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Quasi and dynamic impact performance of hybrid cross-ply banana/glass fibre reinforced polypropylene composites

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**Abstract**

Natural fibres have been in demand as a replacement of synthetic fibres. However, natural fibres have disadvantages such as low mechanical properties compared to synthetic fibres, weak matrix to fibre adhesion and low thermal stability. Therefore, using natural fibres as a single reinforcement is inadequate to satisfy the technical needs of the composite. Hybridisation between natural and synthetic fibres can enhance the properties by taking the advantages of each of the individual fibres. This paper presents the hybridisation effect between banana and glass fibre. The low-velocity impact performance of hybrid cross-ply banana/glass fibre reinforced polypropylene composites were investigated and compared with quasi static indentation. Four types of stacking sequences composites were manufactured using hot compression moulding method, and the test was carried out according to American Society for Testing and Materials (ASTM) D6264 for quasi-static indentation and ASTM D7136 for low-velocity impact. The results revealed that the incorporation of glass fibre in banana fibre reinforced composite leads to higher energy absorption and improved the overall impact performance.

**1. Introduction**

Polymeric composites are currently substituting metals in various fields such as automotive, aeronautical and marine industries owing to their electric, mechanical and thermal properties, low cost and lightweight [1]. Composites require optimal performance, especially in natural fibre reinforced composites where the weakness is the variability in their characteristic properties [2]. Natural fibres have disadvantages of being hydrophilic, lower durability and lower impact strength [3]. The transverse performance of composite laminates is crucial, especially when they are recognised to suffer low-velocity incidents such as tool drops, stone or debris strike and many more [4]. The damage type and size due to an impact generally regulate the residual properties of the structure made of composite laminates [5–8]. Researches have been enhancing the impact damage resistance of composite laminates. One method is hybridisation, to enhance the low velocity damage resistance of composites and to decrease the expenses of the materials [9–12]. Natural fibre reinforced composites are still limited to semi-structural applications due to inherent low resistance towards impact damage is well recognised to minimise the mechanical properties of composite laminates considerably [13]. Most vital factors that influence the impact behaviour of the composite are the stacking sequence and the architecture alongside with the thickness [13, 14].

Impact test can be divided into four groups which are low velocity, high velocity, ballistic and orbital. The low-velocity impact is described to happen at a velocity under 10 m s⁻¹, while high-velocity impact happens in the 10 to 50 m s⁻¹. Ballistic impact happens at 50 to 1000 m s⁻¹, and orbital impact takes place in the range of 2 to 5 km s⁻¹ [15]. Most of the times, low-velocity impact initiates delamination in composites and can cause unexpected catastrophic failure. The damages that form matrix cracking and delamination can cause tremendous subsurface delamination, which is not visible hence lowering the strength and stiffness of the structure [16].

Bunea et al [17] investigates the impact behaviour of the fabric-reinforced hybrid composites with stratified filled epoxy matrix. The outcomes confirmed that a notable effect over the fracture mode of the composites is the
matrix properties and the fibre orientation. Hybrid composites with higher carbon fabric ply with 0° orientation exhibit the highest impact resistance when compared with various angle orientation. The fibre orientation at a variety of angles influences the deformation mechanisms of the fabric-reinforced composites under impact loads [18]. Caminero and Rodriguez [19] discovered that the considerable differences of the angles between adjacent plies led to higher delamination areas, which propagated as a function of the fibre direction. Liu et al [20] analysed the low velocity effects on hybrid epoxy laminates reinforced with unidirectional and five harness satin woven carbon fibre fabric at impact energy levels of 10 J, 17 J and 25 J. It was observed that the inclusion of 90° layers in composite structures led to lowering of response time and growing of delamination alongside the transverse direction. Caminero et al [21] investigated the effect of thickness and ply-stacking sequence on impact behaviour and compression after impact loading of carbon fibre reinforced epoxy plates. It was found an increase of maximum load and a decrease of absorbed energy with the increase of plate thickness. However, a comparable impact behaviour was determined in the case of cross-ply [0/90]±4 and angle-ply [±45]4s. Nor et al [22] noted that higher impact energy effects in more excellent energy absorption. As the laminate thickness increases, the resistance presented by the laminates in delamination increases and absorbs higher energy in delamination mode [23]. Regarding the impact behaviour of the material reinforced epoxy composites, several kinds of damages were suggested such as matrix cracking, fibre breakage and delamination [24, 25].

Banana fibre from the trunk is a secondary crop and abundantly available. Often, the trunk was left to be decomposed after the fruit is harvested. This work will give enhancement to commercialise the banana fibre in engineering applications. The studies of the low-velocity impact on hybrid natural/synthetic composite are scarce. Therefore, in this study, the effects of stacking sequence of cross-ply hybrid banana/glass fibre reinforced polypropylene composite on quasi and low velocity impact are investigated.

2. Experimental procedure

2.1. Materials and equipment
Cross-ply (0/90°) banana fibre (B) with an areal weight of 342.5 g m⁻² used in this study was supplied by J C Overseas Incorporation, India. Cross-ply (0/90°) glass fibre (G) with an areal weight of 600 g m⁻² was supplied by ZKK Sdn. Bhd, Malaysia. Polypropylene pellets with a density of 0.95 g cm⁻³ were supplied by Al Waha, Saudi Arabia. Common properties of banana fibre, glass fibre and polypropylene are tabulated in table 1.

2.2. Composite fabrication
Four different sets of stacking sequences of the composite with a dimension of 250 × 250 mm were manufactured using hot compression moulding machine. Cross-ply banana and glass fibres were placed alternately with PP sheet and hot compressed at 170 °C at 3.5 MPa pressure. The stacking sequence of composites is as shown in figure 1. Two types of non-hybrid composite, BBB and GGG and two types of hybrid composites BGB and GBG were fabricated. Details on the composite fabrication techniques can be referred in Zulkafi et al [29].

Table 2 displays the weight and thickness of each stacking sequence. The difference of weight and thickness varies with types of fibres and ply sequences in the composite.

2.3. Quasi-static indentation test
Quasi-static indentation (QSI) test was performed according to ASTM D6264. The dimensions of the samples were 100 × 100 × thickness mm. The test was performed using INSTRON universal Testing Machine 5585 with 150 kN load cell and a steel hemispherical tip impactor with a diameter of 12.7 mm. The specimens were bolted between the top and bottom support clamping ring with a diameter of 76 mm to prevent slippage in edge supported configuration. Five samples were tested for each stacking sequences. The crosshead displacement speed is 1.27 mm min⁻¹. The penetration energy absorbed by the composite was calculated based on the area under the penetration load-displacement curves.

| Properties        | Banana | Glass | PP  |
|-------------------|--------|-------|-----|
| Tensile strength (MPa) | 550    | 1700–3500 | 22–41.4 |
| Elastic modulus (GPa) | 22–32  | 65–72  | 1.5–2  |
| Elongation (%)     | 3–4    | 3      | 3–700 |
| Density (g cm⁻³)  | 1.35   | 2.58   | 0.91  |

Table 1. Common properties of banana fibre, glass fibre and polypropylene matrix [26–28].
2.4. Low-velocity impact test

Low-velocity impact (LVI) test was performed according to ASTM D7136. The dimensions of the samples were 100 × 100 × thickness mm. The test was performed using a CEAST 9250 drop tower impact machine, a clamping ring of 76 mm diameter and a hemispherical tip cylindrical steel impactor with a diameter of 12.7 mm. A total mass of 10.1210 kg was used in the experimental test delivering a nominal impact velocity of 4.5 m s\(^{-1}\). The total impact energy applied during the test is 102.48 J. The test was conducted with an edge supported configuration similar to quasi-static indentation test. The energy absorbed by the composite was calculated using the area under the load-displacement curves.

3. Results and discussion

3.1. Quasi-static indentation

The typical load-displacement curves of quasi-static indentation for each stacking sequence are plotted in figure 2. The results of the test were analysed based on the force-displacement curves, total energy absorption and specific energy absorption. Initially, an incremental linear trend can be observed on the curve until the peak load reached, followed by a drop in the load. The load drop is due to a decrease in rigidity caused by fibre-matrix debonding and matrix fracture. Once the composite has reached the peak load, damage can be observed. A dent formed on the top surface of the composite will eventually initiate a crack at the maximum indentation [30].

Based on figure 2, non-hybrid GGG composite has the highest peak load of 6.28 kN, followed by hybrid GBG, BGB and non-hybrid BBB composite with 4.69 kN, 3.07 kN and 2.01 kN respectively. The incorporation of stiffer glass fibre increases the resistance to indentation and formation of a shear plug [31]. The highest energy absorbed is 44.94 J in GGG. The energy absorbed reduced from GGG to GBG, BGB and BBB with 27.12 J, 16.32 J and 10.38 J respectively. This phenomenon was supported by Mahdad [32], who stated that stiffer layers at both
upper and lower surfaces of the laminate were able to withstand higher deformations before breaking and have prevented the spread of damage to the sides, thus increasing the maximum load capacity. Table 3 summarises the quasi-static indentation findings. Specific energy absorbed follows a similar trend as the energy absorbed. GGG has almost twice the specific energy absorbed compared to GBG.

### 3.2. Low-velocity impact

The load-displacement curves are plotted for each stacking sequence based on the data generated by CEAST drop impact machine as in figure 3. Based on the curves, all of the samples experienced perforation. Therefore, the peak load can be determined as the maximum load that the samples can withstand. Based on figure 3, the load increased with an increasing layer of glass fibre in the composite. The higher the slope in a load-displacement curve, the stiffer the sample. Thus, making GGG the stiffest sample. The increasing trend of stiffness can be observed from BBB to GGG. For low-velocity impact, the transient response of each composite during impact loading was recorded in terms of load and displacement and the critical impact parameters like peak load, the maximum displacement of peak load and absorbed energy are summarised in table 4.

Generally, a higher peak load and absorbed energy values tend to promote larger damaged areas\[33\]. During LVI fibre fracture due to bending and fibre debonding started to take place and stiffness reduction were observed. These damage observations follow the trends of the QSI test. Russo et al\[34\] believed that the bonding efficiency of composites plays a significant role in improving their impact performance. The pulling out of fibres dissipates a large amount of impact energy. However, the more compact interface resists fibre pull-out by increasing the friction during fibre slipping\[35\].

As in figure 4, the force–time curve yielded almost linear behaviour up to the onset of the damage point. During the test a significant part of the energy of BBB is absorbed through non-elastic mode. Hence the existence of large plateau around maximum load is observed. This shows the capability of plant fibre composite to deflect
the progression of the impacting head during the impact event. However, increasing glass fibre layup reduce the extension of this plateau, where the behaviour between hybrid laminates is limited.

Figure 5 depicts the peak load and maximum displacement at peak load for each stacking sequence. It can be seen that the peak load increase with composite stiffness. The peak load for BBB is 1.22 kN, increasing to BGB, GBG and GGG with 2.13 kN, 3.97 kN and 6.60 kN respectively. GBG exhibited 39.85% less impact load compared to GGG. The displacement at peak load for BBB is 9.09 mm, increasing to BGB, GBG and GGG with 10.33 mm, 11.16 mm and 13.24 mm respectively.

Figure 4. Typical load versus time curve for each stacking sequence.

Figure 5. Peak load and displacement of low-velocity impact for each stacking.

Figure 6. Energy and specific energy absorbed of each stacking in low-velocity impact.
Hybrid composites of BGB and GBG shows a significant improvement compared to non-hybrid BBB. BGB has 42.72% and 12% higher peak load and maximum displacement compared to BBB, while GBG has 46.35% and 7.38% higher peak load and maximum displacement compared to BGB.

Figure 6 shows the absorbed energy and specific absorbed energy of the composite for each stacking up to peak load. Impact resistance is always related to energy absorption, and some researchers believe that the higher the energy absorption, the greater the resistance to impact [34]. Non-hybrid BBB and GGG have absorbed 6.83%, and 37.36% energy from the drop weigh impact energy of 102.48 J. Hybrid BGB, and GBG has absorbed 10.46% and 19.71% energy from the drop weight impact energy. This is due to the high energy absorbing characteristic of glass fibres [31]. This shows that incorporating stiffer fibre (glass) in natural fibre (banana), reinforced thermoplastic composites increase the impact performance. It has been determined that the impact performance of hybrid composites is better than non-hybrid composites.

| Specimen ID | QSI | LVI |
|-------------|-----|-----|
| BBB         | ![Matrix plasticised](image1) | ![Crack lines](image2) |
| BGB         | ![Matrix plasticised](image3) | ![Crack lines](image4) |
| GBG         | ![Fibre pull-out](image5) | ![Crack lines](image6) |
| GGG         | ![Fibre pull-out](image7) | ![Crack lines](image8) |

*Figure 7. The front surface damage for quasi-static indentation and low-velocity impact.*
performance of non-hybrid banana fibre reinforced composites, cannot compete with synthetic fibre reinforced composites. Therefore, hybridisation ought to compensate for natural and synthetic fibres while being environment friendly. Table 4 shows the summary of low velocity impact performance.

| Specimen ID | QSI | LVI |
|-------------|-----|-----|
| BBB         | Plasticised matrix | Diamond-shaped fracture |
| BGB         | Fibre pull-out | Fibre pull-out |
| GBG         | Delamination along crack lines | Delamination |
| GGG         | Matrix bulging and plasticised | Delamination along crack lines |

Figure 8. The rear surface damage for quasi-static indentation and low-velocity impact.

3.3. Damage assessment quasi-static indentation versus low-velocity impact
The low-velocity impact can be treated as a quasi-static indentation event. For low-velocity impact, the failure mode and energy absorption are highly dependent on the specimen size, stiffness and boundary conditions [36–38]. The impact energy for a compliant specimen subjected to LVI is absorbed by primarily in the form of
strain energy, in addition to energy for micro-cracking, fibre breakage and delamination, not accounting for loss from supports and boundary.

Figure 7 shows the front surface damage area for quasi-static indentation and low-velocity impact for each stacking sequence. The perforated area for BBB in LVI samples is more extensive than QSI samples. There is more visible matrix cracking in the LVI samples. BBB has a smooth surface near the perforation area. A smooth surface in the direction of impact indicates fast crack propagation that contributes to their low toughness value [38]. The BGB damage looked similar; however, a larger perforated area is observed in LVI samples. Since the LVI can be treated as a quasi-static event; therefore, the matrix plasticised area in QSI is predicted to crack as in LVI. GBG also shows a comparable trend with BGB. GGG also showed a similar trend; however, the matrix is plasticised and bulged, creating wave-like damage near the perforation area. The difference between QSI and LVI samples is that the LVI fracture is more brittle than QSI. This is due to the sudden impact applied to the samples and the LVI damage area is much larger than the QSI samples.

Figure 8 shows the rear surface damage area for quasi-static indentation and low-velocity impact for each stacking. BBB shows perforated area with diamond shape indicates lower resistance for impact in LVI samples. In QSI samples, the failure occurred when the indented area went through the composite, however without using higher load compare to LVI. This is due to the evidence that there are almost no crack lines visible as much as in LVI samples. In BGB, the damage looked similar in both QSI and LVI samples where the core glass fibres were pull-out through the composite. However, in LVI, the glass fibres breakage can be seen after the impact. GBG in QSI has one primary matrix cracking line across the surface while in LVI, the matrix cracks in every direction. Interestingly GGG in QSI has more plasticised region and bulging matrix near the perforation area. While in LVI samples, the delamination can be observed starting from the perforation area along the matrix cracks.

4. Conclusion

In this study, the effects of stacking sequence of hybrid cross-ply banana/glass fibre reinforced polypropylene composites on quasi static indentation and low-velocity impact are investigated. Based on the results obtained, the incorporation of glass fibre in the composite improves the energy absorption. Hybrid GBG has 63.27% more specific energy absorbed than BBB composite. Hybrid GBG can be considered for specific application for its advantages of being low material cost and lightweight. The hybridisation between banana and glass fibres enhanced the performance by taking the advantages of the characteristics of both banana and glass fibre. The composite can be applied for automotive and aerospace interior parts.

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References

[1] Todor M P, Bulei C, Hepur T and Kiss I 2018 Researches on the development of new composite materials complete/partially biodegradable using natural textile fibers of new vegetable origin and those recovered from textile waste Int. Conf. Appl. Sci. 294 012021
[2] Safri S N A, Sultan M T H, Jawaid M and Jayakrishna K 2018 Impact behaviour of hybrid composites for structural applications: a review Compos. Part B Eng. 133 112–21
[3] Pickering K L, Efendy M A and Le T M 2016 A review of recent developments in natural fibre composites and their mechanical performance Compos. Part A Appl. Sci. Manuf. 83 98–112
[4] Ravandi M, Teo W S, Tran L Q N, Yong M S and Tay T E 2017 Low velocity impact performance of stitched flax/epoxy composite laminates Compos. Part B 117 89–100
[5] Bibo G A and Hogg P J 1998 Influence of reinforcement architecture on damage mechanisms and residual strength of glass-fibre/epoxy composite systems Compos. Sci. Technol. 58 803–813
[6] Giannopoulos I K, Theotokoglou E E and Zhang X 2016 Impact damage and CAI strength of a woven CFRP material with fire retardant properties Compos. Part B 91 8–17
[7] Tan K T, Watanabe N, Iwashiro Y and Ishikawa T 2012 Effect of stitch density and stitch thread thickness on compression after impact strength and response of stitched composites Compos. Sci. Technol. 72 587–98
[8] Tan W, Falzon B G, Chiu I, N S and Price M 2015 Predicting low velocity impact damage and compression-after-impact (CAI) behaviour of composite laminates Compos. Part A 71 212–26
[9] Gustin J, Joneson A, Mahinfalham M and Stone J 2005 Low velocity impact of combination Kevlar/carbon fiber sandwich composites Compos. Struct. 69 396–406
[10] Naik N K and Meduri S 2001 Polymer-Matrix Composites Subjected to Low-Velocity Impact: Effect of Laminate Configuration Compos. Sci. Technol. 61 1429–36
[11] Papa I, Ricciardi M R, Antonucci V, Pagliarulo V and Lopresto V 2018 Impact behaviour of hybrid basalt/flax twill laminates Compos. Part B 133 17–25
[12] Selmy A I, El-baky M A A and Hegazy D A 2019 Mechanical properties of inter-PLY hybrid composites reinforced with glass and polyamide fibers J. Thermoplast. Compos. Mater. 32 267–93
[13] Caprino G and Lopresto V 2000 The significance of indentation in the inspection of carbon fibre-reinforced plastic panels damaged by low-velocity impact Compos. Sci. Technol. 60 1003–12
[14] Hosur M V, Karim M R and Jeelani S 2003 Experimental investigations on the response of stitched/unstitched woven S2-glass/SC15 epoxy composites under single and repeated low velocity impact loading Compos. Struct. 61 89–102
[15] Abrate S 2011 Impact engineering of composite structures CISM International Centre for Mechanical Sciences (526) (Vienna: Springer-Verlag Wien)978-3-7091-0522-1 (https://doi.org/10.1007/978-3-7091-0523-8)
[16] Razali N, Sultan M T H and Javaid M 2019 Impact damage analysis of hybrid composite materials Durability and Life Prediction in Biocomposites, Fibre-Reinforced Composites and Hybrid Composites (Composites Science and Engineering) (The Officers’ Mess Business Centre, Royston Road, Duxford, CB22 4QH, United Kingdom: Woodhead Publishing) 121–13978081022900
[17] Bunea M, Circiumaru A, Bucicumeau M, Birsan I G and Silva F S 2019 Low velocity impact response of fabric reinforced hybrid composites with stratified filled epoxy matrix Compos. Sci. Technol. 169 242–8
[18] Hazzard M K, Hallert S, Curtis P T, Iannucci L and Trask R S 2017 Effect of fibre orientation on the low velocity impact response of thin dyneema composite laminates Int. J. Impact Eng. 100 35–45
[19] Caminero M A and Rodriguez GP 2017 Damage resistance of carbon fibre reinforced epoxy laminates subjected to low velocity impact: effects of laminate thickness and ply-stacking sequence Polym. Test. 63 330–41
[20] Liu H, Falzon B G and Tan W 2017 Experimental and numerical studies on the impact response of damage-tolerant hybrid unidirectional/woven carbon-fibre reinforced composite laminates Compos. Part B 138 101–18
[21] Caminero M A, Garcia-Moreno I and Rodriguez GP 2018 Experimental study of the influence of ply-stacking sequence on the compression after impact strength of carbon fibre reinforced epoxy laminates Polym. Test. 66 360–70
[22] Nor A F M, Sultan M T H, Hamdan A, Azmi A M R and Jayakrisna K 2018 Hybrid composites based on kenaf, jute, fiberglass woven fabrics: tensile and impact properties Mater. Today Proc. 5 11196–207
[23] Sikawar R S, Velmurugan R and Gupta N K 2014 Influence of fiber orientation and thickness on the response of glass/epoxy composites subjected to impact loading Compos. Part B Eng. 60 627–36
[24] Leonard F, Stein I, Souts C and Withers P J 2017 The quantification of impact damage distribution in composite laminates by analysis of x-ray computed tomograms Compos. Sci. Technol. 152 139–48
[25] Tehrani M, Boroujeni A Y, Hartman T B, Haugh T P and Case S W 2013 Mechanical characterization and impact damage assessment of a woven carbon fiber reinforced carbon nanotube—epoxy composite Compos. Sci. Technol. 75 42–8
[26] Agarwal R, Saxena N S, Sharma K B, Thomas S and Pothen I A 2003 Thermal conduction and diffusion through glass-banana fiber polyester composites Indian J. Pure Appl. Phys. 41 448–52
[27] Maddah H A 2016 Polypropylene as a promising plastic: a review Am. J. Polym. Sci. 6 1–11
[28] Wallenberger F T, Watson J C and Li F 2001 Glass Fibers 21 (Materials Park, OH: ASM International) pp 27–34 2001
[29] Zulkafi N, Malingam S D, Fadzullah SH S M, Mustafa Z, Zakaria K A and Subramaniam S 2019 Effect of water absorption on the mechanical properties of cross-ply hybrid pseudo-stem banana/glass fibre reinforced polypropylene composite Mater. Res. Express 6 095326
[30] Subramaniam K, Malingam S D, Feng N L and Bapokutty O 2019 The effects of stacking configuration on the response of tensile and quasi-static penetration to woven kenaf/glass hybrid composite metal laminate Polym. Compos. 40 368–77
[31] Dhar Malingam S, Jumaat F A, Ng L F, Subramaniam K and Ab Ghani A F 2018 Tensile and impact properties of cost-effective hybrid fiber metal laminate sandwich-structures Adv. Polym. Technol. 37 2185–93
[32] Mahdad M, Saada A A, Belaidi I, Mokhtari A and Benidir A 2018 Damage modelling in thermoplastic laminates reinforced with steel and glass fibres under quasi-static indentation loading at low-velocity Adv. Compos. Lett. 27 251–60
[33] Ma H, Jia Z, Lau K, Leng J and Hui D 2016 Impact properties of glass fiber/epoxy composites at cryogenic environment Compos. Part B 92 210–7
[34] Russo P, Acerino D, Simeoli G, Iannace S and Sorrentino L 2013 Flexural and impact response of woven glass fiber composite/ polypropylene composites Compos. Part B Eng. 54 415–21
[35] Simeoli G, Acerino D, Meola C, Sorrentino L, Iannace S and Russo P 2014 The role of interface strength on the low velocity impact behaviour of PP/glass fibre laminates Compos. Part B 62 88–96
[36] Abrate S 1991 Impact on laminated composite materials Appl. Mech. Rev. 44 155–90
[37] Richardson M O and Wisheart M 1996 Review of low velocity impact properties of composite materials Compos. Part A Appl. Sci. Manuf. 27 1123–31
[38] Fadzullah SH S M, Mustafa Z, Ramlu S N R, Yaacob O Q and Yusoff A F M 2016 Preliminary study on the mechanical properties of continuous long pineapple leaf fibre reinforced PLA biocomposites Key Eng. Mater. 694 18–22