stiffeners from three to four. In this case, there was a 9% increase in maximum force (Fig. 7c), and a 11% increase in energy absorption capability (Fig. 7a) for one-way samples. Therefore, decreasing the spacing from 50 mm to 30 mm had a higher effect as compared to decreasing the spacing from 30 mm to 20 mm. It is important to note that the mass of the specimens increased by 14.8% and 13% for the aforementioned cases, respectively. When the specific energy absorption (SEA) of the samples is compared (Fig. 7g), it becomes evident that increasing the number of stiffeners on energy absorption outweighs the effect of increased mass. Moreover, compared to laminates with two-way stiffeners, the laminates with one-way stiffeners, demonstrate superior SEA value.

In two-way stiffened plates, increasing the number of stiffeners from two to four resulted in a significant weight increase of the sample (43%). Simultaneously, the load-carrying capacity and energy absorption capabilities increased by 25% and 19%, respectively. The increased number of stiffeners and reduced spacing between them enhance the structural integrity of the plates by providing additional support and distributing the impact forces more evenly. This results in a higher load-carrying capacity and improved energy absorption capabilities. Additionally, the impact test revealed a reduction in maximum displacement and damage area (Fig. 7).

Based on the observation, there was no separation or debonding between the stiffeners and the plate, and by examining the damage morphologies of the specimens presented in Figs. 5(f)–(j), it becomes evident that plates with a higher number of stiffeners exhibited significantly reduced damage area and delamination propagation. For instance, the one-way samples with four stiffeners had in average 7.9% less delamination area compared to similar cases with two-stiffener. Furthermore, the crack propagation path was mainly restricted to the direction parallel to the stiffeners, with limited propagation in the transverse direction. This trend aligns with the observations from the quasi-static indentation test.

In the case of two-way stiffened plates, the crack growth path exhibited symmetry, hence the damage area expanded radially. On the other hand, in the specimen with four stiffeners, noticeable separation between the stiffeners and the plate occurred. We hypothesize that the integrated fabrication of the specimen could have mitigated this failure. The failure geometry, owing to the symmetry in the arrangement of stiffeners, closely resembled a circle, with the longitudinal and transverse cracks exhibiting similar sizes. The observed reduction in maximum displacement and damage area with increased stiffener count can be attributed to the stiffeners' ability to constrain the deformation and limit the propagation of cracks. This effect is more pronounced in two-way stiffened plates due to the symmetrical arrangement of stiffeners, which provides uniform resistance to impact forces.

By analyzing the specimens' behavior during loading, several observations can be made from the load-displacement diagrams (such as the one shown in Fig. 6a) for the one-way 4-stiffener plate. As the load increased before reaching the peak point (at around 3 mm displacement), changes in the slope of the graph indicated the occurrence of layer separation within the sample, leading to progressive damage until full penetration. At the peak force, the sample experienced cracking and fracture, with the crack starting to propagate and grow until reaching complete penetration (the endpoint of the diagram). This behavioral pattern was observed across all samples.

Inspecting the geometry of the delaminated areas in more detail can give good insights into the effect of the stiffeners and their mechanical effect. Therefore, the dimensional characteristics of damage extent can be summarized into the following four parameters (Fig. 5k):

- Plate deflection,
- Longitudinal crack,
- Transverse crack,
- Delamination area.

The mentioned parameters for specimens with one-way and two-way arrangements under low-velocity impact are calculated and shown in Figs. 7(d)–7(f). Observing the damages imposed on the one-way specimens under quasi-static (Figs. 5a–5c) and low-velocity impact (Figs. 5f–5h) shows that the crack growth in the direction perpendicular to the stiffeners (i.e., the transverse crack) was limited due to higher resistance caused by the presence of the stiffeners in this direction. Additionally, by reducing the distance between the stiffeners, the delamination area and crack growth extent (in both longitudinal and transverse directions) were decreased. In the one-way specimens, the damage in all the three plates had a diamond shape.

On the other hand, according to the reported damage parameters (Fig. 6) and the failure shape (Fig. 5) of two-way stiffened plates, it becomes apparent that the damage areas of the two-way stiffened plates were smaller compared to their corresponding one-way panels. Upon comparing the shape and damage geometry of the plates, it becomes evident that in the two-way stiffened plates, the symmetric arrangement of the stiffeners results in a failure area that closely resembles a circle. It can be argued that the symmetric presence of restrictors in the form of stiffeners in 2-way samples resulted in more uniform crack propagation within the specimens compared to that in the one-way stiffened plates, creating a circular-shaped delamination area in the former versus an oval shape delamination area in the latter. Figure 5 indicates that the minimal distance required for transitioning from an oval damage area to a circular one was approximately 10 mm in our specimens.

Regarding the effect of number of stiffeners, overally, it can be said that in both the one-way and two-way stiffened plates, increasing the number of stiffeners (i.e., decreasing the stiffener spacing) decreased the delamination area, longitudinal crack length, and transverse crack length, especially when the number of stiffeners increases from three to four (Figs. 7d–7f).

Another notable aspect to consider is the effect of stiffener arrangement. Comparing the one-way 4-stiffener and two-way 2-stiffener plates provides insights into the influence of stiffener arrangement while maintaining *similar mass* and the *same number of stiffeners*. Upon comparing the reported parameters from the previous sections, it becomes apparent that the maximum force experienced in the specimen with a two-way stiffener arrangement was higher compared to the one-way specimen (Fig. 7c). Furthermore, the damage area in the two-way arrangement exhibited greater extent (see Figs. 5i and 5j). However, the one-way arrangement demonstrated 7% higher energy absorption capability (Fig. 7a), which can be attributed to the proximity of the impactor to the stiffeners in the one-way 4-stiffener arrangement. These findings suggest that while the two-way arrangement provides better load distribution and higher maximum force, the one-way arrangement offers superior energy absorption, which could be advantageous in applications where energy dissipation is critical.

3.1.3. The impact location effect

The location of low-velocity impact on stiffened plates plays a crucial role in the imposed failure and damage on samples. In this section, various impact positions were considered for the impactor, including one between the stiffeners (Fig. 8a), and others directly on or near to the stiffeners (Fig. 8b). Hence, four types of impact locations were examined:

1. Impact between the stiffeners (Fig. 8a)
2. Direct impact on the stiffener (location 1 in Fig. 8b)
3. Impact on the edge of the stiffener (location 2 in Fig. 8b), and
4. Impact partially tangent to and partially on the stiffener (location 3 in Fig. 8b)

It is important to note that the occurrence of failure in the lower part of impact location 1 and location 3 in Fig. 8(b) was caused by the rebound impact of the impactor on another point of the specimen, a topic that is not discussed in this paper. It must be noted the rebound force was not measured and hence is not considered in the comparisons. The load-displacement graphs are compared in Fig. 8(c), and comparison of delamination area, maximum force, maximum displacement, and absorbed energy is presented in Fig. 9.

Based on the reported results, it is evident that when the impactor directly hits the stiffeners or its side, the damage area and crack propagation decrease substantially. This can be attributed to the stiffeners' ability to distribute the impact energy more effectively, thereby reducing localized damage. The same observations were reported in the literature (Yu et al. 2023). In this scenario, the sample exhibited the highest load-carrying capacity (Fig. 9). It can be concluded that the maximum force sustained by the sample is influenced by the plate's stiffness (Sharif-Khodaei, Ghajari, and Aliabadi 2012; Yu et al. 2023). The increased stiffness enhances the load-carrying capacity of the plate, as evidenced by the higher maximum force sustained. In contrast, impacts at intermediate regions, such as between the stiffeners, result in larger damage areas and greater crack propagation. This is likely due to the lack of additional support in these areas, leading to higher strains and more extensive damage. When the impact is tangent to the stiffener (location 3), the panels exhibit greater flexibility and higher energy absorption (Fig. 9b). This behavior can be explained by the partial engagement of the stiffener, which allows for more deformation and energy dissipation compared to direct impacts. These findings have significant implications for the design of stiffened plates in various applications. For instance, in aerospace and automotive industries, optimizing the placement and design of stiffeners can enhance the impact resistance and overall structural integrity of components.

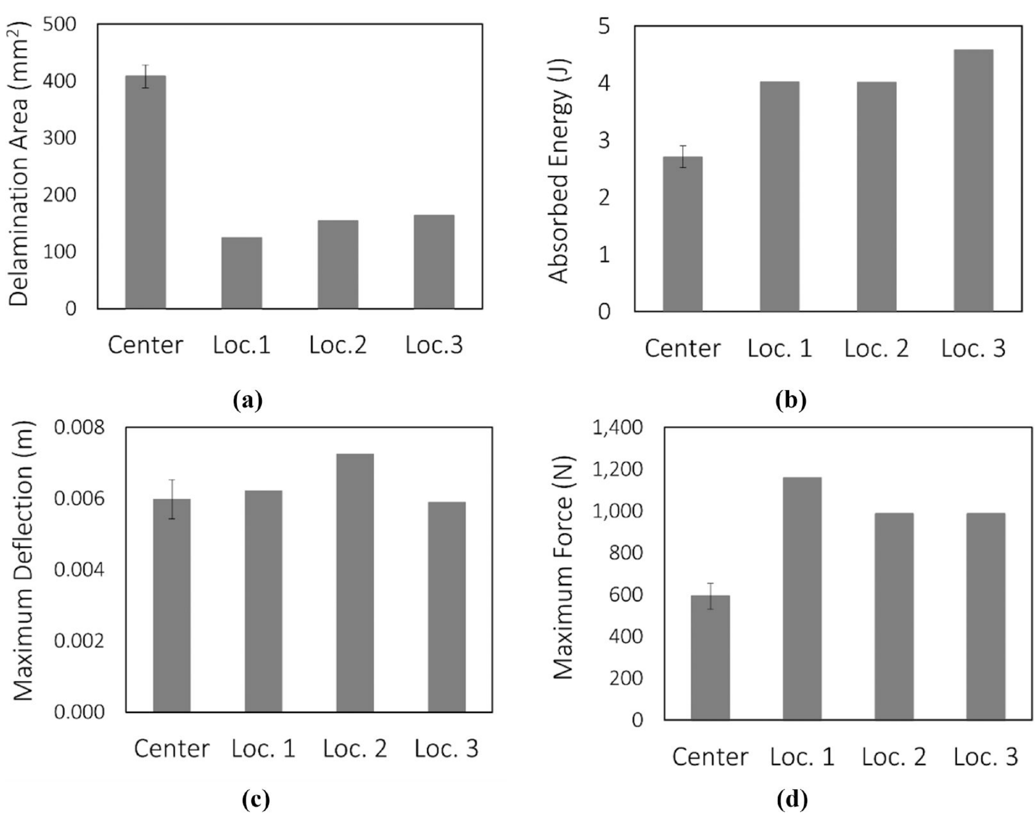


Figure 9. The failure parameters analysis of stiffened plate with different impactor location: (a) delamination area, (b) absorbed energy, (c) maximum deflection, and (d) maximum force.

3.1.4. Comparison between quasi-static and low-velocity impact tests

Upon comparing a similar panel, specifically a one-way 2-stiffener plate, subjected to both quasi-static indentation testing and low-velocity impact loading, several observations can be made. First, when considering an amount of energy equal to energy required for perforation in quasi-static loading (3.4 J), the damage level in the sample under low-velocity impact was significantly lower than in the sample undergoing quasi-static indentation (compare Figs. 10(a) and 10(b)). The lower damage level under low-velocity impact can be attributed to the dynamic nature of the loading, which allows for more energy dissipation through mechanisms such as wave propagation and material inertia. Furthermore, as the impact energy increased, it can be observed that the damage area gradually approached the failure area observed in the quasi-static indentation test. This indicates that higher impact energies can overcome the dynamic effects, leading to similar damage patterns as quasi-static loading. Upon comparing Figs. 10(c) and 10(a), it becomes evident that the failure areas were quite similar. However, the impact energy was approximately 40% greater than the quasi-static perforation energy.

As illustrated in Fig. 10(c), when the load-deflection curves of specimens (one-way and two-way 2-stiffener panels) subjected to quasi-static and low-velocity impact conditions are examined, it is evident that, in line with established literature expectations (Fathi, Liaghat, and Sabouri 2021; Fathi et al. 2021; Nettles and Douglas 2000), the curves exhibit relatively similar trends. This suggests that the quasi-static behavior can be a good indicator of how the corresponding low-velocity

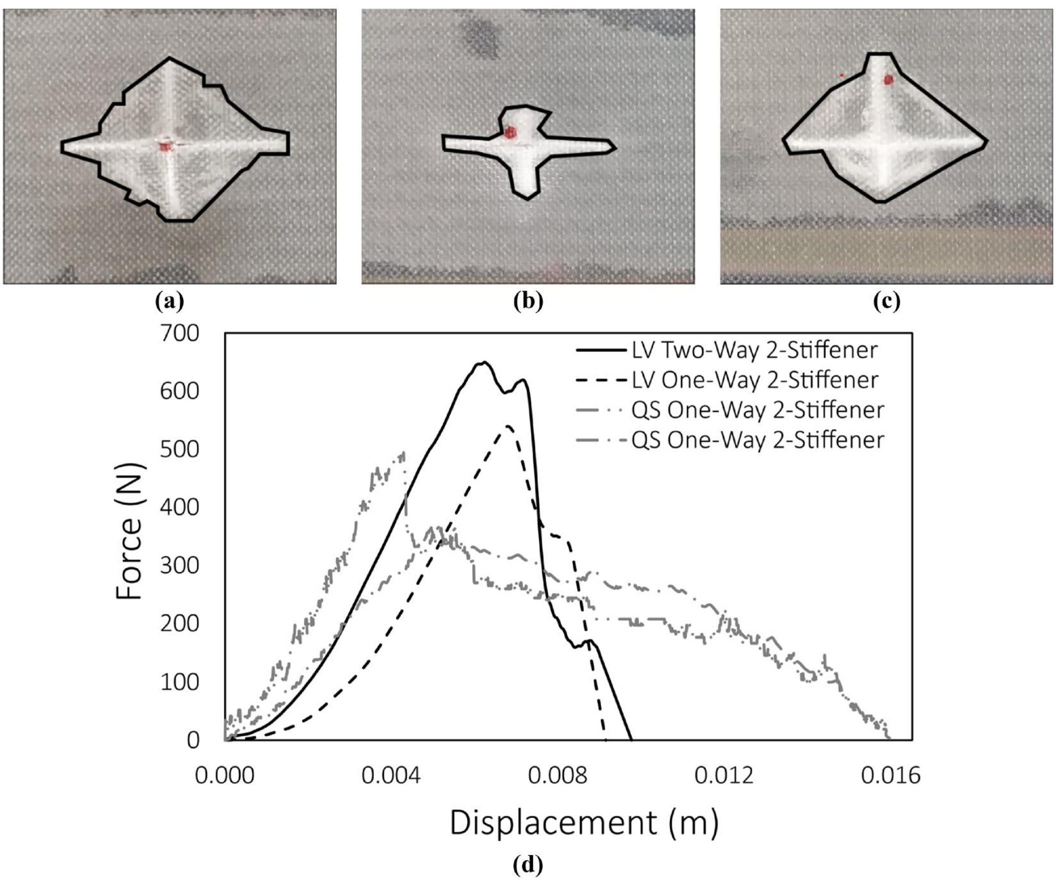


Figure 10. The delamination area of stiffened plate (a) under quasi-static indentation, (b) 3.4 J low-velocity impact, (c) 4.7 J low-velocity impact tests, (d) comparing the load-deflection curves of samples under quasi-static (QS) and low-velocity (LV) impact tests.

impact behavior should be like (Nettles and Douglas 2000). The plateau region observed in the force-displacement curves under quasi-static loading suggests a period of stable crack propagation, whereas the symmetrical curves under low-velocity impact indicate a more uniform distribution of forces throughout the penetration process. It is worth noting that the force-displacement curves of the specimens under quasi-static loading demonstrates a plateau region in the second half of the penetration, while the corresponding curves for low-velocity curves were relatively symmetrical (Bull, Spearing, and Sinclair 2015). Importantly, it should be emphasized that the initial stiffness of the samples against penetration is relatively close for both loading types.

These findings suggest that quasi-static tests can serve as a useful approximation tool for predicting the behavior of stiffened plates under low-velocity impacts, which is valuable for preliminary design and testing in engineering applications.

3.1.5. Experiment limitations and comparison with the other impact mitigation techniques

In recent years, various impact mitigation techniques have been developed to improve the energy absorption and damage resistance of composite structures. State-of-the-art methods include the use of hybrid composite materials (Safri et al. 2018), auxetic structures (Hedayati, Sadighi, and Gholami 2025), and advanced sandwich panels with specialized core materials (Schäfer, Nestler, and Kroll 2024; Yungwirth et al. 2011). These techniques focus on enhancing the energy dissipation capacity, improving delamination resistance, and optimizing the structural integrity of composites under dynamic loading conditions. In comparison, the current study investigates stiffened composite plates, which have gained attention for their potential to improve structural stiffness and strength while maintaining low weight. The stiffened panel approach offers a solution for improving impact resistance by strategically enhancing local stiffness in targeted areas. The addition of local stiffness in specific regions of the plate enables an efficient distribution of stress, which helps in absorbing and dissipating impact energy more effectively, ultimately enhancing the overall performance of the structure under dynamic loading conditions. Moreover, by incorporating stiffeners, it becomes possible to explore the equivalent behavior of stiffened plates to sandwich panels, while benefiting from a visible core that allows for the detection of potential defects, unlike the hidden cores in traditional sandwich panels.

Although this study aimed to provide new insights into the mechanical behavior of stiffened composite plates, there are several limitations that must be considered. First, the sample size used in the experiments was relatively small, and the results may not fully capture the variability that would be observed in a larger sample, particularly for aerospace applications. Expanding the sample size in future studies could enhance the generalizability of the findings. Additionally, while efforts were made to ensure the internal and external validation and repeatability of the experiments, the tests were conducted under controlled laboratory conditions, which may not fully represent real-world environmental factors such as temperature variations, humidity, and long-term loading conditions. As such, the findings of this study should be reexamined under different environmental conditions. The study also focused on specific geometrical configurations of stiffeners, which may not encompass all potential applications of stiffened composite plates. Exploring a broader range of geometries and material properties in future research could provide a more comprehensive understanding. Moreover, while the drop-weight impact tests included both captured and non-captured impacts, the behavior under multiple impacts or rebound conditions remains an area for further investigation. The experimental setup also presented certain limitations, such as constraints on the specific impact energy levels due to the capacity of the drop-weight machine and challenges associated with manually capturing the weight after the first impact, which could introduce variability in test outcomes. Furthermore, potential misalignment during impact positioning and minor inconsistencies in weight release timing could contribute to deviations in the results. Addressing these limitations in future work would strengthen the generalizability of the findings and offer deeper insights into the performance of stiffened composite plates in various applications.

Finally, it is important to consider the lifecycle costs and manufacturing challenges associated with these alternatives. Stiffened plates may offer advantages in terms of simpler manufacturing processes, as they do not require the use of complex core materials found in sandwich panels. However, the cost of producing and assembling the stiffeners, as well as potential challenges related to the precise placement of stiffeners, could affect overall production efficiency and cost. Additionally, the long-term durability and maintenance costs of stiffened composite plates should be evaluated in future research to determine the full lifecycle implications of this technology. As an initial intuition of the authors, since the stiffened plates do not suffer from the same drawbacks as sandwich panels—such as undetected defects and moisture penetration in the core, which can weaken structural integrity over time—the visible core in stiffened plates allows for easier identification of faults and proactive replacement of damaged parts before they lead to catastrophic failures, offering better lifecycle performance. A future analytical comparison of these factors with those of sandwich panels would provide a more comprehensive understanding of the practical viability of these materials in aerospace and other high-performance applications.

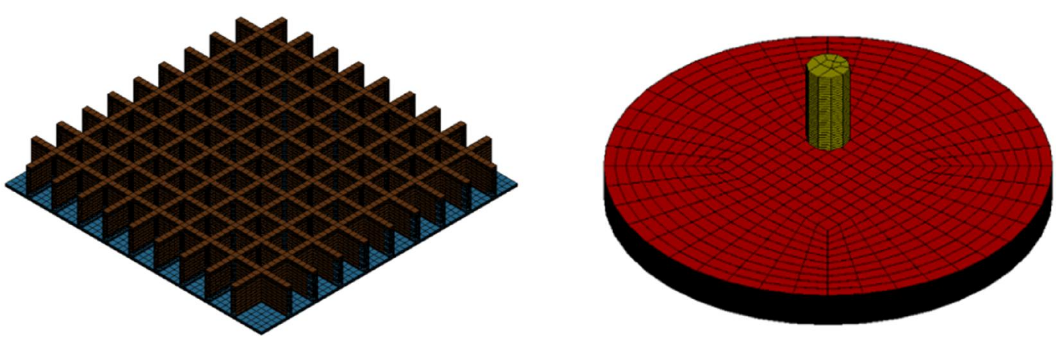
3.2. Validation of the numerical model

In this section, with the goal of validating the FE approach, three low-velocity impact scenarios were considered and numerically simulated. The first case consisted of a composite sandwich panel with foam core with dimensional and material characteristics used in the experimental work by Shokrieh and Fakhar (2012). The second case was a composite stiffened plate based on the presented experimental work in this paper. The third numerical model consisted of a hail impactor based on our previous works (Lalisani et al. 2023; Sadighi et al. 2023). The finite element model of a 2-way stiffened panel, used for the parametric study in Section 3.4, and the model of the sandwich panel, used for numerical validation in the current section, are shown in Fig. 11.

Figure 12(a) compares the experimental and numerical force history curves of the sandwich panel under a 20 J low-velocity impact loading. The trends of curves were similar, and the difference between the peak forces of the numerical and experimental curves was <4.1%.

Figure 12(b) compares the predicted and experimental force-displacement curves of the stiffened composite plate under a 4.7 J low-velocity impact. As it can be seen, there is a good agreement between the results predicted by the numerical model and the experimental test.

Finally, based on the model developed in our previous studies (Lalisani et al. 2023; Sadighi et al. 2023), an FE model was constructed for the hail impact, and the results were compared



(a) (b)

Figure 11. Finite element modeling: (a) 2-way stiffened plate (used for parametric study in section 3.4), (b) sandwich panel used for finite element validation.

with those obtained from experimental investigation undertaken by Carney et al. (2006). The results, again, showed a strong agreement between the experimental and numerical results (Fig. 11c).

It is well known that a finer mesh produces more accurate results in FE modeling, while it increases the computational time. Hence, a mesh sensitivity analysis was carried out to find the optimal element/mesh size that has no significant effect on the analysis results. In the mesh sensitivity study, the number of elements along the edge of the laminate was varied between 10 and 120 elements for a 10 cm × 10 cm sandwich panel under a 20 J low-velocity impact test. Mesh convergence was obtained using at least 80 elements per length. Hence 80 elements per length was chosen for discretization of the final sandwich and stiffened plates simulations.

3.3. Equivalency between stiffened plate and sandwich panel

The primary aim of the research was to identify a stiffened composite plate that could match the deflection of a reference sandwich panel. This equivalent stiffened plate ideally needs to achieve either equal or lower maximum stress and equal or lower mass, while also exhibiting equivalent deformation under similar loading conditions.

The reference sandwich panel was the one proposed by Shokrieh and Fakhar (2012). The maximum displacement, von Mises stress, and mass of three proposed equivalent stiffened composite plates are compared to those of the reference sandwich panel (1 mm thick upper/lower faces and 10 mm thick PVC foam core) in Table 3. The geometrical characteristics mentioned in Table 3 are schematically depicted in Fig. 1(c). The first equivalent stiffened plate shared a comparable mass and height with the sandwich panel. In contrast, the second and third plates had similar mass to the referenced sandwich panel but were only half the height, featuring different thicknesses of stiffeners.

Table 3 shows that the proposed equivalent stiffened plates with a variety of geometries show decreased maximum deflection and von Mises stress compared to those of the composite sandwich panel under 5 m/s low velocity impact. For example, the equivalent stiffened plate with 1 mm face sheet and stiffeners with 6 mm height and 5 mm thickness had slightly lower maximum deflection (i.e., 3.4%) and 19.3% lower von Mises stress compared to the reference sandwich panel, while they had 3.4% higher mass.

3.4. Numerical parametric study of low-velocity hail impact

As a case study, this section aims to conduct a numerical study of stiffened plates subjected to low-velocity hail impact following an experimental investigation of their behavior under various loading conditions. When investigating the behavior of a stiffened plate subjected to low-velocity hail impact, various parameters come into play, influencing the results. In this particular numerical study, the focus was on minimizing the maximum deflection and mass of the plate. The following input parameters were taken into consideration:

Table 3. Equivalent parameters of stiffened composite plate.

Parameter	Sandwich $H = 12$ mm	Stiffened plate 1 $H = 10$ mm $t = 5$ mm $D = 10$ mm	Stiffened plate 2 $H = 6$ mm $t = 10$ mm $D = 10$ mm	Stiffened plate 3 $H = 6$ mm $t = 5$ mm $D = 5$ mm
Maximum deflection (mm)	4.6	4.51 (↓2.1%)	4.44 (↓3.4%)	4.30 (↓6.5%)
Von Mises stress (MPa)	440	385 (↓12.5%)	374 (↓15%)	355 (↓19.3%)
Mass (g)	28.8	29.5 (↑2.4%)	30.7 (↑6.7%)	29.8 (↑3.4%)

H: height of sandwich plate or stiffeners, *t*: thickness of the stiffeners, *D*: distance between stiffeners.

- Height of the stiffeners
- Spacing between the stiffeners
- Thickness of the stiffeners
- Array configuration of the stiffeners

The selection of parameter ranges for stiffener geometry was guided by several key considerations. To align with the focus on thin and lightweight structures, particularly relevant for aerospace applications, a stiffener height range of 2 mm to 20 mm was chosen. The spacing range of 5 mm to 40 mm was selected to encompass a wide spectrum of designs, from dense stiffener arrangements to configurations where the spacing is double the stiffener height. A range of 5 mm to 30 mm was considered for stiffener thickness, exploring a broad range of thickness with the maximum being 1.5 times the stiffener height. It is important to note that these parameter ranges represent a case study and may need to be adjusted for other applications, such as civil structures, which may require thicker and taller stiffeners.

It is important to note that the face plate lay-up in all models was consistent with the one described in the validation section (Section 3.2). The impactor utilized in the analysis was an ice impactor with a diameter of 5 cm, and it had an initial velocity of 25 m/s. The diameter was selected as a case study to facilitate the parametric investigation and analysis of the stiffened plate's response to low-velocity ice impacts. The initial velocity of the ice impact was determined and considered based on terminal velocity analysis. Under different falling conditions, the terminal velocity of a 5 cm diameter hail stone is in the range of 25–30 m/s (Dieling, Smith, and Beruvides 2020), and hence a velocity of 25 m/s was chosen for this study.

To achieve optimal designs for the stiffened plates, a comprehensive consideration of both input parameters (height, spacing, thickness, and arrangement type) and output parameters (maximum deflection and mass) was crucial. To better represent the significant output parameters as a single meaningful variable (to take into account mass and deflection simultaneously), a non-dimensional variable, namely γ, was introduced:

$$\gamma = \frac{\delta \times M}{\delta_o \times M_o} \tag{2}$$

where δ_o and M_o refer to the deflection and mass of the reference simple plate (without stiffeners), and δ and M refer to the deflection and mass of the stiffened plate. An ideal structure would have minimal mass and deflection, i.e., low γ value. The amount of this parameter for different spacings, heights, thickness, and arrangements of stiffeners for one-way stiffened plates are plotted in Fig. 13.

Based on Fig. 13, when the thickness of stiffeners in the one-way arrangement was doubled from 10 mm to 20 mm, a significant change in the value of γ occurred, increasing by 71%. A similar trend was observed for the two-way arrangement, where doubling the stiffener thickness resulted in a 75% increase in γ. Furthermore, altering the height of stiffeners also played a crucial role in determining γ. Increasing the height from 6 mm to 12 mm led to a 37% and 46% increase in γ for one-way and two-way arrangements, respectively.

The spacing between stiffeners was also examined as a parameter, but its impact on γ was less compared to the thickness and height of the stiffeners. When the spacing was halved (from 40 mm to 20 mm), γ increased by only 14% in one-way arrangement and 20% in two-way arrangement. Additionally, comparing the behavior of samples with similar geometrical parameters but different arrangements revealed that under hail impact, the two-way arrangement exhibited a 39% better performance (Fig. 13).

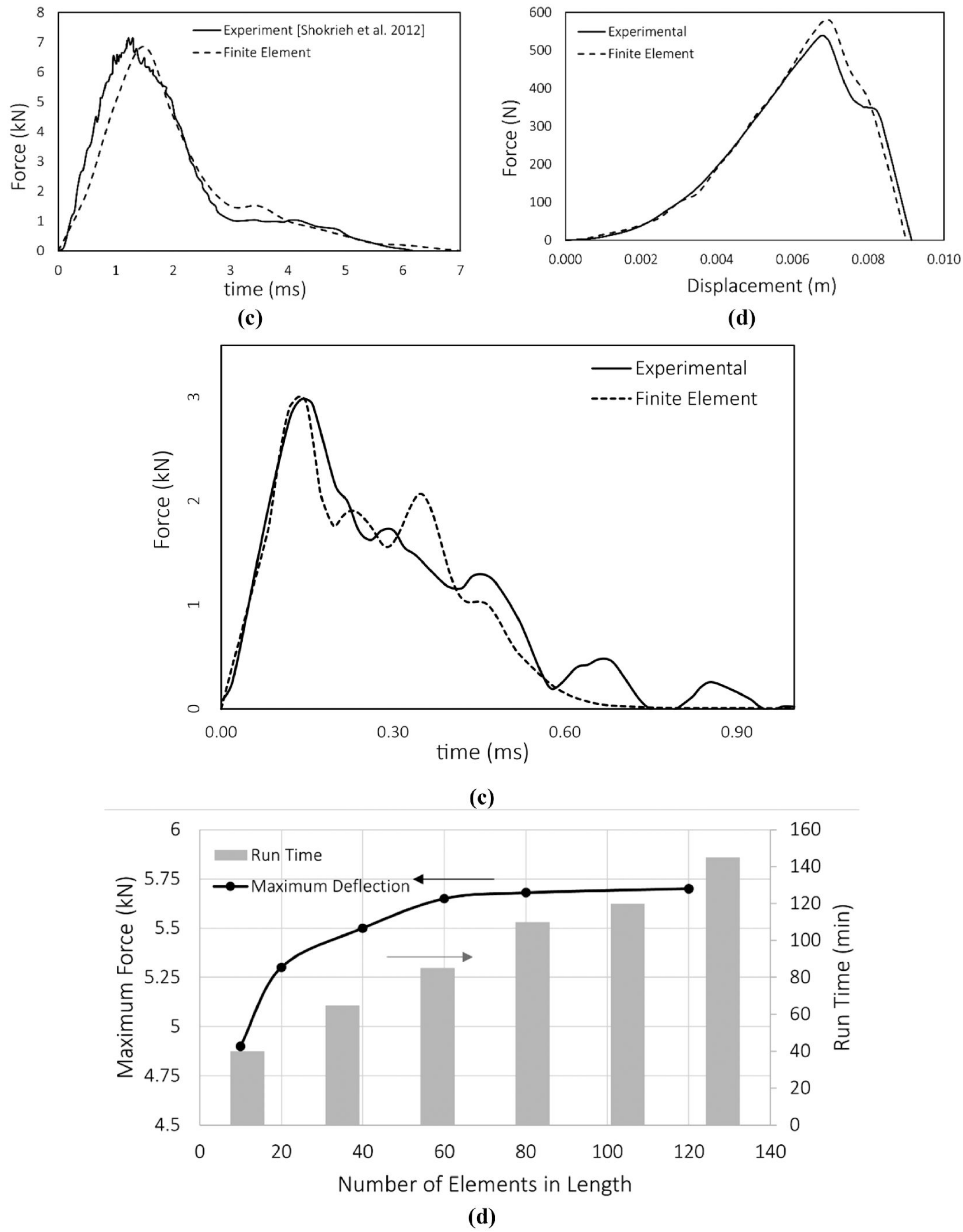


Figure 12. Validation of FE modeling: (a) force-time curves of sandwich plate under low-velocity impact, (b) force-displacement curves of stiffened composite plate under low-velocity impact test, (c) force-time curves of hail impact, and (d) mesh sensitivity analysis of the sandwich panel under low-velocity impact.

In order to investigate the simultaneous effects of the input parameters, a Taguchi analysis with an L9 (3×3) arrangement was employed. The factors considered in the analysis were the height, spacing, and thickness of the stiffeners. The considered levels of the parameters are:

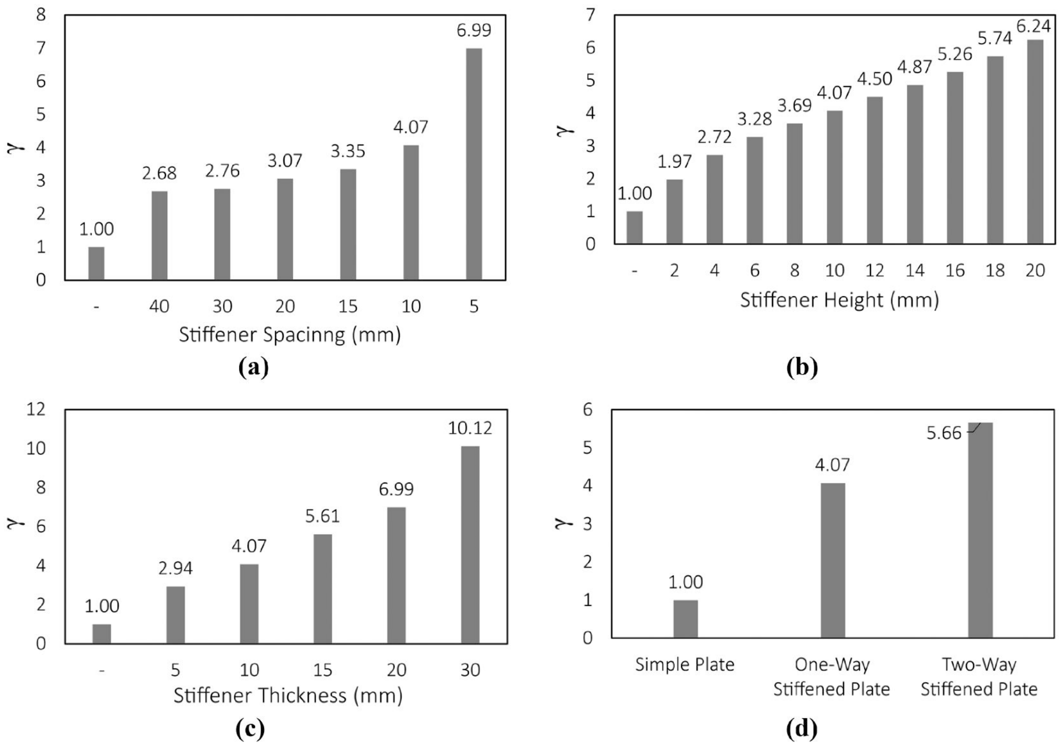


Figure 13. The amount of γ of different models under hail impact in one-way stiffened plates. The effects of (a) different spacing between stiffeners, (b) different stiffeners' height, (c) different stiffeners' thickness, and (d) different arrangement of stiffeners.

- 5, 10, and 20 mm for the stiffener height,
- 5, 10, and 20 mm for distance between stiffeners,
- 5, 10, and 20 mm for the stiffener thickness,

Through the linear model analysis of the Taguchi method, optimal designs were determined. For the one-way arrangement, the optimum geometric parameters were:

- Height: 10 mm,
- Spacing: 10 mm, and
- Thickness: 5 mm.

while for the two-way arrangements, they were:

- Height: 5 mm,
- Spacing: 10 mm, and
- Thickness: 10 mm.

To compare the effect of input parameters on the output, analysis of variance for signal to noise (S/N) ratios in the Taguchi method was performed and the results for the one-way stiffened plates are reported in Table 4. Since the recommended F-Value for L9 (3,3) is greater than 9.2 (Alaswad, Benyounis, and Olabi 2016), the results showed that all three parameters had a significant effect on the results, and none of them can be neglected. Nonetheless, it should be noted that the thickness of stiffeners had the highest F-Value, meaning that this parameter had the highest effect on the results among all parameters. This aligns with the earlier observations and

Table 4. Analysis of variance for S/N ratios in Taguchi analysis.

Source	DF	Seq SS	F-Value
Height	3	72.55	14.06
Spacing	3	51.46	9.95
Thickness	3	89.05	18.25
Residual error	3	5.89	
Total	12	218.95	

findings. The same by analysis of variance for S/N ratios was performed for the two-way stiffener plates, and similar results were obtained. It is important to note that sequential sums of squares (Seq SS) serve as measures of variation for various parameters within the model and offer a means to assess the effectiveness of these parameters.

4. Conclusion and outlook

This article aims to investigate the behavior of stiffened composite plates as an alternative to sandwich panels. The focus is on achieving comparable low-velocity impact behavior, increased strength, and similar weight. Experimental investigations were conducted on stiffened plates under various loadings, considering different geometrical parameters. A parametric study was performed to identify the optimal design for hail impact in stiffened composite structures. Based on the results, it can be concluded that the impact position of the impactor can significantly affect the induced peak force, with a potential of 100% increase in its amount as a result of changing the position of impact location.

In addition, by examining the damage morphologies of the specimens, it is evident that the crack propagation path was primarily confined to the direction parallel to the stiffeners, with limited propagation observed in the transverse direction. Also, the distance between the impact location and stiffeners influenced the spread of damage, resulting in a 25% reduction in the damage area for the two-way stiffened specimen compared to the one-way specimen while keeping the mass constant. The analysis of parametric study revealed that by selecting appropriate geometric parameters, it is possible to enhance the structure's behavior under hail impact and achieve an optimal design. The parametric study analysis revealed that the thickness of stiffeners had the most significant impact on the behavior of stiffened plates under hail impact. For the equivalency study between stiffened plates and sandwich structure, as an example, for a 12 mm thick sandwich panel, an equivalent stiffened plate with reduced thickness and 19.3% lower maximum stress could be obtained, indicating improved displacement and strength.

Furthermore, to facilitate broader industry adoption and to extend the scope of this research, future studies could focus on evaluating high-velocity impacts, as well as exploring multi-functional integration of stiffened composite plates in advanced applications such as aerospace, automotive, and structural engineering. These stiffened composite plates could potentially replace sandwich panels in applications such as aircraft bodies, civil structures, and other areas where sandwich panels are currently used. Additionally, examining the effects of multiple impacts over the service life of the plates, and comparing this behavior with that of existing sandwich panels, could provide valuable insights for designers in choosing between the conventional sandwich panels and the proposed stiffened composite plates discussed in this paper.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Alaswad, A., K. Y. Benyounis, and A. G. Olabi. 2016. "Optimization Techniques in Material Processing." In *Reference Module in Materials Science and Materials Engineering*, 1–22. Elsevier. https://doi.org/10.1016/B978-0-12-803581-8.04004-2

Anghileri, M., L. M. L. Castelletti, F. Invernizzi, and M. Mascheroni. 2005. "A Survey of Numerical Models for Hail Impact Analysis Using Explicit Finite Element Codes." *International Journal of Impact Engineering* 31 (8): 929–944. https://doi.org/10.1016/j.ijimpeng.2004.06.009

Appleby-Thomas, G. J., P. J. Hazell, and G. Dahini. 2011. "On the Response of Two Commercially-Important CFRP Structures to Multiple Ice Impacts." *Composite Structures* 93 (10): 2619–2627. https://doi.org/10.1016/j.compstruct.2011.04.029

Assarar, M., M. Bentahar, A. El Mahi, and R. El Guerjouma. 2015. "Monitoring of Damage Mechanisms in Sandwich Composite Materials Using Acoustic Emission." *International Journal of Damage Mechanics* 24 (6): 787–804. https://doi.org/10.1177/1056789514553134/ASSET/IMAGES/10.1177_1056789514553134-IMG5.PNG

Avilés, F., and M. Aguilar-Montero. 2010. "Mechanical Degradation of Foam-Cored Sandwich Materials Exposed to High Moisture." *Composite Structures* 92 (1): 122–129. https://doi.org/10.1016/j.compstruct.2009.07.004

Bayat, M. R., M. M. Mashhadi, and O. Rahmani. 2018. "Low-Velocity Impact Response of Sandwich Cylindrical Panels with Nanotube-Reinforced and Metal Face Sheet in Thermal Environment." *Aeronautical Journal* 122 (1258): 1943–1966. https://doi.org/10.1017/aer.2018.104

Block, D. L., M. F. Card, Jr, and M. M. Martin. 1965. "Buckling of Eccentrically Stiffened Orthotropic Cylinders."

Bull, D. J., S. M. Spearing, and I. Sinclair. 2015. "Investigation of the Response to Low Velocity Impact and Quasi-Static Indentation Loading of Particle-Toughened Carbon-Fibre Composite Materials." *Composites Part A: Applied Science and Manufacturing* 74: 38–46. https://doi.org/10.1016/j.compositesa.2015.03.016

Cai, W., L. Zhu, and X. Qian. 2022. "Dynamic Responses of Steel Plates under Repeated Ice Impacts." *International Journal of Impact Engineering* 162: 104129. https://doi.org/10.1016/j.ijimpeng.2021.104129

Cai, W., L. Zhu, T. X. Yu, and Y. Li. 2020. "Numerical Simulations for Plates under Ice Impact Based on a Concrete Constitutive Ice Model." *International Journal of Impact Engineering* 143: 103594. https://doi.org/10.1016/j.ijimpeng.2020.103594

Carney, K. S., D. J. Benson, P. DuBois, and R. Lee. 2006. "A Phenomenological High Strain Rate Model with Failure for Ice." *International Journal of Solids and Structures* 43 (25–26): 7820–7839. https://doi.org/10.1016/j.ijsolstr.2006.04.005

Chattopadhyay, B., P. K. Sinha, and M. Mukhopadhyay. 1993. "Finite Element Analysis of Blade-Stiffened Composite Plates under Transverse Loads." *Journal of Reinforced Plastics and Composites* 12 (1): 76–100. https://doi.org/10.1177/073168449301200105

Chen, H., M. Wang, and R. Bai. 2006. "The Effect of Nonlinear Contact upon Natural Frequency of Delaminated Stiffened Composite Plate." *Composite Structures* 76 (1–2): 28–33. https://doi.org/10.1016/j.compstruct.2006.06.005

Chen, J., Y. Zhong, Q. Luo, and Z. Shi. 2021. "Static and Dynamic Analysis of Isogrid Stiffened Composite Plates (ISCP) Using Equivalent Model Based on Variational Asymptotic Method." *Thin-Walled Structures* 163: 107671. https://doi.org/10.1016/j.tws.2021.107671

Cui, J., S. Yan, Y. Zhao, and L. Jiang. 2023. "Low-Velocity Impact and Residual Compression Performance of Carbon Fiber Reinforced Composite Stiffened Plates." *Applied Composite Materials* 30 (4): 1185–1206. https://doi.org/10.1007/s10443-023-10121-z

Daniel, I. M., E. E. Gdoutos, K.–A. Wang, and J. L. Abot. 2002. "Failure Modes of Composite Sandwich Beams." *International Journal of Damage Mechanics* 11 (4): 309–334. https://doi.org/10.1106/105678902027247

Dhakal, H. N., H. Ghasemnejad, Z. Y. Zhang, S. O. Ismail, and V. Arumugam. 2019. "The Post-Impact Response of Flax/up Composite Laminates under Low Velocity Impact Loading." *International Journal of Damage Mechanics* 28 (2): 183–199. https://doi.org/10.1177/1056789517751239/ASSET/IMAGES/LARGE/10.1177_1056789517751239-FIG13.JPEG

Dieling, C., M. Smith, and M. Beruvides. 2020. "Review of Impact Factors of the Velocity of Large Hailstones for Laboratory Hail Impact Testing Consideration." *Geosciences* 10 (12): 500. https://doi.org/10.3390/geosciences10120500

Dolati, S., A. Fereidoon, and A. R. Sabet. 2014. "Experimental Investigation into Glass Fiber/Epoxy Composite Laminates Subjected to Single and Repeated High-Velocity Impacts of Ice." *Iranian Polymer Journal* 23 (6): 477–486. https://doi.org/10.1007/s13726-014-0242-y

Faggiani, A., and B. G. Falzon. 2010. "Predicting Low-Velocity Impact Damage on a Stiffened Composite Panel." *Composites Part A: Applied Science and Manufacturing* 41 (6): 737–749. https://doi.org/10.1016/j.compositesa.2010.02.005

Fathi, A., G. Liaghat, and H. Sabouri. 2021. “An Experimental Investigation on the Effect of Incorporating Graphene Nanoplatelets on the Low-Velocity Impact Behavior of Fiber Metal Laminates.” *Thin-Walled Structures* 167: 108162. https://doi.org/10.1016/j.tws.2021.108162

Fathi, A., G. Liaghat, H. Sabouri, M. Chizari, H. Hadavinia, and S. Chitsaz Charandabi. 2021. “Experimental Investigation of Quasi-Static Behavior of Composite and Fiber Metal Laminate Panels Modified by Graphene Nanoplatelets.” *Journal of Reinforced Plastics and Composites* 40 (13–14): 518–532. https://doi.org/10.1177/0731684420985275

Ganesh Ram, S. 2021. *Can Hail Impacts Trigger Delaminations? (A Qualitative Study to Evaluate the Consequences of Hail Ice Impact on Composite Structures)*. Delft University of Technology, Delft, The Netherlands.

Gao, W., Z. Yu, A. Ma, and Z. Guo. 2022. “Numerical Simulation of Composite Grid Sandwich Structure under Low-Velocity Impact.” *Science and Engineering of Composite Materials* 29 (1): 516–528. https://doi.org/10.1515/secm-2022-0176

Gong, S. W., and K. Y. Lam. 1999. “Transient Response of Stiffened Composite Plates Subjected to Low Velocity Impact.” *Composites Part B: Engineering* 30 (5): 473–484. https://doi.org/10.1016/S1359-8368(99)00002-5

Gruben, G., S. Sølvernes, T. Berstad, D. Morin, O. S. Hopperstad, and M. Langseth. 2017. “Low-Velocity Impact Behaviour and Failure of Stiffened Steel Plates.” *Marine Structures* 54 (7491): 73–91. https://doi.org/10.1016/j.marstruc.2017.03.005

Hedayati, R., A. Yousefi, and M. Bodaghi. 2022. “Sandwich Structures with Repairable Cores Based on Truncated Cube Cells.” *Composites Part B: Engineering* 243: 110124. https://doi.org/10.1016/j.compositesb.2022.110124

Hedayati, R., and M. Sadighi. 2015. *Bird Strike an Experimental, Theoretical and Numerical Investigation*. Woodhead Publishing, Cambridge, UK.

Hedayati, R., and M. Sadighi. 2016. “Effect of Using an Inner Plate between Two Faces of a Sandwich Structure in Resistance to Bird-Strike Impact.” *Journal of Aerospace Engineering* 29 (1): 1–11. https://doi.org/10.1061/(ASCE)AS.1943-5525.0000505

Hedayati, R., and S. Ziaei-Rad. 2011. “Foam-Core Effect on the Integrity of Tailplane Leading Edge During Bird-Strike Event.” *Journal of Aircraft* 48 (6): 2080–2089. https://doi.org/10.2514/1.C031451

Hedayati, R., and S. Ziaei-Rad. 2014. “New Bird Model for Simulation of Bird Strike on Various Layups Used in Transparent Components of Rotorcrafts.” *Journal of Aerospace Engineering* 27 (1): 76–85. https://doi.org/10.1061/(asce)as.1943-5525.0000225

Hedayati, R., M. Sadighi, and E. Gholami. 2025. “Design of 2D Re-Entrant Auxetic Lattice Structures with Extreme Elastic Mechanical Properties.” *Mechanics Based Design of Structures and Machines* 53 (2): 923–942. https://doi.org/10.1080/15397734.2024.2377263

Hernandes, J. A., S. F. M. Almeida, and A. Nabarrete. 2000. “Stiffening Effects on the Free Vibration Behavior of Composite Plates with PZT Actuators.” *Composite Structures* 49 (1): 55–63. https://doi.org/10.1016/S0263-8223(99)00125-7

Hu, C., Z. Xu, D. Chen, M. Huang, C. Cai, J. Qiu, and X. He. 2024. “A Novel Integrated Modeling Strategy for Predicting Damage Mechanisms and Energy Dissipation of Composite Stiffened Structures under Low-Velocity Impact and Compression.” *Aerospace Science and Technology* 153: 109454. https://doi.org/10.1016/j.ast.2024.109454

Huang, X., W. Qu, L. Xiao, and Y. Lu. 2024. “A Subharmonic Modulation-Based Approach for Debonding Damage Detection of Composite Stiffened Plates.” *Nondestructive Testing and Evaluation* 39 (4): 802–831. https://doi.org/10.1080/10589759.2023.2228980

Kim, H., and J. N. Keune. 2007. “Compressive Strength of Ice at Impact Strain Rates.” *Journal of Materials Science* 42 (8): 2802–2806. https://doi.org/10.1007/s10853-006-1376-x

Kim, H., and K. T. Kedward. 2000. “Modeling Hail Ice Impacts and Predicting Impact Damage Initiation in Composite Structures.” *AIAA Journal* 38 (7): 1278–1288. https://doi.org/10.2514/2.1099

Lalisani, A. B., M. Sadighi, T. Goudarzi, and R. Hedayati. 2023. “Optimized Stiffened Plates as Equivalent Structures for Sandwich Panels Under Ice Impact,” *The 31th Annual International Conference of Iranian Society of Mechanical Engineers & 9th Conference on Thermal Power Plants.*

Laplante, G., A. E. Marble, B. MacMillan, P. Lee-Sullivan, B. G. Colpitts, and B. J. Balcom. 2005. “Detection of Water Ingress in Composite Sandwich Structures: A Magnetic Resonance Approach.” *NDT & E International* 38 (6): 501–507. https://doi.org/10.1016/j.ndteint.2005.01.006

Li, D. H., and S. Ma. 2023. “Dynamic Thermomechanical Analysis on Stiffened Composite Plates with Damage.” *Journal of Thermal Stresses* 46 (12): 1267–1295. https://doi.org/10.1080/01495739.2023.2253877

Li, D. H., Y. Liu, and X. Zhang. 2014. “Low-Velocity Impact Responses of the Stiffened Composite Laminated Plates Based on the Progressive Failure Model and the Layerwise/Solid-Elements Method.” *Composite Structures* 110 (1): 249–275. https://doi.org/10.1016/j.compstruct.2013.12.011

Liao, C.-L., and J. N. Reddy. 1990. “Analysis of Anisotropic, Stiffened Composite Laminates Using a Continuum-Based Shell Element.” *Computers & Structures* 34 (6): 805–815. https://doi.org/10.1016/0045-7949(90)90351-2

Liu, C., Y. X. Zhang, and L. Ye. 2017. "High Velocity Impact Responses of Sandwich Panels with Metal Fibre Laminate Skins and Aluminium Foam Core." *International Journal of Impact Engineering* 100: 139–153. https://doi.org/10.1016/j.ijimpeng.2016.09.004

Liu, J., Q. Fei, D. Jiang, D. Zhang, and S. Wu. 2020. "Experimental and Numerical Investigation on Static and Dynamic Characteristics for Curvilinearly Stiffened Plates Using DST–BK Model." *International Journal of Mechanical Sciences* 169: 105286. https://doi.org/10.1016/j.ijmecsci.2019.105286

Liu, Z., J. Niu, and R. Jia. 2021. "Dynamic Analysis of Arbitrarily Restrained Stiffened Plate under Moving Loads." *International Journal of Mechanical Sciences* 200: 106414. https://doi.org/10.1016/j.ijmecsci.2021.106414

Nettles, A. T., and M. J. Douglas. 2000. "A Comparison of Quasi-Static Indentation to Low-Velocity Impact."

Olsson, R., R. Juntikka, and L. E. Asp. 2013. "High Velocity Hail Impact on Composite Laminates – Modelling and Testing." *Solid Mechanics and Its Applications* 192: 393–426. https://doi.org/10.1007/978-94-007-5329-7_9/FIGURES/28

Patel, M., S. Patel, S. Ahmad, and C. Guedes Soares. 2024. "A Comparative Assessment of the Dynamic Responses of Solid Plate, Stiffened Plate, and Sandwich Plate of Equal Masses Under Explosive Loadings." https://doi.org/10.1115/OMAE2024-129919

Peng, L. X., X. C. He, G. X. Mei, and Y. J. Shen. 2024. "Dynamic Response Analysis of Ribbed Plate Resting on Viscoelastic Pasternak Foundation via MLS Meshless Method." *International Journal of Structural Stability and Dynamics* 24 (17): 2450191. https://doi.org/10.1142/S0219455424501918

Rajaneesh, A., I. Sridhar, and S. Rajendran. 2014. "Relative Performance of Metal and Polymeric Foam Sandwich Plates under Low Velocity Impact." *International Journal of Impact Engineering* 65: 126–136. https://doi.org/10.1016/j.ijimpeng.2013.11.012

Ramnath, B. V., K. Alagarraja, and C. Elanchezhian. 2019. "Review on Sandwich Composite and Their Applications." *Materials Today: Proceedings* 16: 859–864. https://doi.org/10.1016/j.matpr.2019.05.169

Sadighi, M., R. Alderliesten, A. Fathi, B. Soltannia, and R. Hedayati. 2023. "Delamination Link-Ups in Composite Laminates Due to Multiple Hail Impacts." *Engineering Structures* 294: 116729. https://doi.org/10.1016/j.engstruct.2023.116729

Safri, S. N. A., M. T. H. Sultan, M. Jawaid, and K. Jayakrishna. 2018. "Impact Behaviour of Hybrid Composites for Structural Applications: A Review." *Composites Part B: Engineering* 133: 112–121. https://doi.org/10.1016/j.compositesb.2017.09.008

Schäfer, K., D. Nestler, and L. Kroll. 2024. "Impact Compressive Properties of Polyurethane Foams with 3D Continuous Fibre Reinforcement." *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*. https://doi.org/10.1177/14644207241304639

Sharif-Khodaei, Z., M. Ghajari, and M. H. Aliabadi. 2012. "Determination of Impact Location on Composite Stiffened Panels." *Smart Materials and Structures* 21 (10): 105026. https://doi.org/10.1088/0964-1726/21/10/105026

Shokrieh, M. M., and M. N. Fakhar. 2012. "Experimental, Analytical, and Numerical Studies of Composite Sandwich Panels under Low-Velocity Impact Loadings." *Mechanics of Composite Materials* 47 (6): 643–658. https://doi.org/10.1007/s11029-011-9244-4

Sinha, G., and M. Mukhopadhyay. 1994. "Finite Element Free Vibration Analysis of Stiffened Shells." *Journal of Sound and Vibration* 171 (4): 529–548. https://doi.org/10.1006/jsvi.1994.1138

Sinha, L., S. S. Mishra, A. N. Nayak, and S. K. Sahu. 2020. "Free Vibration Characteristics of Laminated Composite Stiffened Plates: Experimental and Numerical Investigation." *Composite Structures* 233 (2019): 111557. https://doi.org/10.1016/j.compstruct.2019.111557

Song, Z., J. Le, D. Whisler, and H. Kim. 2018. "Skin-Stringer Interface Failure Investigation of Stringer-Stiffened Curved Composite Panels under Hail Ice Impact." *International Journal of Impact Engineering* 122: 439–450. https://doi.org/10.1016/j.ijimpeng.2018.09.014

Soto, A., E. V. González, P. Maimí, J. A. Mayugo, P. R. Pasquali, and P. P. Camanho. 2018. "A Methodology to Simulate Low Velocity Impact and Compression after Impact in Large Composite Stiffened Panels." *Composite Structures* 204: 223–238. https://doi.org/10.1016/j.compstruct.2018.07.081

Sun, W., Z. Guan, T. Ouyang, R. Tan, and X. Zhong. 2018. "Effect of Stiffener Damage Caused by Low Velocity Impact on Compressive Buckling and Failure Modes of T-Stiffened Composite Panels." *Composite Structures* 184 (2017): 198–210. https://doi.org/10.1016/j.compstruct.2017.09.084

Tang, D., W. Zhang, L. Li, and X. Ye. 2021. "Theoretical and Experimental Modeling of Beam-Type Flexural Wave Behaviours of Orthogonally Stiffened Plates." *International Journal of Mechanical Sciences* 198: 106395. https://doi.org/10.1016/j.ijmecsci.2021.106395

Tang, Z., C. Hang, T. Suo, Y. Wang, L. Dai, Y. Zhang, and Y. Li. 2017. "Numerical and Experimental Investigation on Hail Impact on Composite Panels." *International Journal of Impact Engineering* 105: 102–108. https://doi.org/10.1016/j.ijimpeng.2016.05.016

Teimouri, H., R. T. Faal, and A. S. Milani. 2025. "Impact Response of Fractionally Damped Rectangular Plates Made of Viscoelastic Composite Materials." *Applied Mathematical Modelling* 137: 115678. https://doi.org/10.1016/j.apm.2024.115678

Thinh, T. I., and T. H. Quoc. 2010. "Finite Element Modeling and Experimental Study on Bending and Vibration of Laminated Stiffened Glass Fiber/Polyester Composite Plates." *Computational Materials Science* 49 (4): S383–S389. https://doi.org/10.1016/j.commatsci.2010.05.011

Timoshenkov, S. P., and S. W. Krieger. 1959. *Theory of Plates and Shells.* McGraw-Hill, United States.

Tippmann, J. D., H. Kim, and J. D. Rhymer. 2013. "Experimentally Validated Strain Rate Dependent Material Model for Spherical Ice Impact Simulation." *International Journal of Impact Engineering* 57: 43–54. https://doi.org/10.1016/j.ijimpeng.2013.01.013

Torkestani, A., M. Sadighi, and R. Hedayati. 2015. "Effect of Material Type, Stacking Sequence and Impact Location on the Pedestrian Head Injury in Collisions." *Thin-Walled Structures* 97: 130–139. https://doi.org/10.1016/j.tws.2015.09.015

Wahl, L., S. Maas, D. Waldmann, A. Zürbes, and P. Frères. 2014. "Fatigue in the Core of Aluminum Honeycomb Panels: Lifetime Prediction Compared with Fatigue Tests." *International Journal of Damage Mechanics* 23 (5): 661–683. https://doi.org/10.1177/1056789513505892/ASSET/IMAGES/LARGE/10.1177_1056789513505892-FIG20.JPEG

Wang, X., J. S. Hansen, and D. C. D. Oguamanam. 2004. "Layout Optimization of Stiffeners in Stiffened Composite Plates with Thermal Residual Stresses." *Finite Elements in Analysis and Design* 40 (9–10): 1233–1257. https://doi.org/10.1016/j.finel.2003.06.003

Wu, B., J. Lin, R. Hedayati, G. Zhang, J. Zhang, and L. Zhang. 2021. "Dynamic Responses of the Aero-Engine Rotor System to Bird Strike on Fan Blades at Different Rotational Speeds." *Applied Sciences* 11 (19): 8883. https://doi.org/10.3390/app11198883

Yan, Y., M. Wang, Y. Zhang, D. Wu, Y. Wang, X. Qing, and Y. Wang. 2024. "A Low-Velocity Impact Localization Method for Composite Stiffened Plate Based on AIC and WPT." *IEEE Sensors Journal* 24 (7): 10993–11002. https://doi.org/10.1109/JSEN.2024.3368563

Yu, R., W. Luo, H. Chen, and J. Liu. 2023. "Experimental Research on Dynamic Behavior of Stiffened Plates under Drop-Weight Impacts of a Wedge Impactor." *Materials* 16 (8): 3128. https://doi.org/10.3390/ma16083128

Yue, N., A. Broer, W. Briand, M. Rébillat, T. Loutas, and D. Zarouchas. 2022. "Assessing Stiffness Degradation of Stiffened Composite Panels in Post-Buckling Compression-Compression Fatigue Using Guided Waves." *Composite Structures* 293 (October 2021): 115751. https://doi.org/10.1016/j.compstruct.2022.115751

Yungwirth, Christian J., John O'Connor, Alan Zakraysek, Vikram S. Deshpande, and Haydn N. G. Wadley. 2011. "Explorations of Hybrid Sandwich Panel Concepts for Projectile Impact Mitigation." *Journal of the American Ceramic Society* 94 (s1): s62–s75. https://doi.org/10.1111/j.1551-2916.2011.04501.x

Zhao, W., and R. K. Kapania. 2016. "Buckling Analysis of Unitized Curvilinearly Stiffened Composite Panels." *Composite Structures* 135: 365–382. https://doi.org/10.1016/j.compstruct.2015.09.041

Zhu, Q., and Z. Yu. 2023. "A Modified Strain-Rate-Dependent Spring-Mass Model for Response Prediction of Composite Laminates Subjected to Low-Velocity Impact." *International Journal of Aerospace Engineering* 2023: 1–17. https://doi.org/10.1155/2023/2121209

Zou, J., Z. Lei, R. Bai, D. Liu, H. Jiang, J. Liu, and C. Yan. 2021. "Damage and Failure Analysis of Composite Stiffened Panels under Low-Velocity Impact and Compression after Impact." *Composite Structures* 262: 113333. https://doi.org/10.1016/j.compstruct.2020.113333