International Journal of analytical and Numerical Methods in Mechanical Design
Vol 3., Issue 2, Summer & Autumn 2024, 17-20

Comparative Study of Low-Velocity Impact on Carbon Fiber and Glass Fiber Composite Cylinders

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Received 15 August 2024, Accepted 25 October 2024

Abstract

This paper presents an analytical and numerical study of low-velocity impact response in composite cylinders made of carbon fiber, glass fiber, and hybrid layups. A triangular approximation was used to model the analytical force–time history [1,2], while finite element (FE) simulations were performed using Abaqus/Explicit [7,19]. Four configurations were analyzed: carbon-only, glass-only, carbon-outside/glass-inside, and glass-outside/carbon-inside. The analytical model derives closed-form expressions for impulse, contact duration, displacement, and stiffness [3,5]. Results show that CFRP cylinders exhibit higher peak forces and shorter contact durations, while GFRP cylinders undergo larger displacements and absorb more energy through deformation [4,6,23]. Hybrid specimens display intermediate responses, with stacking sequence strongly influencing the outcome [8,9,13].

Keywords: Low-velocity impact, Carbon fiber reinforced polymer (CFRP), Glass fiber reinforced polymer (GFRP), Hybrid composites, Composite cylinder, Analytical modeling, Energy absorption, Stacking sequence, Structural response

1. Introduction

Fiber-reinforced composites are widely used in aerospace, automotive, marine, and energy applications due to their high strength-to-weight ratio [16]. Among these, CFRP are valued for their high stiffness but are relatively brittle and costly [1,2]. GFRP, in contrast, are cheaper and tougher but less stiff [3,4].

Cylindrical structures such as pipelines, pressure vessels, and shells are often exposed to accidental low-velocity impacts [23,24]. Understanding the comparative performance of CFRP, GFRP, and hybrids is essential for safe and optimized design. While several studies explored impact response of plates [10,12,14], fewer works addressed cylindrical shells. The present study combines analytical and numerical approaches to compare CFRP, GFRP, and hybrid cylinders.

2. Literature Review

brate [1,15] and Cantwell & Morton [2] provided the fundamentals of low-velocity impact modeling. Later studies confirmed that CFRP laminates exhibit high stiffness but brittle failure [6,24], whereas GFRP laminates sustain larger deformations [3,22]. Hybrid composites combining CFRP and GFRP have been shown to balance stiffness and toughness [4,8,9,13,18].

Experimental investigations [11,20,21] and numerical studies [7,19] highlight the role of impact energy, stacking sequence, and thickness on structural response. However, most works focus on flat plates [23], leaving a gap in the study of composite cylinders. This paper addresses this gap.

3. Materials and Methods

3.1 Analytical Model:

The impactor kinetic energy is defined as:

$$E_0 = \frac{1}{2}mv^2 = mgh$$

Impulse:

$$I = \int_0^{t_c} F(t)dt$$

Force–time history (triangular approximation [1]):

$$F(t) = \begin{cases} t\dfrac{2F_{max}}{t_c} & 0 \le t \le \dfrac{t_c}{2} \\ 2F_{max}\left(1 - \dfrac{t}{t_c}\right) & \dfrac{t_c}{2} < t \le t_c \end{cases}$$

Impulse simplifies to:

$$I = \frac{1}{2}t_{max}F_c = mv$$

Displacement (energy balance [5]):

$$E_0 = \frac{1}{2}\delta \quad , \quad \delta_{max}F_{max} = \frac{2E_0}{F_{max}}$$

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Stiffness:

$$k = \frac{F_{max}}{\delta_{max}} = \frac{F_{max}{}^2}{2E_0}$$

Hybrid modulus (rule of mixtures [25]):

$$E_{eq} = \sum_{i=1}^{n} V_i E_i$$

Where V_i and E_i are the volume fraction and modulus of each ply.

Table 1
Mechanical properties of CFRP and GFRP:

Property	***CFRP***	***GFRP***
Density (kg/m³)	1380	2000
Young's modulus (GPa)	120	70
Shear modulus (GPa)	15	5
Poisson's ratio	0.24	0.23

3.2 Numerical Model:

Numerical simulations were performed using Abaqus/Explicit [7,19]. The cylinder was modeled as a shell structure. Its geometric specifications included a radius of 24.25 mm, a length of 250 mm, and a thickness of 3.25 mm. The cylinder was considered to consist of 9 polymeric layers, each layer being defined as either carbon fiber-reinforced polymer (CFRP) or glass fiber-reinforced polymer (GFRP) depending on the configuration [22].

For the layer modeling, the Composite Layup capability of the software was utilized. In this definition, the mechanical properties of each layer (Young's modulus, shear modulus, Poisson's ratio, and density) were input according to the data in Table 1. The stacking sequence was considered for four different configurations: all CFRP, all GFRP, CFRP outer – GFRP inner, and GFRP outer – CFRP inner.

Mesh (meshing) was performed using reduced shell elements S4R. These elements are suitable for nonlinear shell analyses with large deformations. The mesh size was adaptively chosen such that the mesh was finer near the contact region (center of the cylinder) and coarser further away.

The impactor was modeled as a rigid spherical body (radius 8 mm) with a mass of 3.2 kg. The initial velocity corresponding to a drop from a height of 0.30 m was computed and applied to the impactor.

Boundary conditions fixed the cylinder at both ends (clamped). Contact between the impactor and the cylinder surface was defined using a general surface-to-surface contact formulation. Normal contact behavior was Hard Contact and frictional behavior was modeled as penalty with a coefficient of friction of 0.2 [14].

For monitoring results, the following outputs were extracted from the model:

- Force–time history at the contact point,
- Central axial displacement of the cylinder,
- Kinetic, internal, and contact energies,
- Von Mises stress contours and the cylinder's deformation.

These data were used for comparison with analytical results and for studying the behavior of the composites under impact.

4. Results

4.1 Analytical Results:

Results matched expected differences in stiffness and displacement [3,4,5].

- CFRP: higher peak force, shorter contact time.
- GFRP: larger displacement, longer duration.
- Hybrids: intermediate, stacking sequence mattered [8,9,13].

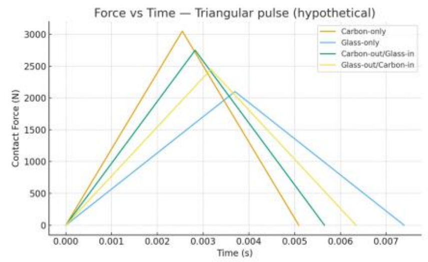

Fig 1. Force–time (analytical)

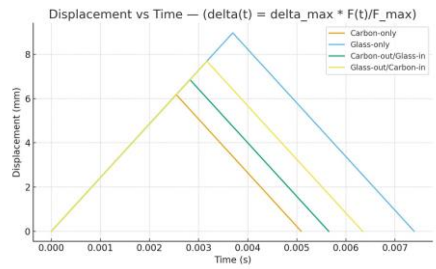

Fig 2. Displacement–time (analytical)

4.2 Numerical Results:

Numerical simulations validated analytical trends [7,19]. CFRP cylinders carried higher loads but lower displacement, while GFRP cylinders showed larger deflection. Stress contours showed concentration near impact site (Figure 7) [6,24].

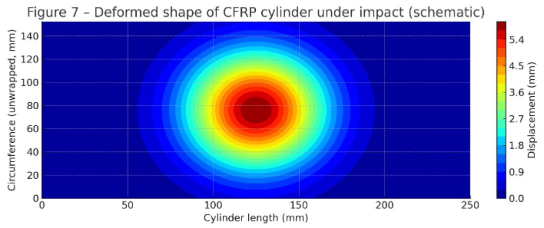

Fig 3. Deformed CFRP cylinder under impact:

Figure 3 illustrates the deformed shape of the CFRP cylinder under impact, showing localized displacement near the impact point. Figure 8 presents the energy histories for all configurations. The kinetic energy decreases as the impact progresses, while internal energy rises as the cylinder deforms. A small contact energy peak occurs around mid-contact, representing the transient energy transfer at the impact interface.

Energy histories demonstrated transfer from kinetic to internal energy, with minor contact energy peak (Figure 8) [18,20].

Figure 4 – Energy histories (kinetic, internal, contact):

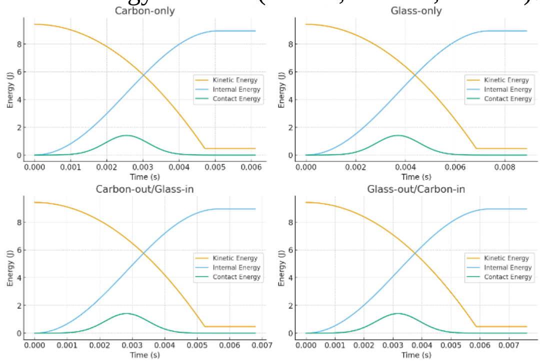

Fig 4. Approximate energy histories for each specimen (analytical approximation). Kinetic Energy (initial ≈ 9.42 J) decreases during contact while Internal Energy increases; a small Contact Energy peak appears near mid-contact. Residual kinetic energy (~0.47 J) is left to represent rebound/uncaptured energy.

4.3 Parametric Study:

- Thickness ↑ → stiffness ↑, displacement ↓ [21].
- Carbon ply ratio ↑ → higher peak load [22].
- Impact energy ↑ → displacement scales as $\propto \delta_{max}\sqrt{E_0}$

5. Discussion

- Results confirm CFRP are stiffer but brittle [2,6], while GFRP are more ductile [3,23]. Hybrids offer tunability [4,8,13].
- The role of the outer ply is critical: carbon outside → higher stiffness; glass outside → higher absorption [9,25].
- Analytical formulas help predict stiffness and displacement trends without full experiments [1,5].

6. Conclusion

- CFRP → high peak load, low displacement.
- GFRP → lower load, higher displacement.
- Hybrids → balance properties, stacking sequence matters.
- Thickness and energy significantly affect behavior [21,25].

This combined analytical–numerical study provides design insights for composite cylinders under accidental impacts.

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