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Using Experimental Observation and Numerical Analysis for Examining the Responses of Carbon and Kevlar Fibers in Cylindrical Composites Exposed to Low-Velocity Impact

Simin Dokht Rayat [a], M.Fazel Hajikarimi [b], Ali Rahmati [b], Hamed Ghasemi [b] ,*

[a] *Ako Sanat Qarn Company, Center of Technology Incubators of Qazvin Islamic Azad University, Qazvin, Iran*
[b] *Department of Mechanical Engineering ,Qa.C., Islamic Azad University ,Qazvin, Iran*
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Abstract

Recently, sandwich composites have been in high demand in the air, maritime, and land transportation industries. Particularly, epoxy matrix composites reinforced with carbon fiber have become desirable structural materials due to their high static strength and stiffness characteristics. On the other hand, if Kevlar fibers are used as a substitute for or alongside graphite fibers for reinforcement, the damage tolerance of composite materials may be significantly enhanced. The current research investigated how four composite cylinders constructed of Kevlar and carbon fiber react to low-velocity impact. These cylinders can be classified physically as carbon-only, Kevlar-only, carbon-outside/Kevlar-inside, or Kevlar-inside/carbon-outside. A drop-weight impact device containing a free-falling spherical steel impactor was used to apply the impact to the samples. Abaqus/Explicit software based on finite element modeling (FEM) was employed to assess the impact behavior of specimens. Then, the composite cylinders were modeled as standard shell composite lay-ups, while the impactor was represented as a stiff analytical part. The results demonstrated that carbon fiber was less effective at absorbing energy than Kevlar fiber and that the carbon-only specimen had the strongest contact force and the least deflection compared to the other samples. To further validate the analysis, empirical and numerical findings were carefully compared.

Keywords: Carbon fiber, cylindrical composite, finite element modeling, Kevlar fiber, low-velocity impact.

1. Introduction

POLYMER matrix composites are widely used in aerospace construction, sporting equipment, pressure vessels, offshore facilities, and automobile parts. In many applications, these composite structures are likely to encounter impact load. Different polymer matrix composite materials are widely used in many industries [1]. For example, polymers and composites have many uses in oil and natural gas exploration and production, ranging from structural elements to drilling fluid ingredients [2]. Fluor polymers are mostly utilized as interiors and protective coverings for metallic equipment and pipelines in the oil and gas industry to stop corrosion and contamination of oil products. Composite pipes are constructed from various components, including epoxy resins, carbon fiber, and fiberglass. Each of these components is chosen based on the requirements of the particular application, and the final composite material can be customized to meet certain performance standards.
Numerous studies have extensively studied the impact of the low-velocity behavior of laminated composite structures. For instance, Naik et al. [3] studied the impact behavior of glass and carbon composites both separately and in combination with different configurations. They concluded that hybrid configurations had better compressive strength and lower notch sensitivity than only glass or only-carbon composites. It was also found that the carbon-outside/glass-inside hybrid configuration had less transverse displacement than the other hybrid configurations tested. Moreover, the glass-outside/ carbon-inside configuration exhibited a longer impact duration than the other hybrid configurations. Zhu and Chai [4] presented a rigorous theoretical model for a quasi-static response panel. They computed the impact force-displacement response of a composite sandwich panel subjected to low-velocity impact. The effect of size was also included in the mathematical model.
Various studies have examined the damage behavior of sandwich structures under low-velocity impact loading [5], [6], among which composite laminated plates and sandwich panels were widely employed. However, Kumar et al. [7] adopted a different approach and explored the impact response and impact-induced damages of graphite/epoxy laminated cylindrical shells. While some studies have offered analytical solutions for the impact response of laminated plates [8], [9], several researchers have employed finite element (FE) analysis for this purpose [10], [11]. For example, Her and Liang [12] used the Ansys LS-DYNA software to calculate the transient impact response of laminated composites and cylindrical and spherical shells. Using experimental and finite element techniques, Kaneko et al. [13] studied carbon fiber-reinforced plastic (CFRP)

*Corresponding author, Email address: hmdqasemi@gmail.com

cylinders subjected to transverse impact loading. David-West et al. [14] reported the effect of ply orientation on the resistance of the impact strike and the impact behavior of composite cylinders of different stacking configurations. Khalili et al. [15] used Abaqus/Explicit and Abaqus/Implicit software to study the impact response of curved composite panels. Using experimental and numerical methods, Kistler and Waas [16], [17] studied the response of laminated plates with cylindrical curves to low-velocity accidental impact.

Overall, several theories have been proposed for the low-velocity impact of composite polymers, some relying on empirical outcomes, others on numerical findings [18], [19]. In 2019, Ismail et al. [20] investigated the effects of combining kenaf and glass fiber to create hybrid composites with different weight ratios on their low-velocity impact response and post-impact properties [20]. The study involved four key processes: composite manufacture, low-velocity impact testing, dye penetrant evaluation of the composites affected, and compression testing of impacted samples after dye penetrant evaluation. The findings demonstrated the capabilities of the selected composites for product development with zero carbon. In another work, empirical research was conducted to generate mechanical properties of two-phase polymer matrix composites reinforced with various thermoplastic nanofibers [21].

As a major advance in 2022, the low-velocity behavior of SiC nanoparticle-reinforced polymer matrix composites (PMCs) was investigated considering different weight fractions of nanoparticles, artificial aging time, and impact energy [22]. Ashothaman et al. [23] examined the biodegradable polylactic and PMC reinforced with synthetic and natural fibers. Despite its drawbacks, they indicated that PLA is mainly used for ecological polymers, including low glass transition temperature. Rajkumar et al. [24] examined the low-velocity impact (LVI) response of sisal-natural rubber (NR)-based flexible green composite in various stacking sequences, including sisal/rubber/sisal (SRS) and sisal/rubber/sisal/rubber/ sisal (SRSRS). Using hemispherical and conical impactors, they examined the effect of impactor shape on the LVI response of the proposed composite. In their study, Tu et al. [25] manufactured fiberglass-reinforced composites (FRCs) by autoclaves or hot presses and obtained significant results. Another experimental work investigated the LVI response of 3D-integrated woven spacer sandwich composites made of high-performance glass fiber-reinforced fabric and epoxy resin [26]. The authors used a hand lay-up process for generating spacer sandwich composites with various characteristics and experimented with them under LVI.

Despite the great interest in polymer composites, there are still many limitations and gaps that must be addressed. The use of carbon and Kevlar fibers in the literature has been largely overlooked. In this regard, the present study aimed to examine the response to the LVI of four cylindrical composite structures made of either carbon or Kevlar fibers or a combination of both. Specifically, contact force, contact duration, and deflection of the specimens were investigated experimentally. An FE analysis was conducted to confirm the results numerically. Since Kevlar fibers examined here have many applications in the industry due to their high resistance to shock and impact loading, the findings will interest those involved in this field. Hence, it is essential to understand the behavior of these fibers when subjected to dynamic loads and LVI. For further validation of the experimental data, impulse force was calculated for each specimen. The novelty of this research lies in the agreement between empirical and numerical results that demonstrate the accuracy of the analyses.

2. Material and Methods

A. Materials and Geometry

Two examples of synthetic fibers with exceptional strength are Kevlar and carbon fiber. Carbon fiber is more widely employed in areas outside textiles, such as boat building and aerospace production, whereas Kevlar is largely used in protective gear and bullet-resistant items **Error! Reference source not found.**. In this research, four cylindrical composite specimens (Fig. 1) were used: (a) carbon-only, (b) Kevlar-only, (c) Kevlar-outside/carbon-inside, and (d) carbon-outside/Kevlar-inside. Specimens (a) and (b) were made of nine woven layers of carbon and Kevlar fiber, respectively. Sample (c) had five outer layers of Kevlar fiber and four inner carbon fiber layers. Sample (d) was composed of five outer layers of carbon fiber and four inner layers of Kevlar fiber. Each cylinder's internal diameter, thickness, and length were 48.5 mm, 3.25 mm, and 250 mm, respectively. It is important to note that the carbon and Kevlar fibers had a density of 200 and 230 g/m^2, respectively.

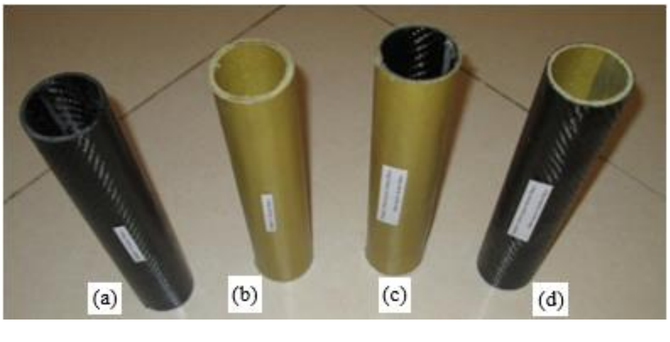


Fig 1. The specimens used in the study: carbon-only (a), Kevlar-only (b), Kevlar-outside/carbon-inside (c), and carbon-outside/Kevlar-inside (d)

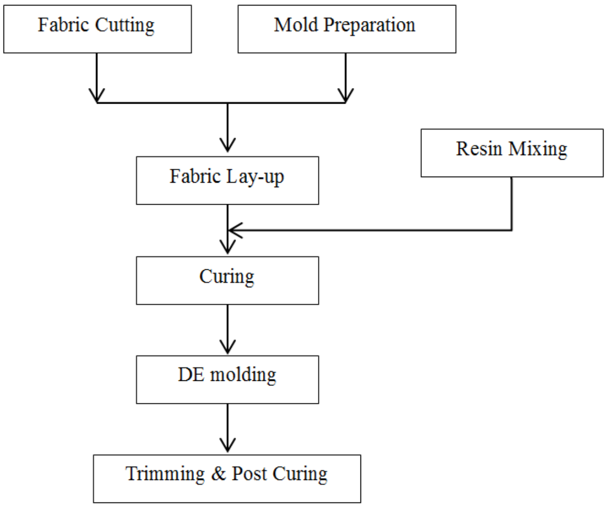


Fig 2. The manufacturing process of the specimens

A hand lay-up process was used to manufacture the specimens, as shown in Fig. 2. More specifically, woven fibers (T300) of carbon and Kevlar were combined using EC130LV epoxy resin. The mixture ratio of resin and hardener (W340) was 100:30, and the fiber volume fraction of the specimens was 0.5.

A tensile test was conducted to determine the mechanical properties of the specimens. In this test, an instrument elongates the specimen at a constant rate and continuously measures and records the specimen's applied load and elongation. The tests were performed under the ASTM D3039 standard, which is used to determine the mechanical properties of PMCs. Table 1 lists these properties (i.e., density, Young's modulus, shear modulus, and Poisson's ratio).

Table 1

The Properties of Carbon and Kevlar Fiber Laminates

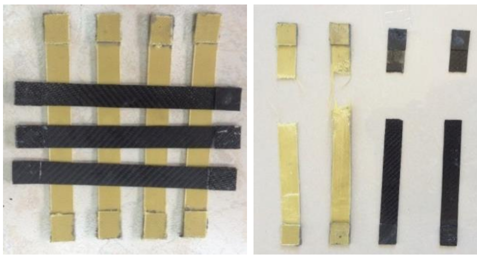
Materials		Carbon fiber	Kevlar fiber
Density (kg/m^3)	P	1380	1380
Young's modulus (GPa)	E_x	120	60
	E_y	120	60
Shear modulus (GPa)	G_{xy}	15	7.5
	G_{xz}	15	7.5
	G_{yz}	9	5
Poisson's ratio	υ_{xy}	0.24	0.12

The tensile tests were conducted at the Iran Polymer and Petrochemical Institute, Tehran, Iran. Fig. 3 displays the tensile machine and the carbon and Kevlar laminates before and after the tests.

B. Impact Test

Impact tests were performed in the Composite Materials Research Laboratory at Amirkabir University of Technology, Tehran, Iran. A drop-weight impact apparatus with a free-falling mass (Fig. 4) was used to apply impact on the four specimens. The specimen boundary conditions were clamped. This apparatus recorded data for the first impact. From the beginning to the end of the impact, an accelerometer attached to the top of the projectile measured the contact force history and plotted those data in the form of acceleration-time curves. In other words, in order to obtain the displacement-time curve of the contact force, it was necessary to integrate the acceleration-time curves twice.

(a)



(b) (c)

Fig 3. The tensile test apparatus used in the study: (a) together with the carbon and Kevlar laminates before (b) and after (c) the tensile test

Fig 4. The drop-weight impact apparatus used in the study

The test setup consisted of the specimen holder and a spherical steel impactor released from a height of 300 mm. The mechanical and geometrical properties of the impactor are given in Table 2.

Table 2
PROPERTIES OF THE IMPACTOR

Material	Steel
Density (kg/m^3)	7800
Young's modulus (GPa)	200
Poisson's ratio	0.3
Diameter (mm)	16
Total mass (kg)	3.2

The impact energy of the impactor was calculated as 9.42 J using (1):

$$\Pi = m.g.h \qquad (1)$$

where m stands for mass, g is gravity acceleration, and h represents the height or vertical distance between the impactor and the specimen.

3. Finite Element Model

The FE modeling of the impact behavior of the cylindrical composites under investigation was carried out using Abaqus software 6.10.1.

A. Impactor Modeling

There are three methods of modeling the impactor in Abaqus. The first method considers the impactor a deformable solid body, and the material is assigned to the body. Indeed, the deformable solid body is any arbitrarily-shaped axisymmetric two-dimensional or three-dimensional part that can be created or imported. A deformable part deforms under mechanical, thermal, or electrical load. By default, Abaqus/CAE creates deformable parts.

The second method assumes that the impactor is a discrete rigid part that must be meshed. A discrete rigid part is similar to deformable parts in that it can take on any arbitrary shape. However, it is used in contact analysis to model non-deformable bodies. Finally, the third method treats the impactor as a rigid analytical part that cannot be meshed. A rigid analytical part corresponds to a discrete rigid in terms of its use in contact analysis to represent a rigid surface. However, its shape is not arbitrary; rather, it must be formed from a set of sketched lines, arcs, and parabolas [28].

B. Cylinder Modeling and Mesh Pattern

In order to model composite cylindrical laminates, three options are available: conventional shell, continuum shell, and solid elements. Conventional shell composite layups comprise plies made of different materials in varying orientations. These layups can contain different numbers of plies in different regions. The behavior of a conventional shell section is defined in terms of its response to stretching, bending, torsion, and transverse shear. The method that should be used in this case is section integration. Conventional shells have been meshed using S4R elements, four-node conventional shell elements with reduced integration.

Continuum shell composite layups are modeled using continuum shell elements that fully discretize an entirely three-dimensional body but have kinematic behavior based on shell theory. These layups are expected to have a single element in their thickness, which contains multiple plies as defined in the ply table. We suppose the region is assigned a continuum shell. In that case, the composite layup contains multiple elements, each containing plies defined in the ply table, and the analysis results will be different. Continuum shells have been meshed using SC8R elements, which are eight-node continuum shell elements with reduced integration.

Finally, a solid composite layup is similar to conventional and continuum shell layups, but it is used when the following conditions are met simultaneously:

- The transverse shear effects are predominant.
- It is not possible to ignore the normal stress.
- Accurate inter-laminar stresses are required, such as near localized regions of complex loading or geometry [17].

Solid composite layups enable a more realistic simulation of the impactor using the C3D8R element [16]. Continuum shell AND CONVENTIONAL SHELL ELEMENTS USED FOR MESHING THE CYLINDERS are shown in Fig. 5.

In the present study, the conventional shell composite layup was used. For this layup, three integration points were considered in the thickness of each layer, with Simpson's rule used as the integration method. A total of 12,444 nodes and 12,356 quadrilateral elements were created in numerical simulations. Fig. 6 illustrates the modeling of the impactor and composite cylinders. Numerical analysis was performed using the finite elements solver Abaqus/Explicit in Abaqus 6.10, and the time step was 0.01 s.

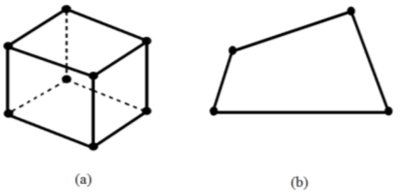


Fig 5. Continuum shell (SC8R) (a) and conventional shell (S4R) (b) elements.

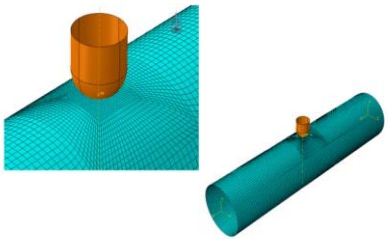


Fig 6. Modeling of the impactor using a rigid analytical shell and modeling of composite cylinders using the S4R element.

C. Contact Modeling

For contact modeling, many contact laws can be considered. In the present study, the hard contract law was applied, where the contact constraint is applied when the clearance between the two surfaces becomes zero. The impactor and the target were set as master surface and slave nodes, respectively. The impact duration between the two bodies is very short, normally within a few microseconds. Contact is the most important aspect of impact analysis [12]. The impact transient response is investigated based on the following assumptions:

● There is no friction between the impactor and the composite structure.
● The damping effect in the composite structure is ignored.
● The gravity force during the impact period is ignored.
● The impactor is a rigid body.

D. Solution Method

The dynamic load can be modeled in Abaqus using an explicit or implicit algorithm. Abaqus/Explicit is an explicit dynamic FE program that provides a nonlinear, transient, and dynamic analysis of solids and structures using explicit time integration. With its powerful contact capability, reliability, and computational efficiency, this program is highly appropriate for quasi-static applications that involve discontinuous nonlinear behavior. In an explicit scheme, the analysis cost increases linearly with the size of the problem; however, in an implicit scheme, the analysis cost rises much faster than the problem size. This makes Abaqus/Explicit more attractive for large-scale problems [28].

4. Results and Discussion

This section begins with the experimental results of the study, followed by the results of the FE analysis undertaken to validate the experimental findings numerically.

A. Experimental Results

A total of 2,043 quantity data were collected to calculate the contact force. Fig. 7 demonstrates the experimental results for the contact force history of the study specimens when subjected to LVI. As can be seen, the carbon-only, carbon-outside/Kevlar-inside, Kevlar-outside/carbon-inside, and Kevlar-only specimens had the greatest maximum contact force history, respectively. Furthermore, it is evident that the order is almost reversed for contact duration. In other words, as carbon fiber increased in the outer part of the cylinder composites, the maximum contact force increased, and the duration time decreased. Also, comparing the results of carbon-outside/Kevlar-inside and Kevlar-outside/carbon-inside specimens shows that the outer layers played the dominant role because the contact occurred between the outer layer and the impactor. Thus, the carbon-outside/ Kevlar-inside specimen had greater maximum contact force and shorter contact duration than the Kevlar-outside/carbon-inside composite cylinder.

Compared to the other two specimens, Kevlar-only and Kevlar-outside/carbon-inside specimens exhibited decreased maximum contact forces due to the presence of Kevlar fiber in the outer part. This indicates that Kevlar fiber was more efficient at absorbing energy than carbon fiber. Regarding contact force, the difference between carbon-only and carbon-outside/Kevlar-inside was much smaller than between Kevlar-only and Kevlar-outside/carbon-inside. This is because the indentation occurred in the upper layer. In other words, the velocity and energy were insufficient to get to and damage the inner layers and achieve the plastic phase.

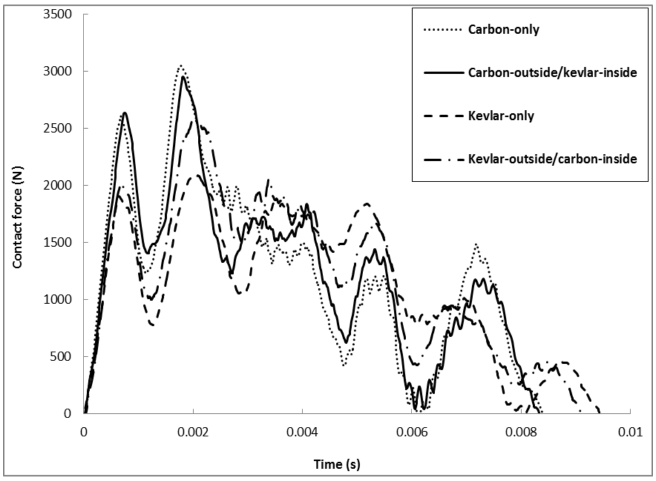


Fig 7. Experimental results for the contact force history of the specimens under study

B. Numerical Verification

The experimental results of the study were compared with FE results. This numerical verification was necessary since FE simulations could accurately predict the impact events. Moreover, the use of laboratory results in the design of real components is known to cause a number of problems, which can be attributed to the fact that test configurations rarely replicate the actual component conditions, especially with regard to constraints [29].

A few discrepancies were observed between the two sets of results, which can be explained by the following:

• The experimental tests showed the possibility of local plastic deformation, but the cylinders were perfectly elastic in numerical analysis.
• During the experimental tests, friction losses existed along the rails between the edge supports and contact surfaces, but the friction forces were considered negligible in FE modeling.
• In the real specimens, the layers were not bonded perfectly, but in FE modeling, all layers were assumed to be perfectly bonded.

Table 3 and Table 4 compare experimental and numerical data for maximum contact force and contact duration, respectively. The data presented in these tables reveal minimal discrepancies between the two data sets.

Table 3
EXPERIMENTAL AND NUMERICAL RESULTS FOR MAXIMUM CONTACT FORCE (N).

	Carbon - only	Kevlar - only	Kevlar-outside/ carbon-inside	Carbon-outside/ Kevlar-inside
Experimental data	3042	2097	2576	2952
Numerical data	2997	2075	2653	2911
Percentage of discrepancy	1.5	1	2.9	1.4

Table 4
EXPERIMENTAL AND NUMERICAL RESULTS FOR CONTACT DURATION (S).

	Carbon-only	Kevlar -only	Kevlar-outside/ carbon-inside	Carbon-outside/ Kevlar-inside
Experimental data	0.0084	0.0095	0.0091	0.0083
Numerical data	0.0077	0.0088	0.0091	0.0078
Percentage of discrepancy	9.1	7.95	< 0.5	6.4

Figs. 8-11 present experimental and numerical data for each specimen concerning contact force history separately. Again, a strong agreement between the two sets of results can be observed. Moreover, it is clear that the specimens exhibited similar contact force behavior. Due to the inertial effect, the contact force oscillated strongly in all cases. The difference between the numerical and empirical findings in Table IV emphasizes the correctness of the analysis of the selected polymer composite.

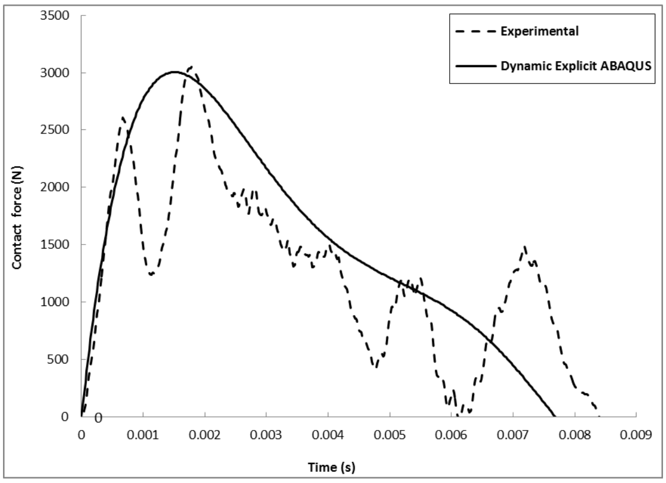


Fig 8. Experimental and numerical results for the contact force history of the carbon-only specimen.

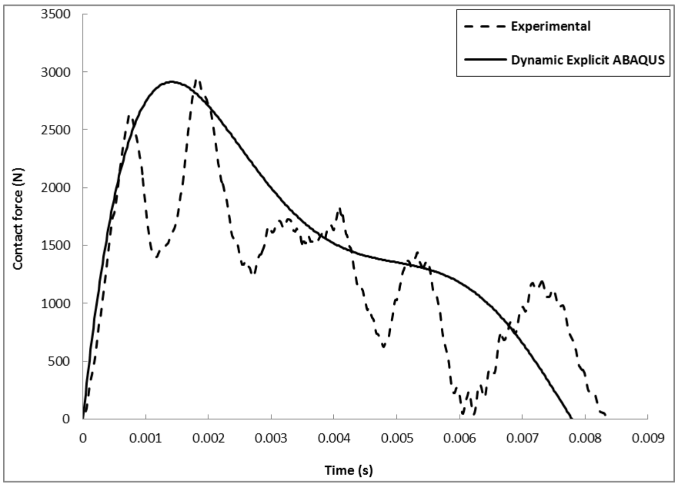


Fig 9. Experimental and numerical results for the contact force history of the carbon-outside/Kevlar-inside specimen.

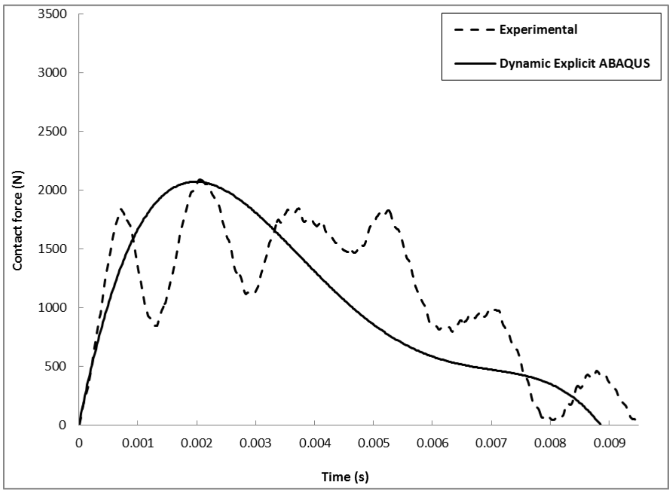


Fig 10. Experimental and numerical results for the contact force history of the Kevlar-only specimen.

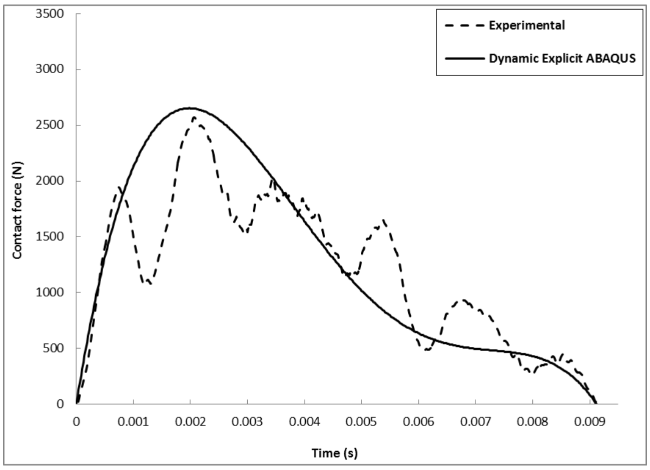


Fig 11. Experimental and numerical results for the contact force history of the Kevlar-outside/carbon-inside specimen.

The deflection of composite cylinders was another concern in this study, which was characterized by the displacement of a node located at the central point of the top face of each specimen. The deflection histories of the cylinder composites under investigation are shown in Fig. 12. Clearly, the maximum and minimum deflections belong to the Kevlar-only and carbon-only specimens, respectively. In addition, it is interesting to note that the maximum deflection value decreases when the contact force increases.

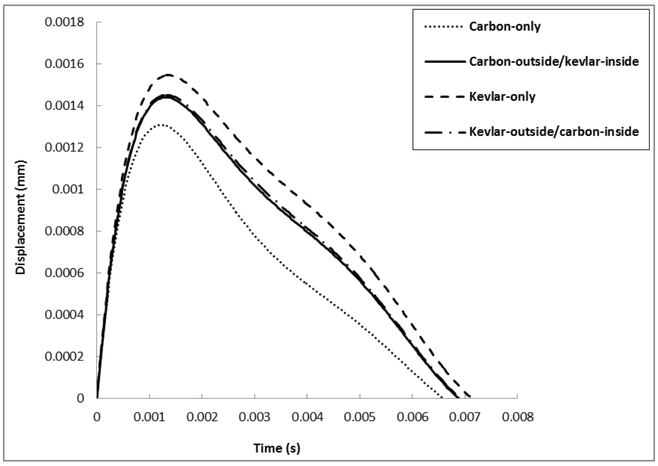


Fig 12. Numerical results for the deflection history of the specimens under study.

Further validation of the study results was performed using the impulse-momentum theorem to calculate impulse force for all specimens. According to this theorem, an object's momentum change equals the impulse applied to it. Foo et al. **Error! Reference source not found.** calculated the impulse by the integral of the area under the sinusoidal curve on a force-time graph. Since force is a vector quantity, an impulse is also a vector quantity in the same direction. Moreover, when an impulse is applied to an object, it causes an equivalent vector change in its linear momentum in the same direction. Comparing the experimental and numerical results for the impulse force revealed a strong correlation between the two data sets (Table 5). The slight difference between numerical and empirical findings substantiates the authenticity and reliability of the outcomes.

Table 5

EXPERIMENTAL AND NUMERICAL RESULTS FOR THE IMPULSE FORCE (J).	Carbo n-only	Kevlar -only	Kevlar-outside/ carbon-inside	Carbon-outside/ Kevlar-inside
Experimental data	11.2	10.3	11.3	11.1
Numerical data	12.1	10	11.7	12
Percentage of discrepancy	7.4	3	3.4	7.5

5. Conclusions

The current study examined four composite cylinders (i.e., carbon-only, Kevlar-only, Kevlar-outside/carbon-inside, or carbon-outside/Kevlar-inside) under LVI with an emphasis on contact force, contact duration, and deflection. Furthermore, the experimental data were verified using FE analysis. It was found that Kevlar fiber was more effective at absorbing energy than carbon fiber. Moreover, the carbon-only sample showed the highest contact force and the lowest deflection among all the cylindrical composites. The Kevlar-only specimen also had the minimum contact force and maximum deflection. Another observation was that the Kevlar-only and carbon-only samples had maximum and minimum contact durations, respectively. Finally, a strong agreement was found between experimental and numerical results. In terms of impulse force, for instance, the numerical and empirical results based on the four modes of carbon-only, Kevlar-only, Kevlar-outside/carbon-inside, and carbon-outside/Kevlar-inside were different by 7.4%, 3%, 3.4%, and 7.5%, respectively. The carbon/Kevlar hybrid fabric, which combines the greatest qualities of Kevlar and carbon fiber, provides a high strength-to-weight ratio, excellent conformability, durability against impacts, abrasion resistance, dimensional stability, and fatigue resistance.

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