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Effect of Angle Orientation and Fibre Hybridization on Impact Behaviour of Glass, Basalt and Arenga Pinnata Composites

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Abstract

Natural fibre-reinforced polymer composites have been developed to reduce dependencies on petroleum-based fuels in replacing the usage of synthetic fibre-reinforced polymer composites. Therefore, in this work, the use of mineral-based (basalt fibres) and plant-based (Arenga Pinnata fibres) to fabricate FRP composites was studied. Twelve composites, including glass fibre-reinforced polymer composites, were manufactured using the vacuum bagging technique at 0° and 45° fibres orientations. The effects of orientation and type of FRP composites on the impact resistance behaviour and damage modes were evaluated according to ASTM 7136 standard. The impact properties of the FRP composites were variably affected by the fibre orientation angle. For an instant, the UDB45 and UDG45 had almost similar energy absorbed and impact energy values, which were 32.7J and 267 kJ/m2, respectively. However, for the Arenga Pinnata FRP composites, 45o orientation (UDAP45) presented the lowest impact strength which was 81.16% and 77.93% lower than UDAP45 and WAP, respectively. Microstructure observation showed that the crack started from the middle of the impacted area and propagated along with fibres direction for all types of FRP composites.

Discipline: Mechanical Engineering.

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1 Introduction

Synthetic fibre-reinforced composite materials have been extensively used in aerospace, automobile and allied industries because of their inherent advantages over other conventional materials. These composites are also light, have high durability, high stiffness, resistance to corrosion, and impact, and high fracture toughness and flexural strength (Ram et al., 2021; Al-Furjan et al., 2022). However, due to some reasons, especially the depletion of petroleum sources and awareness of environmental concerns, the industries are intrigued to reduce their dependencies on petroleum-based fuels. Therefore, attention has been shifted to the fabrication and production of natural fibre-reinforced polymer composites, which is an alternative leaning towards more sustainable and environmentally friendly materials to replace conventional petroleum-based fibre-reinforced polymer composites. Natural fibres offer a lot of desirable properties such as low density, biodegradability, high specific modulus and strength, and cheaper and more flexibility during processing than synthetic fibres (Fiore et al., 2015; Yahaya et al., 2016). Basalt fibres are identified as potential options for reinforcing fibres to replace glass fibres since the main components of basalt fibres are similar to glass fibres (Sapiai et al., 2021). Basalt fibres are mineral fibres extruded from basalt rocks, which consist of SiO_2, Al_2O_3, CaO, MgO, Fe_2O_3, and FeO as the main components that make them have superior mechanical strength, thermal stability and chemical resistance (Hashim et al., 2019; Matykiewicz et al., 2019). Arenga Pinnata fibre is the most eligible plant-based material that has attracted many researchers in producing naturally fibres reinforced polymer composites due to its high durability and good resistance to seawater (Khalid et al., 2017; Ticoalu et al., 2014).

In high-performance uses, the impact damage and impact properties must be considered during the design process for safety precautions. For instance, in aerospace industries, structures made of FRP composites are susceptible to transverse impact, especially in the case of low-velocity impact. Damage such as matrix cracking, fibre breakage, and delamination occurs at certain specific plies inside the FRP laminates. A few factors influence the impact damage in FRP laminates, including the type of fibre, the thickness of fibre, the orientation of fibre, the fibre-matrix arrangement of the stacking sequence, the volume of fibre, matrix properties, impact velocity, geometrical parameters of the impacting projectile, and service condition (Akadiri et al., 2012; Alomari et al., 2020; Giasin et al., 2022). A low-velocity impact by foreign material is a major issue for composite laminate since it can cause damage to the internal materials, reducing the strength of the composite component and may be difficult to detect. The best criteria for composite plates that provide high resistance to low-velocity impact loads should consider a variety of material qualities as well as the method of manufacturing the composite product (Alomari et al., 2020). The energy absorption capacity and impact resistance of FRP composites can be enhanced by fibre hybridization (Stephen et al., 2021).

Therefore, this article is aimed at studying the effect of fibre hybridization and orientation in improving the impact resistance of the glass fibre-reinforced polymer composites (GFRP), basalt fibre-reinforced polymer composites (BFRP), hybrid basalt-glass fibre-reinforced polymer composites (BGFRP) and Arenga Pinnata reinforced polymer composites (APFRP). The study also focuses on studying the damage pattern at the interfaces when the fibres are aligned in different orientations. Fibre hybridization is an active strategy for toughening composites and improving impact resistance. These hybrid products have superior mechanical capabilities, higher toughness, and more flexibility, and are manufactured at a low cost and weight (Farhood et al., 2021; Sapiai et al., 2021). much research on the low-velocity impact behaviour of hybrid composites has been conducted based on sample size, material, and impactor type, with the majority of them focusing on the effect of stacking sequence, particularly for the interlayer hybrid structure, in which it was shown that different stacking sequences had significant influences on failure modes and energy absorption (Zhang et al., 2018). In a study conducted to improve the impact response by hybridization, it was reported that glass or carbon fibres can be replaced by basalt fibres due to their increased strength, modulus and better failure strain. E-glass/basalt laminates or basalt/basalt laminates offer superior results since basalt composites have better features in terms of impact behaviours and damage caused by glass composites, and also offer lower values than carbon fibres in general (Demirchi et al., 2020). Yogeesha et al. (2021) reported that basalt is an inorganic fibre that possesses high stiffness but has poor impact properties due to its brittle nature. They studied hybrid basalt-aramid/epoxy hybrid interply composites, in which $(0^{1}{}_{A}/0^{3}{}_{B}/0^{1}{}_{A})$ laminates were found to absorb higher impact loads due to better distribution of shock loads and possess 10.86% higher impact strength compared to $(30^{1}{}_{A}/0^{3}{}_{B}/30^{1}{}_{A})$ and 17.6% higher impact strength compared to $(45^{1}{}_{A}/0^{3}{}_{B}/45^{1}{}_{A})$ laminates. Giasin et al. (2022) found that the S2/FM94 Glass Fibre Composites fabricated using $[0]_{32}$ fibre orientation was the least resistant to impact at all tested energy levels, in which the composite was severely damaged and failed purely due to shear stresses without delaminating. Additionally, the impact tests showed that the composite with $[0/90/90/0]_{8s}$ configuration absorbed more energy with less penetration depth.

Abundant works of literature are available for this research work but only limited information exists in comparison with Arenga Pinnata fibres composites. Hence, this work is an attempt to study the potential of natural-based composites with different orientation angles on the impact behaviour of BFRP, hybrid BGFRP and APFRP composites. The FRP composites were fabricated using unidirectional dan woven basalt, glass and Arenga Pinnata fibres with the polyester resin via the vacuum bagging method. In order to explore the fracture behaviour of FRP composites, morphological examination of fractured surfaces was performed by digital camera.

2 Method

2.1 Materials

For the fabrication of FRP composites, three types of fibres were used which included glass fibres, basalt fibres and Arenga Pinnata fibres. In this study, the unidirectional of these fibres were aligned and stacked in 0° and 45° orientations. The glass fibres were supplied by Innovative Pultrusion Sdn. Bhd., while the basalt fibres were manufactured by Zhejian GBF Basalt Fibre Co.

Ltd. An ISO Polyester resin used as a matrix was supplied by Carbon Tech Global Sdn. Bhd with a mixing ratio of 100:2 (resin: catalyst).

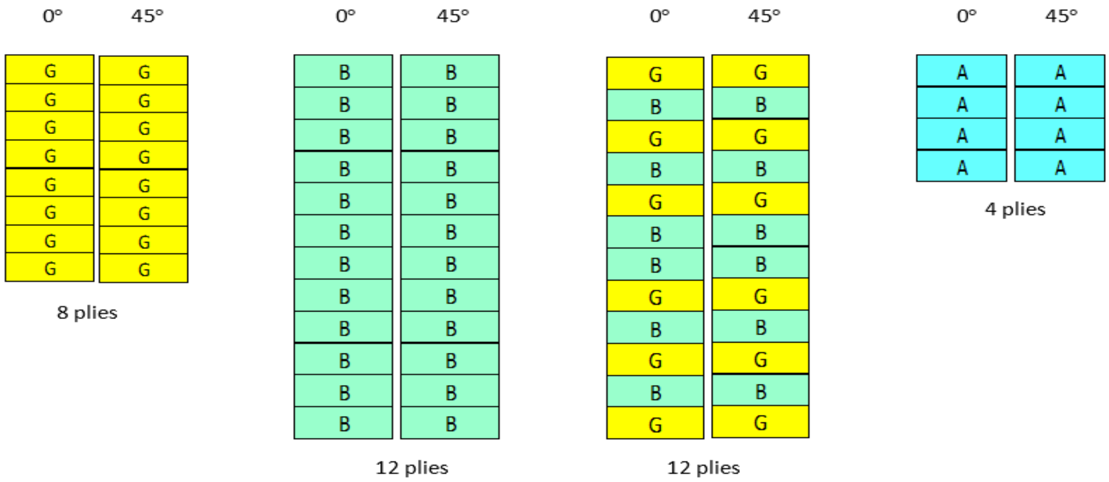
2.2 Specimen Fabrication

The FRP composites were fabricated using vacuum bagging methods. The FRP composite has different plies of glass, basalt and Arenga Pinnata fibres, in which the number of plies was decided based on the thickness of the fibres. For example, 8 plies of glass fibres were used to fabricate 0° and 45° direction of glass fibres reinforced polymer composite, 12 plies of basalt fibres were used to fabricate 0° and 45° direction of basalt fibres reinforced polymer composite, while 4 plies of Arenga Pinnata fibres were used to fabricate 0°, 45° and woven direction of Arenga Pinnata fibres reinforced polymer composite. However, for woven direction, both glass and basalt FRP composites used 14 plies of fibres. The final FRP composite plates were targeted to have a thickness of 5 mm as required for the drop weight test based on ASTM D7136. Table 1 and Figure 1 illustrate the systems of the FRP composites involved in this study.

Table 1: The designation of the FRP composite systems.

Designation	Description
UDB0	12 plies of unidirectional basalt fibres aligned in 0o
UDG0	8 plies of unidirectional glass fibres aligned in 0o
UDGB0	6 plies of unidirectional basalt fibres hybrid with 6 plies of unidirectional glass fibres aligned in 0o
UDAP0	4 plies of unidirectional Arenga Pinnata fibres aligned in 0o
UDB45	12 plies of unidirectional basalt fibres aligned in 45o
UDG45	8 plies of unidirectional glass fibres aligned in 45o
UDGB45	6 plies of unidirectional basalt fibres hybrid with 6 plies of unidirectional glass fibres aligned in 45o
UDAP45	4 plies of unidirectional Arenga Pinnata fibres aligned in 45o
WB	14 plies of woven basalt fibres
WG	14 plies of woven glass fibres
WGB	7 plies of woven basalt fibres hybrid with 7 plies of woven glass
WAP	4 plies of woven Arenga Pinnata fibres

Unidirectional type of fibres in FRP composites systems



Woven type of fibres in FRP composites systems

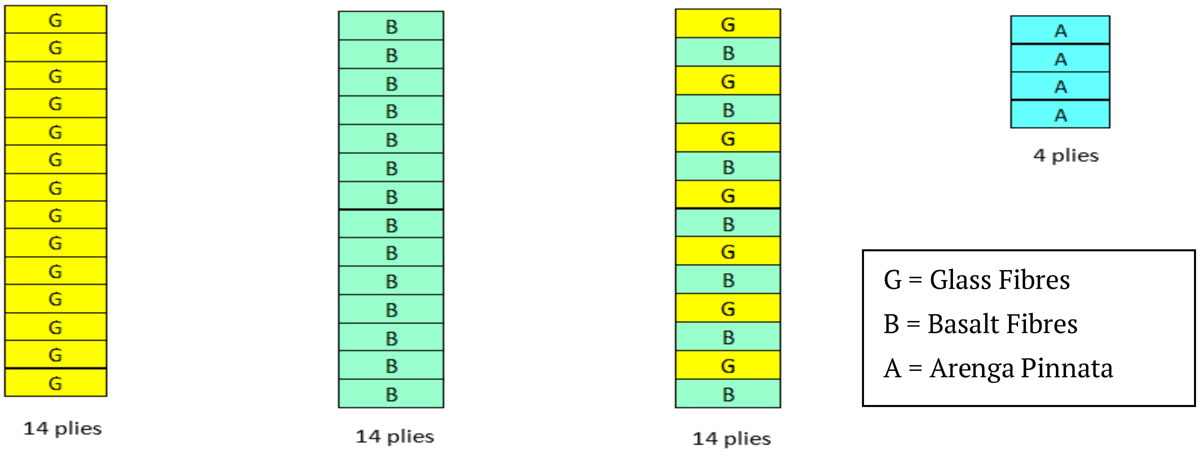


Figure 1: FRP Composites in different stacking sequences.

2.3 Drop Weight Impact Test

The drop weight impact test was performed using Instron Dynatup 8250 Drop Weight Impact Tester machine according to the ASTM D7136. All the FRP composites were prepared with dimensions of 50 mm x 50 mm x 5 mm, as illustrated in Figure 2. The impactor tower was fitted with a 5.5 kg of load and a hemispherical tip impactor of 12.5 mm diameter.

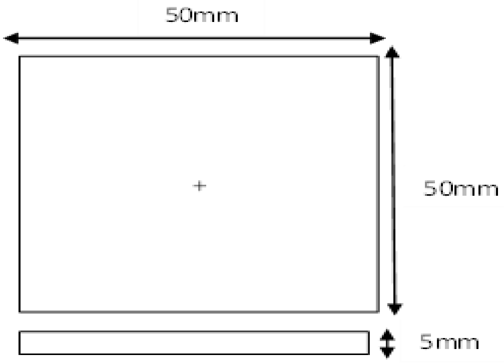


Figure 2: Schematic of FRP composites dimension; 50 mm x 50 mm x 5 mm.

3 Result and Discussion

The impact performance of the basalt fibre-reinforced polymer composites (BFRP), glass fibre-reinforced polymer composites (GFRP), basalt-glass fibre-reinforced polymer composites (BGFRP), and Arenga Pinnata fibre-reinforced polymer composites (APFRP) was evaluated at 30J of impact energy. The effect of the fibre architecture and fibre orientation i.e., aligned in [0°], [+45°/-45°] and woven was determined based on peak response force, absorbed energy and impact strength, and surface damage inspection via digital camera. Figure 3 shows the impact force-deflection curves for BFRP (UDB0, UDB45 and WB), GFRP (UDG0, UDG45 and WG), BFGFRP (UDBG0, UDBG45 and WGB), and APFRP (UDAP0, UDAP45 and WAP) composites. Each graph of the load-deflection curves has an ascending and descending section to perform the flexural load along the vertical axis and the deflection after applying load along the horizontal axis. The impact bending stiffness can be seen in the ascending section of the slope due to the material's ability to withstand impact force in flexure. Impact deflection is the strength of a composite under-effect bending at the start point of the impact process (Murat et al., 2009; Ozdemir et al., 2018). In Figure 3, it can be seen that the load-deflection curves have different behaviour for different types of FRP composites as they determine the FRP composite specimens as rebounding, penetration and perforation after being subjected to impact load. For UDBG0, UDB0, UDB45, UDAP0, UDAP45 and WAP composites, the impact load steadily increased until perforation occurred. These curves show that the descending section of the curve is entirely a softening curve with no rebounding segment. The perforation type of curve occurs once the load in the descending segment reaches a relatively constant value due to the friction applied between the impactor and the composite surface specimen (Ozdemir et al., 2018). For UDBG45, UDG0 and UDG45, the impact load steadily increased until penetration occurred. The penetration occurs when the impact energy rises, the FRP composite surface absorbs all of the energy and the impactor does not rebound from it as can be seen in Figure 3 (b). The load-deflection curves of the woven type for WB, WG and WGB rebounding after maximum load determine that the impactor does not penetrate and perforate into the FRP composites. The rebounding occurs when the curve consists of an ascending segment of loading and a descending area which is combining loading and unloading as can be seen in Figure 3 (c). The descending section shows the partial weakening of the material and partial rebounding of the impactor. The area between the associated load-deflection curve and the horizontal axis up to the beginning of the curve's friction region can be used to calculate the absorbed energy of a perforated FRP composite.

It can be seen that at 0° direction, the UDB0, UDG0 and UDBG0 recorded about 29.75J, 29.91j and 29.55J for the energy absorbed, respectively. At 45° direction, the energy absorbed for UDB45, UDG45 and UDBG45 was recorded to be about 32.7J, 32.77J and 28.8J, respectively. Meanwhile, the energy absorbed for woven types was recorded at about 6.83J, 6.32J and 6.53J for WB, WG and WGB, respectively. The results concluded that both BFRP and GFRP have comparable impact properties. Therefore, the hybridization of basalt with glass fibres also resulted in comparable impact properties. For impact strength, the GFRP composites are slightly higher as compared to BFRP composites with 0.54 %, 0.21% and 4.93% for 0°, 45° direction and woven type, respectively. It can be concluded that the impact strength of BFRP and GFRP was also comparable. Therefore, in the current situation, the development of natural fibre composites to replace synthetic fibres in reducing the dependence on petroleum sources will be achieved when using basalt to replace glass fibres. The comparable impact properties between basalt and glass fibres might be due to the similar percentage and composition since basalt and glass fibres have higher silica content as reported by Dhand et al. (2014), Bulut et al. (2017) and Sapiai et al. (2021). However, in this study, Arenga Pinnata fibre was also introduced as a natural fibre-based product to attempt the potential of replacing the usage of glass fibre. In this study, APFRP composites were compared with GFRP composites. The results show that the energy absorbed for UDAP0, UDAP45 and WAP was lower by 65.36%, 71.35% and 66.21% as compared to UDG0, UDG45 and WG, respectively. As such, it can be concluded that it is difficult to control the properties of the natural fibres based i.e., Arenga Pinnata fibres due to the variety of the quality. Most of the literature stated that the natural fibres depend on various factors such as chemical structure like cellulose, the degree of polymerization, orientation and crystallinity which are affected by conditions during the growth of the plant as well as the age of the plant from which the fibres are extracted (Saba et al., 2015). In impact performance, as can be seen in Figure 3, the load-displacement graphs of APFRP composites show the perforation with oscillated peak load curves which indicated that the APFRP composites are easily cracked due to the lower strength of the fibres and lower perforation. A lower perforation threshold indicates that the composite laminate is less resistant to impactor penetration (Ismail et al., 2019). However, there is still hope to replace the synthetic fibres i.e., glass fibres with some alteration. The characteristic of fibres architecture includes fibres continuity, fibres orientation, fibre crimping and fibres interlocking which is believed to enhance the overall performance of composites (Majeed et al., 2013; Bajuri et al., 2016; Sreenivasan et al., 2015). For instance, in this study, the Arenga Pinnata fibres were aligned, studied and evaluated at 0°, 45° and woven directions. The result shows that the impact strength of UDAP0 and WAP was 84.46 kJ/m^2 and 83.13 kJ/m^2, which increased by about 80.78% and 77.93% as compared to UDPA45, respectively.

The damage pattern in Table 3 was obtained from a digital camera, which presented the front and back view of the BFRP, GFRP, BGFRP and APFRP composites after being subjected to impact loading. In impact loading, matrix crack propagation in the thickness direction is harmful since the strength fibres inside the composites might block their expansion. All the FRP laminates are vulnerable to impact damage due to the brittleness of the polyester resin and the ability to absorb impact energy. When impact energy is greater than the energy required to break the fibres, the damage may propagate and break the composites (Ismail et al., 2019; Zhang et al., 2018). During the impact event, the force is required to cause composite damage via delamination, fibre fracture and matrix cracking. The damage pattern observed may vary depending on the fibre orientation. As can be seen, for the 0° direction, the damage started in the middle of the impacted area and propagated along with the fibre direction for all types of FRP composites.

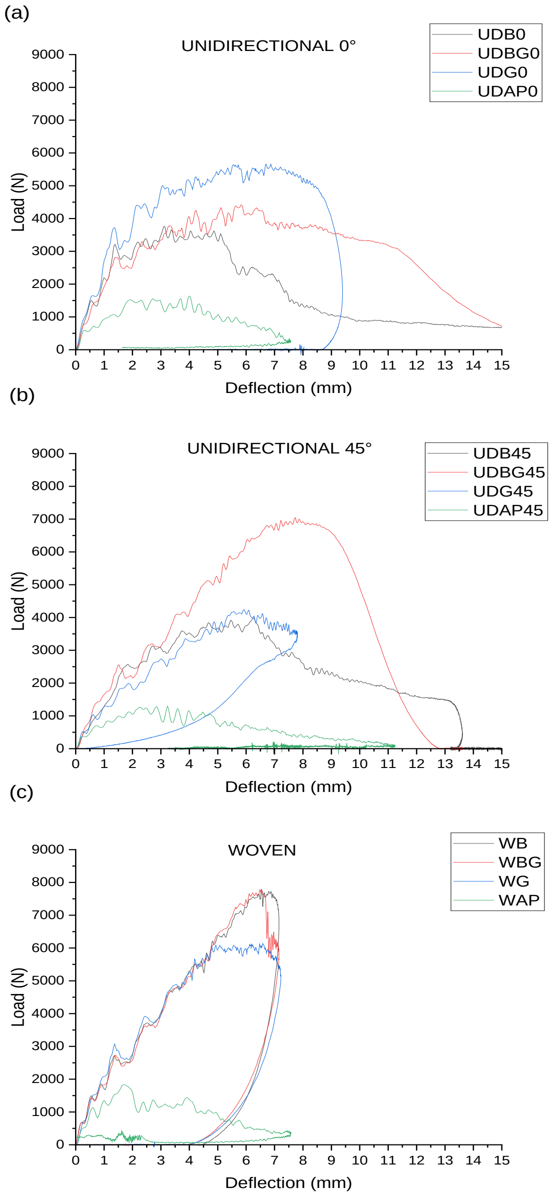


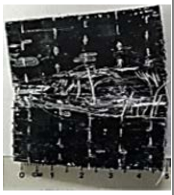
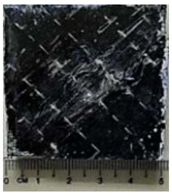
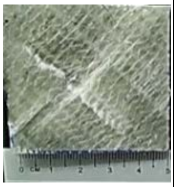
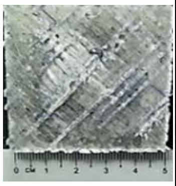
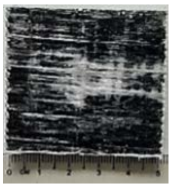
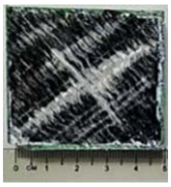
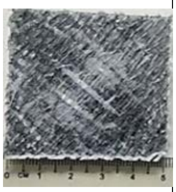
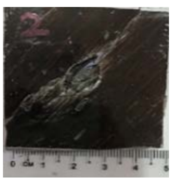
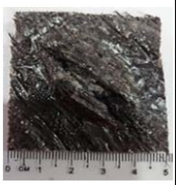
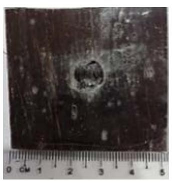
Figure 3: Typical load-deflection curves of BFRP, GFRP, BGFRP and APFRP composites aligned in (a) 0°, (b) 45° and (c) woven direction.

Table 2: Impact properties of BFRP, GFRP, BGFRP and APFRP composites at impact energy of 30J.

Composite	Peak load (kN)	Deflection (mm)	Energy Absorbed (J)	Impact Strength (kJ/m^2)
UDB0	3562.75±284.61	2.84±0.38	29.75±1.81	242.55
UDG0	5679.35± 33.02	6.25±0.25	29.91±0.54	243.85
UDGB0	4646.5±321.31	5.83±0.08	29.55±0.52	240.92
UDAP0	1508.9±179.04	3.85±0.18	10.36±1.82	84.46
UDB45	3979.65±7.14	5.79±0.67	32.70±0.42	266.60
UDG45	4056.7±257.81	5.98±0.3	32.77±0.20	267.17
UDGB45	7344.45±424.48	6.99±0.27	28.8±0.91	234.80
UDAP45	1732.55±620.91	16.99±19.54	9.39±0.50	46.72
WB	7548.15±334.67	6.83±0.41	28.77±0.41	234.56
WG	6039.35±139.65	6.32±0.42	30.19±0.10	246.14
WGB	7784.8±5.66	6.53±0.09	29.37±0.03	239.45
WAP	1611.9±348.32	3.43±0.777	10.20±1.72	83.13

In 45° orientation, the damaged area of the composites especially UDG45 and UDBG45 was marked as “X” as the crack propagated in a [+/-45°] fibres direction. The woven type of BFRP, GFRP, GBFRP and APFRP composites obtained a spherical damage pattern around the impacted surface due to the delamination starting in the middle impacted area and propagating along warp and weft direction. Based on the observation and analysis of the damaging impact, UDB45 and UDG45 composites gave a better result compared to UDB0 and UDB0 composites due to the orientation of 0° that formed a bending and cracking of fibre in a horizontal direction which was totally due to the perforation that led to fibre breakage on the front and back view. For 45° orientation, the composites formed surface deformation at [+/-45°] fibre orientation which led to matrix cracking partially before propagation. The fibre orientation in the laminate can affect its impact energy absorption capability, with an [+45/-45] interface showing the least impact damage (Giasin et al., 2022). Furthermore, the fibre orientations of each FRP composite play a significant role in mitigating the effect of fibre orientation as it is shown that woven types give a higher peak load due to less deflection and rebounding. In conclusion, the damage pattern is an indicator to estimate the energy absorption mechanism via matrix cracking, fibre breakage and delamination in fibre-reinforced polymer composites (FRP) systems after being subjected to impact loading (Norazean et al., 2015).

Table 3: Damage fracture of BFRP, GFRP, BGFRP and APFRP composites from front and back views.

FRP Composites	0°		45°		Woven	
	Front View	Back View	Front View	Back View	Front View	Back View
BFRP						
GFRP						
BGFRP						
APFRP						

4 Conclusion

The impact behaviour of BFRP, GFRP, BGFRP and APFRP composites has been successfully developed and investigated. The finding of this research can be summarised as follows: The impact behaviour of FRP composites was affected by the orientation and fibre type. The result shows that in [45°] fibre orientation, UDB45 and UDBG45 achieved higher energy absorbed and impact energy. In contrast with APFRP composites, 45° orientation (UDAP45) presented the lowest impact strength with 81.16% and 77.93% lower than UDAP45 and WAP. The damage pattern observed may vary depending on the fibre orientations. In the 0° direction, the damage started in the middle of the impacted area and propagated along with the direction of the fibres. In 45° orientation, the damaged area of the composites especially UDG45 and UDBG45 was marked as "X" as the crack propagated in a [+/-45°] fibres direction. The woven type of FRP composites obtained a spherical damage pattern around the impacted surface as the crack propagated in the weft and warp fibre direction. BFRP and GFRP have comparable impact properties as basalt and glass fibres have similar percentages and composition of higher silica content. Therefore, the hybridization of basalt and glass fibres gives similar behaviour as basalt and glass fibres alone. Energy absorbed for UDAP0, UDAP45 and WAP were lower by 65.36%, 71.35% and 66.21% as compared to UDG0, UDG45 and WG, which concluded that impact properties of plant-based natural fibres are inferior to impact properties of synthetic fibres as compared to mineral based natural fibres.

5 Availability of Data And Material

Data can be made available by contacting the corresponding author.

6 Acknowledgement

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