MATEC Web of Conferences **398**, 01009 (2024) https://doi.org/10.1051/matecconf/202439801009
MTME-2024

Investigating Stacking Configuration and Fiber Hybridization Effects on Low-Velocity Impact Behavior in Twill Woven Carbon/Flax Composites

Manzar Masud[1] *and Aamir Mubashar*[1*]

[1]Computational Mechanics Group, Department of Mechanical Engineering, School of Mechanical and Manufacturing Engineering, National University of Sciences and Technology (NUST), H-12, Islamabad, Pakistan

Abstract. In this study, experimental research has been done to investigate and analyze the effects of fiber hybridization and stacking configurations on the impact performance of carbon/flax bio-hybrid composite laminates. A total of four composite laminates with pure carbon, sandwich, symmetric, and asymmetric stacking configurations were manufactured and investigated in terms of low-velocity impact test with varying energies between 30J and 75J. Both qualitative and quantitative analysis were performed to analyze the damage and failure patterns in the composite layups and were compared with the pure carbon-based layup to identify the effects stacking configuration. The experimental findings showed the symmetric layup having a consistent distribution of flax fiber layers, showed the most enhanced performance as compared to the carbon-based layup Moreover, damage and failure modes differed among layups and increased with varying impact energies. Furthermore, to enable the thorough comparison of the configurations, Composite Performance Index (CPI) was developed, which suggests that bio-hybrid configurations when designed optimally with a suitable number of evenly distributed flax layers, can equal or exceed the performance of a pure carbon fiber configuration.

1 Introduction

Composite materials are subjected to variety of stress and load bearing conditions throughout their operation life span, with low velocity impact (LVI) posing a significant challenge, particularly for aerospace applications. The aerospace industry favours carbon fiber-reinforced polymer (CFRP) composites because of their high specific stiffness and strength, however, carbon fibers have low toughness which results in poor damage resistance [1,2].
Various approaches have been utilized to improve the impact damage resistance of composite laminates in response to this challenge. One such method involves hybridization, which commonly integrates fibres with high strain-to-failure characteristics to strengthen the

* Corresponding author : aamir@smme.nust.edu.pk

damage resistance of composites against the LVI. This approach also aims to lower material costs concurrently [3,4].

Hybridized FRPs (Fiber Reinforced Polymers) traditionally rely on synthetic fibers like carbon and glass, raising concerns about resource depletion, pollution, and recyclability. With a growing focus on sustainability, there's a rising interest in using renewable resources like natural fibers in lightweight applications [5,6]. Natural fibers offer environmental benefits, lower density, and improved damping properties. Moreover, natural fibers have become increasingly appealing due to their advantageous properties, especially in certain non-structural and semi-structural applications within the automotive and sports sectors. Hybrid composites combining carbon and natural fibers offer diverse properties and potential advantages, addressing brittleness common in CFRPs. Flax fiber, known for its eco-friendliness and cost-effectiveness [7], is gaining popularity in bio-hybrid composites. Combining flax and carbon fibers leverages the environmental and economic benefits of flax with the enhanced hygrothermal and mechanical resistance of carbon, resulting in composites with enhanced strength, durability, and energy absorption [8].

In hybrid laminates, the stacking configurations of fibers during manufacturing significantly influences composite characteristics when combining synthetic and natural fibers. Various researchers have explored how fiber hybridization and stacking configuration influence the mechanical and impact resistance response of bio-hybrid composite materials [9–12]. It is very important to mention that, establishing generalized effective procedures for all hybridizations in composite laminate production is impossible due to the multitude of parameters influencing design and development. In one study, Wang et al. [13] studied the influence of carbon fiber content and hybridization method on LVI response in five unidirectional bio-hybrid flax/carbon laminates. The results showed higher carbon content enhanced specific energy absorption, with flax layer placement on the surface exhibiting high energy absorption at low impact energies. In another study by Sarasini et al. [14], it was experimentally concluded that, placing flax fabric on the skin side of carbon/flax composites laminates enhanced the damage resistance as well the energy absorption ability. Likewise, Al-Hajaj [15] et al. studied the impact damage behavior of bio-hybrid carbon/flax composite laminates, incorporating cross-ply flax fibers and woven carbon fibers during manufacturing. Their findings indicated that the use of cross-ply flax fibers led to improved impact performance. In a similar work, Bahrami et al. [16] explored the tensile, impact, and damping properties of woven flax carbon hybrid composites. Impact testing was conducted at a single energy level, revealing that the hybrid bio composite demonstrated impact resistance comparable to that of carbon-based layups. Hence, previous studies validate that combining flax and carbon fabrics enhances impact resistance. This synergy between natural and synthetic fibers offers promising potential for further advancements in composite materials engineering. However, the effects of flax fiber dispersion and changes in stacking configurations on the impact performance in low-velocity situations for 2x2 twill woven carbon/flax bio-hybrid composite laminates, remain unexplored. Additionally, common stacking configurations in aerospace and automotive industries, such as sandwich, symmetric and asymmetric configurations, have not undergone systematic investigation under low velocity impact. Another innovative aspect of this research involves examining how the arrangement and distribution of natural fibres i.e., flax fibres within the carbon/flax composite laminate affect impact resistance, specifically focusing on parameters such as permanent indentation and damage area.

Hence, this study aims to experimentally explore how hybridization effects the response to LVI loading. Bio-hybrid composite laminates were produced by combining 2x2 twill-woven flax and carbon fabrics. LVI testing was conducted on the bio-hybrid composite layups to assess their performance in terms of peak impact force, damaged area and damage indentation. Furthermore, a thorough comparison was made by introducing Composite

Performance Index (CPI) to evaluate and benchmark the bio-hybrid composite laminates against pure carbon-based laminates. This study methodically investigates the impact resistance performance of the bio-hybrid carbon/flax composite laminates, aiming to reduce environmental impact and carbon footprint.

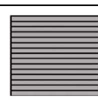
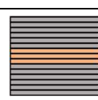
2 Materials and Methods

2.1 Preparation of bio-hybrid composite samples

Woven carbon fabric (supplied by TEi Composites Ltd., Taiwan) and woven flax fabric (supplied by Easy Composites Ltd., United Kingdom) were hybridized with laminating epoxy resin (supplied by RIAERO Ltd.) to manufacture the bio-hybrid composites. Both fabrics have 2x2 twill configuration and an areal weight of 200 g/m^2. Before impregnating the fabric, the amine hardener agent provided by RIAERO Ltd. was combined with the RAIERO laminating epoxy resin in a 2:1 weight ratio to ensure a uniform mixture and expedite the polymerization process. The epoxy-hardener combination has a combined viscosity of approximately 1400 mPa.s at room temperature and has clear liquid appearance. The pot life of the hardener-epoxy mixture according to the technical data sheet [17] is around 115 minutes at 25°C. All composite square panels (500 × 500 mm^2) were manufactured using the vacuum bagging process to ensure the proper consolidation of composite layers and the expulsion of air and excess resin.

Considering the disparities in mechanical properties between synthetic and natural fibers, the spatial arrangement of carbon and flax fibers within the composite laminate is expected to be a determinant in the laminate's response to the out of plane deformation and stresses due to impact. Table 1 shows the investigated stacking sequences along with label, lamination type, thickness and fibre volume fraction of each stacking configuration.

Table 1. Formatting sections, subsections and subsubsections.

Label	Lamination Type	Stacking Configuration	Schematic Grey: Carbon Orange: Flax	Carbon to Flax Ratio	Thickness (mm)	Volume Fraction of Fibre (%)
C	Carbon Control	$[C_{15}]$		-	4.2 ± 0.1	61.3
S	Sandwich	$[C_6F_3C_6]$		4	5 ± 0.1	55.2
A-CF	Asymmetric	$[C_{11}F_3C]$		4	5 ± 0.1	55.4
SU	Symmetric	$[CFC_5FC_5FC]$		4	5 ± 0.1	55.8

2.2 Low Velocity Impact Test

The impact resistance of the bio-hybrid composite laminates was evaluated in accordance with ASTM D7136 test protocol [18], using a drop-weight tower (BESMAK Materials Testing Machines, Turkey) as shown in figure 1. The impactor for the drop tower device is cylindrical, 16mm in diameter, and has a hemispherical nose at the tip. To determine the contact force between the composite laminate surface and the impactor tip, the impactor was equipped with a load cell. 9.67 kg was maintained as the combined mass of the impactor and carriage for all testing, and the impact energy was adjusted by varying the impactor's release position and height. The maximum height of 1000mm can be adjusted in the drop weight tower. The data acquisition system was used to determine the various important parameters during the impact such as specimen deflection and impact force.

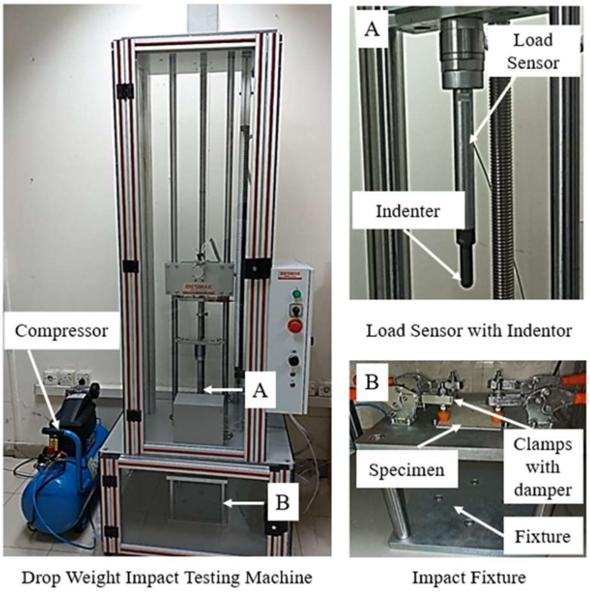


Fig. 1. Impact resistance testing performed on drop weight impact testing machine.

According to the ASTM D7136 test protocol [18], the flat specimen having dimensions of 150mm × 100 mm was cut from the manufactured square composite plates. Four rubber clamps were used to secure the specimen to the impact test fixture after it had been cut, as illustrated in figure 2. These rubber clamps were employed to dampen the impact's vibrations. An energy conservation equation was employed during the experimentation procedure to determine the impactor's release height. To properly comprehend how bio-hybrid composite laminates respond to LVI, three distinct impact energies varying from 30J to 60J were used in this study's LVI experiments, which were performed at room temperature. Three repeats were performed at each specified impact energy level for each composite configuration. The impact energy, impact velocities, and impactor's release height employed in the LVI test are displayed in table 2.

Table 2. Drop weight test parameters used during the low velocity impact testing

Impact energy (J)	Impact velocity (m/s)	Release height (m)	Mass of impactor (kg)	Number of manufactured specimens
30	2.49	0.32	9.67	3
45	3.05	0.47	9.67	3
60	3.52	0.63	9.67	3

3 Results and Discussions

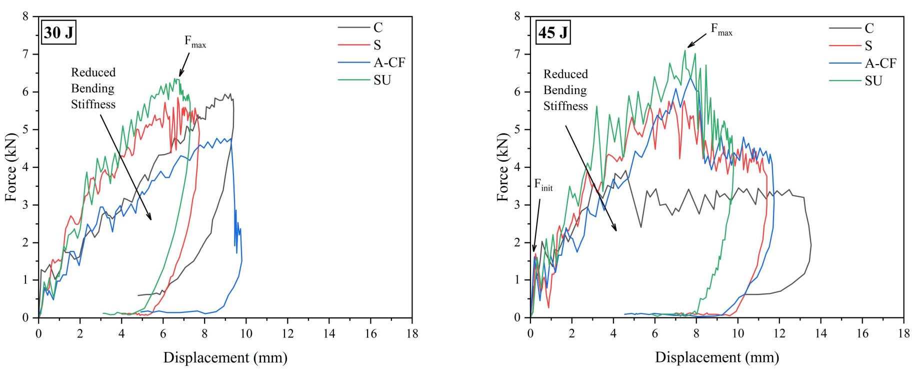
3.1 Effect of stacking sequence on the impact response

In this section, the impact performance of four different stacking configurations of bio-hybrid carbon/flax composite laminates are evaluated and compared in terms of force-displacement curves and impact resistance in terms of damage area. In addition, the failure modes and damage propagation in all stacking configurations were also investigated and determined using a thorough macroscopic damage characterization. A detailed discussion of these findings is presented in the subsequent sections.

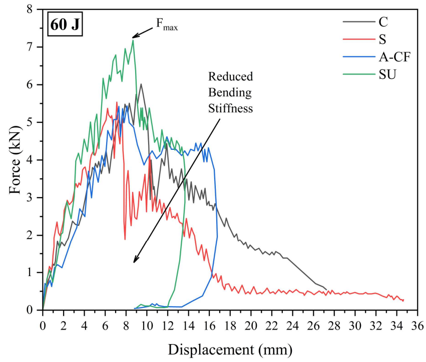
3.1.1 Comparison of Force-displacement response

The force-displacement curves for the four stacking sequences of carbon/flax hybrid composite laminates at impact energies of 30J, 45J and 60J are shown in figure 2, which also depicts the typical behavior of composite samples under low velocity impact (LVI). The force-displacement curves give the significant information occurred during the regarding the low velocity impact experimentation such as peak displacement, peak force, displacement at peak force, bending stiffness and damage process i.e., damage initiation and propagation.

There are three primary stages to the impact process: contact, deformation, and rebound or perforation. As the specimen is dropped from a height, the kinetic energy produced due to impactor is converted into the elastic energy. As a result of this energy exchange, contact force due to impact increases until it achieves the peak impact force, or F_{max}, as illustrated in figure 2. This correlates with the trends of force-displacement curve reported in literature [19]. A portion of the energy is absorbed and dispersed by the material during the impact event, while the remaining energy is stored as elastic energy that remains undissipated and is used to initiate the impactor's rebound. The force-displacement curve shows this rebound as a drop-in impact force. The impactor penetrates the laminate and is indicated as a continually growing displacement in the force-displacement curve if the laminate is unable to withstand the impact energy. In this study, a closed force-displacement curve was found for all stacking configurations for the low impact energies of 30J and 45J, indicating that the impactor rebounded and the samples were not perforated during the impact. Similar behaviour for showing the closed force-displacement curve has also been reported by Shah SZH et al. [20]. However, at the impact energy of 60J, only the composite configurations A-CF and SU remained unperforated by the indenter while the remaining two configurations i.e., 'C' and S failed to sustain the impact load.



(a) (b)



(c)

Fig. 2. Force vs displacement response of carbon/flax composite laminate configurations at various impact energies (a) 30J, (b) 45J and (c) 60J.

The material's bending stiffness, also known as its dynamic modulus, is shown by the slope of the force-displacement curves as shown in figure 2 [20]. It has been demonstrated that this depends on the loading rate in a variety of polymers. The material's damage transition and propagation are indicated by changes in the force-displacement curve's gradient during an impact test. At the impact energies of 30J, 45J and 60J, the stacking sequence SU exhibited the highest bending stiffness during early stages of impact. Also, the same configuration SU sustained the highest load at these impact energies.

The analysis of the force-displacement curves given in Figure 2 also shows that the initial decline in force signifies the onset of failure within a laminate. At impact energies of 30J and 45J where all the three stacking configurations withstood the impact loading, the unloading curves gradually transition into a smoother trajectory after reaching the maximum force. This confirmed the absence of significant damage as result of LVI. On the other hand, at the impact energy of 60J where the perforation of the impact occurred in the case of C and S stacking configuration, a sawtooth profile was observed. The summary of the LVI test for the four investigated stacking configurations is given in table 3.

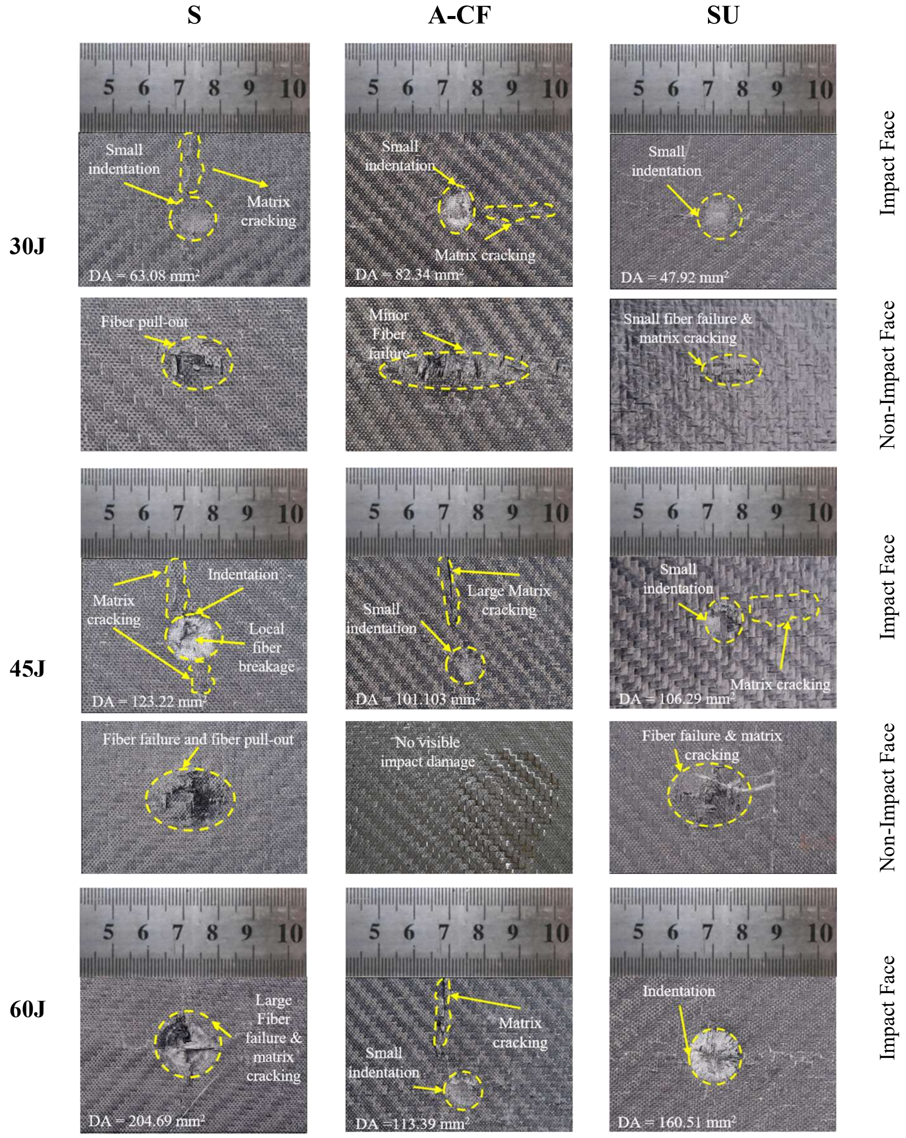
Table 3. Experimental results from impact testing on various stacking configurations of carbon / flax composite laminates.

Impact Energy	Specimen Stacking Configuration	Peak Impact Force (kN) (SD)	Displacement at peak force (mm)	Maximum Displacement (mm)
30J	C	5.95 (± 2.45N)	9.24	9.40
	S	5.87 (± 2.05N)	6.71	7.75
	A-CF	4.77 (± 1.15N)	8.59	9.79
	SU	6.34 (± 3.39N)	6.65	7.31
45J	C	3.92 (± 2.89N)	4.59	13.53
	S	5.83 (± 3.18N)	7.42	11.40
	A-CF	6.39 (± 1.07N)	7.71	11.75
	SU	7.08 (± 1.46N)	7.45	9.79
60J	C	6.02 (± 2.35N)	9.45	27.24
	S	5.54 (± 0.84N)	7.12	34.64
	A-CF	5.43 (± 0.70N)	8.10	16.76
	SU	7.18 (± 1.46N)	8.67	13.66

The analysis and comparison of experimental results for investigated stacking configurations in table 3 concluded that the symmetric layup of flax and carbon fibers, in which the flax layers are distributed throughout the layup and have a ratio of 3 to 12, exhibited the best impact performance in terms of resistance to maximum load and ability to withstand higher energy impacts than a laminate made up of all composite layers. The impact strength of the laminate was enhanced by increased energy absorption and the addition of more flexible flax fibers spaced equally between the carbon fibers.

3.1.2 Damage and failure in laminates after low velocity impact

For all of the investigated bio-hybrid composite configurations, the damage area due to impact and indentation induced by the impactor trip was measured with the help of digital image processing. The damaged area for the impacted and non-impacted faces of S, A-CF and SU configurations is given in figure 3.



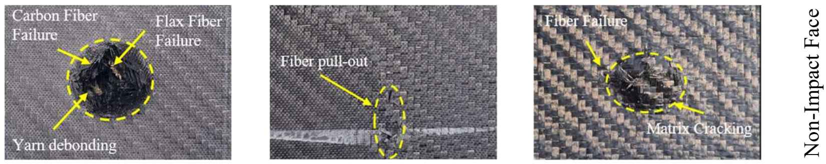


Fig. 3. Analyzing macroscopic failure modes on both impact and non-impact sides of bio-hybrid carbon/flax composite laminates in three stacking configurations (S, A-CF and SU) under varied impact energy levels: 30J, 45J and 60J.

During the low velocity impact, the mass of the impactor was 9.67 kg, and changes in the impactor's height were used to vary the velocity. Permanent indentation, which causes localized fiber failure, delamination, and plastic deformation of the matrix material, especially close to the impact site, is one of the main processes for energy absorption in bio-hybrid composite laminates. At the impact energy of 30J, permanent indentation was observed at the impact face of every stacking sequence. On the non-impact face, however, there was evidence of some kind of fiber failure or damage, which coupled with matrix cracking in stacking sequence SU. At 45J, the most commonly observed damage type on the impact face was indentation mixed with matrix cracking, whereas the non-impact sides of laminates displayed matrix cracking with either fiber pull-out or fiber failure. On the other hand, at 60J, only A-CF and SU stacking configurations sustained the impact. The impact face of A-CF exhibited small indentation along with matrix cracking, whereas the SU configuration exhibited both matrix cracking and fiber breakage.

Figure 9 shows the variation in damage area at the impact energies of 30J, 45J and 60J for three stacking configurations i.e., S, A-CF and SU. In all the layups, it can be observed that the variation in damage behaves linearly with the increase in impact energy. The overall comparison of the damage areas on the impact surface of the bio-hybrid composite laminates highlights that, at 45J and 60J, the highest damage was observed by the sandwich type stacking configuration S.

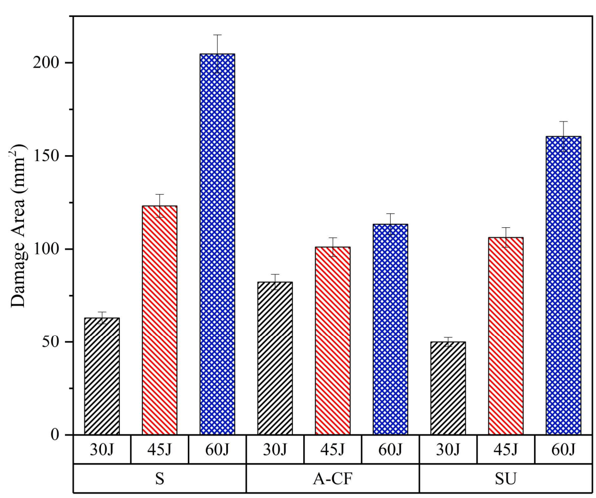


Fig. 4. Comparison of impact resistance of three stacking configurations (S, A-CF and SU) bio-hybrid carbon/flax composite laminates at varied impact energies of 30J, 45J and 60J in terms of damaged area.

3.2 Composite Performance Index (CPI)

In this section, a composite performance index (CPI) has been defined in order to assess the impact performance of the different layups. The index measures how the incorporation of flax fibers in different configurations would affect performance, starting with a layup with solely carbon fiber layers as the basis of performance. Equation 1 was used to compute the CPI for each layup.

$$CPI = \frac{Peak\ Impact\ Force_{Laminate}}{Peak\ Impact\ Force_{Carbon\ Laminate} - Peak\ Impact\ Force_{Laminate}} \quad (1)$$

A value of CPI higher than one indicates that the bio-hybrid layup shows better performance than the only carbon fiber based laminate. Figure 10 shows the variation of CPI with impact energies for different stacking configurations. At 30J, the symmetric configuration SU shows 6.5% better impact performance than the baseline ‘C’ configuration, whereas the other configuration asymmetric configuration A-CF shows 20% lower impact performance. A change in trend can be seen at 45J, in which all the bio-hybrid stacking configurations performed better than the baseline configuration. At 60J, the SU configuration exhibited 15.9% enhanced performance than the baseline ‘C’ configuration and the performance of S and A-CF configurations was comparable to the baseline configuration. This shows that the inclusion of flax layers in carbon layers is generally beneficial to improve the impact strength of the composite laminate. The uniform dispersion of natural flax fibres in the bio-hybrid composite laminate improves the peak force and, thus, the composite layup's resistance to impact-induced deformation. It is also concluded that symmetric laminates performed better than the other composite laminates in terms of impact loading.

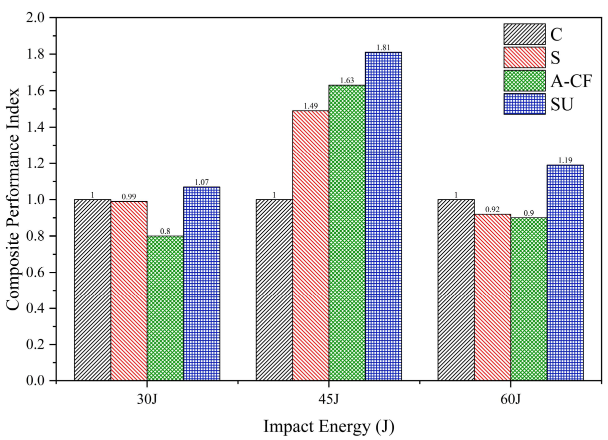


Fig. 5. Composite Performance Index (CPI) of stacking configurations at 30J, 45J and 60J.

4 Conclusion

In this research, the low velocity impact behaviour of various stacking configurations manufactured from carbon and flax twill woven fabrics was experimentally investigated to develop the sustainable eco-friendly bio-hybrid natural composites. Four composite laminates, each with 15 plies, were manufactured with various stacking configurations. Impact responses were investigated at energy levels from 30J to 60J to analyze the influence of flax fiber positions on the characteristics of carbon/flax bio-hybrid composites in comparison with the pure carbon fiber layup. Among the tested layups, the symmetric stacking configuration SU exhibited the highest peak impact force at 30J, 45J, and 60J due to even flax fiber distribution and deformation coordination, indicating the most resistance encountered against the applied impact force. The main damage patterns observed on the impact face of bio-hybrid composite laminates as a result of LVI at low impact energy of were indentation as a result of plastic deformation and matrix cracking; whereas, on the non-impact face, fiber pull-out and fiber failure were detected. It was also observed that variation in damage area increased linearly with the increase in impact energy. Furthermore, a Composite Performance Index (CPI) was also introduced in this research to compare the impact performance of bio-hybrid composites with the pure carbon fiber based layup. The CPI analysis demonstrated that the SU symmetric stacking sequence, characterized by a uniform distribution of flax fiber layers throughout the thickness of the layup, outperformed all other configurations in terms of impact performance. The study suggests that combining carbon and flax layers in bio-hybrid composite laminates is beneficial for semi-structural uses in automotive and sports sectors, offering environmental benefits and sustainability.

References

1. M. Umar bin Ashraf, A. Mubashar, M. Masud, H. Ejaz, S. Hameed Hussain, and M. Subhan Dilawar, Compos Struct 117925 (2024)
2. M. Masud, M. S. M. Al Kharusi, M. U. Ali, A. Mubashar, S. J. Hussain, A. Tariq, G. U. Rehman, M. H. Akhtar, and S. Javeed, Polymers (Basel) **13**, 3491 (2021)
3. M. R. Ricciardi, I. Papa, V. Lopresto, A. Langella, and V. Antonucci, Compos Struct **214**, 476 (2019)
4. M. K. Gupta, M. Ramesh, and S. Thomas, Polym Compos **42**, 4981 (2021)
5. S. Parbin, N. K. Waghmare, S. K. Singh, and S. Khan, Procedia Comput Sci **152**, 375 (2019)
6. M. R. Sanjay, P. Madhu, M. Jawaid, P. Senthamaraikannan, S. Senthil, and S. Pradeep, J Clean Prod **172**, 566 (2018)
7. E. A. D. M. Kamaraj and S. Datta, Advanced Composite Materials **29**, 443 (2020)
8. E. Nisini, C. Santulli, and A. Liverani, Compos B Eng **127**, (2016)
9. F. Pinto, L. Boccarusso, D. De Fazio, S. Cuomo, M. Durante, and M. Meo, Compos Struct **242**, 112148 (2020)
10. Q. Lyu, B. Wang, Z. Zhao, and Z. Guo, Thin-Walled Structures **180**, 109743 (2022)
11. I. D. G. Ary Subagia, Y. Kim, L. D. Tijing, C. S. Kim, and H. K. Shon, Compos B Eng **58**, 251 (2014)
12. A. Wang, X. Wang, and G. Xian, Polym Test **104**, (2021)
13. A. Wang, X. Liu, Q. Yue, and G. Xian, Thin-Walled Structures **187**, 110764 (2023)
14. F. Sarasini, J. Tirillò, S. D'Altilia, T. Valente, C. Santulli, F. Touchard, L. Chocinski-Arnault, D. Mellier, L. Lampani, and P. Gaudenzi, Compos B Eng **91**, 144 (2016)
15. Z. Al-Hajaj, B. L. Sy, H. Bougherara, and R. Zdero, Compos Struct **208**, 346 (2019)
16. M. Bahrami, J. A. Butenegro, M. Mehdikhani, Y. Swolfs, J. Abenojar, and M. A. Martinez, Polym Compos (2023)
17. RIAERO, (2023)
18. A. D7136/D7136M-15, (2015)
19. U. Kureemun, M. Ravandi, L. Q. N. Tran, W. S. Teo, T. E. Tay, and H. P. Lee, Compos B Eng **134**, 28 (2018)

20. S. Z. H. Shah, P. S. M. Megat-Yusoff, S. Karuppanan, R. S. Choudhry, F. Ahmad, Z. Sajid, P. Gerard, and K. Sharp, Int J Mech Sci **189**, (2021)