Current Research in Green and Sustainable Chemistry 5 (2022) 100284

Contents lists available at ScienceDirect

Current Research in Green and Sustainable Chemistry

journal homepage: www.elsevier.com/journals/current-research-in-green-and-sustainable-chemistry/2666-0865

Effect of fiber stacking sequence and orientation on quasi- static indentation properties of sustainable hybrid carbon/ramie fiber epoxy composites

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ARTICLE INFO

Keywords:
Natural fiber
Hybrid composite
Sustainability
Indentation resistance
Absorbed energy
Damage assessment

ABSTRACT

Hybrid polymer composites reinforced with synthetic and natural fibers are gaining more interest in current composite technology in an effort to promote sustainability without sacrificing the performance of synthetic fiber reinforced polymer composites. The goal of this study is to see how the fiber stacking sequence of carbon and ramie fiber, as well as the orientation of ramie fiber, affects the quasi-static indentation behaviour of carbon/ramie fiber reinforced epoxy hybrid composites. The hybrid composite specimens were made using a hand layup approach followed by a hot pressing process. The quasi-static indentation properties of carbon/ramie fiber reinforcements in epoxy matrix were investigated using a hemispherical indenter at varying indenter displacement rates of 10, 20, and 30 mm/min for the stated stacking sequence and orientation. The indentation resistance qualities of carbon/ramie fiber reinforced epoxy hybrid composites were evaluated in terms of indentation force, hybrid composite specimen energy absorption capability, and hybrid composite specimen damage caused by hemispherical indenter penetration. The results reveal that a carbon/ramie fiber reinforced epoxy hybrid composite with 5 ramie fiber layers has better energy absorption capabilities, absorbing 114.926 J at a 20 mm/min indentation rate. Similarly, the indentation force in hybrid composites increases as the number of carbon/ramie fiber layers increases. These results indicate that carbon/ramie fiber reinforced epoxy hybrid composites have a great potential towards low velocity impact applications.

1. Introduction

Natural and synthetic fiber reinforced polymer composites have remarkable mechanical, damping, anticorrosion and durability properties. Composites are employed as structural materials in a variety of industries, including marine, aircraft and construction [1]. Because of their high specific strength, polymer composites are used as a metal alternative in a range of applications. Carbon fibers among the synthetic fibers employed as reinforcement, are regarded as one of the best performers in polymer matrix composites due to their capacity to improve the properties of polymer matrix composites [2–4]. Carbon fibers have exceptional properties such as increased specific strength and elongation at break, which allow them absorb more energy when subjected to impact loads. Carbon fiber, when reinforced in polymer composites has this ability making it a good choice for impact-resistant applications including helmets, dampers for machine installation, defense systems and bullet-proof components.

Carbon fiber reinforced composites are slightly stiffer than synthetic fiber reinforced polymer composites due to their superior mechanical

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https://doi.org/10.1016/j.crgsc.2022.100284
Received 31 December 2021; Received in revised form 21 January 2022; Accepted 22 January 2022
Available online 25 January 2022

characteristics. This feature inhibits carbon fiber reinforced polymer composites from achieving remarkable performance in a few impact-resistant applications, such as bullet-proof apparel [5]. The new trend of developing hybrid composites can help with this problem. Natural fibers have been discovered to be environmentally friendly and to have higher shock-absorbing properties [6]. Ramie a semitropical perennial plant with the scientific name Boehmeria nivea, is a major source of natural plant fiber. Ramie fibers, which are derived from the plant's stem, were previously employed primarily in textile applications. However, in the more current scenario synthetic fibers have surpassed natural fibers in textile fields. As a result, the large supply of Ramie fibers went undiscovered and was forced to be used as landfills.

It was proposed to produce hybrid composites with natural fibers as extra reinforcement in order to increase the sustainability of synthetic fiber reinforced polymer composites and to tailor composite materials for specific purposes [7]. Ramie fiber was recognized as an extra reinforcement in synthetic fiber reinforced polymer composites due to its copious availability and mechanical qualities. The development of hybrid composites using synthetic and natural fibers aids in the attainment of a balance between environmental concern and composite performance [8–10].

Aslan et al. studied the tensile characteristics of hybrid sisal-glass fiber reinforced polypropylene composites and discovered that increasing the weight percentage of glass fiber in the composite showed a favorable trend in the composite's tensile modulus and tensile strength [11]. When Yahaya et colleagues investigated the properties of kenaf-aramid fiber reinforced hybrid polymer composites, they discovered that the sequence of fiber mats in the polymer composite had a significant impact on the composite's flexural strength and flexural modulus [12]. The impact properties of neem-abaca-glass fiber reinforced hybrid polymer composites were highlighted by Kaliappan et al. [13]. They come to the conclusion that increasing the weight percentage of neem fiber in a composite enhances the impact properties of the polymer composite.

In the recent literature, many hybrid polymer composites with synthetic and natural fibers as reinforcements have been documented [14–17]. Mechanical parameters such as tensile, flexural, and impact properties were determined. However, to the author's knowledge, relatively little research on the quasi-static indentation properties of synthetic and natural fiber reinforced polymer composites has been published. This work investigates the effect of fiber stacking sequence and orientation in carbon/ramie fiber reinforced epoxy hybrid composite on the response properties of quasi-static indentation test. The incurred damages in the carbon/ramie fiber reinforced epoxy hybrid composite specimens were also further analyzed for more inferences.

2. Materials and methods

2.1. Materials

The bidirectional Cycom 934 prepreg carbon fiber mat as shown in Fig. 1(a) essential for the preparation of carbon/ramie fiber reinforced epoxy hybrid composite was procured from M/s. Cytec Engineered Materials Pvt Ltd, United States. Also, the unidirectional ramie fiber as shown in Fig. 1(b) was obtained from KORI (Konsorsium Ramie Indonesia), Indonesia. The fibers obtained from different suppliers were used as such without further processing as well as the chemical composition and mechanical properties of ramie fiber are as presented in Table 1 and Table 2 respectively. A metal plate as shown in Fig. 2 was used as the base for preparation of composite specimens. Moreover, no separate resin is purchased for the preparation of hybrid composite specimens since the Cycom 934 prepreg carbon fiber mat has epoxy resin to bond the fibers.

2.2. Composite fabrication

Hand lay-up technique was followed for stacking the fibers as per the sequence and ramie fiber orientation portrayed in Table 3 with specimens code for preparation of carbon/ramie fiber reinforced epoxy hybrid composites to size 300 mm × 300 mm [21]. Five hand laid carbon/ramie fiber reinforced epoxy hybrid composites plates with fibers following the stacking sequence and orientation presented in Table 3 was hot pressed for 60 min at a temperature of 170 °C individually by placing over the

Table 1
Chemical composition of Ramie fiber [18].

Chemical composition	Quantity
Cellulose (wt.%)	68.6–76.2
Lignin (wt.%)	0.6–0.7
Hemicellulose (wt.%)	13.1–16.7
Pectin (wt.%)	1.9
Wax (wt.%)	0.3
Micro fibril angle (°)	7.5

(a) (b)

Fig. 1. Fiber materials used as reinforcement (a) Bidirectional Woven Carbon Fiber Prepreg (b) Unidirectional Ramie Fiber.

Table 2
Mechanical properties of Ramie fiber [19,20].

Properties	Value
Tensile strength (MPa)	560
Young's modulus (GPa)	24.5
Elongation (%)	2.5
Diameter (μm)	34
Density (g/cc)	1.55

Fig. 2. Base metal plate used for hot pressing process.

Table 3
Fiber stacking sequence and orientation of ramie fiber with composite specimen.

Specimens code	Number of ramie fiber layers	Number of carbon fiber layer	Fiber stacking sequence (R = Ramie, C = Carbon)	Orientation of ramie fiber
CR1	1	2	C/R/C	0
CR2	2	3	C/R/C/R/C	0/90
CR3	3	4	C/R/C/R/C/R/C	0/90/0
CR4	4	5	C/R/C/R/C/R/C/R/C	0/90/0/90
CR5	5	6	C/R/C/R/C/R/C/R/C/R/C	0/90/0/90/0

Fig. 3. Hot pressing processes in oven.

metal plate as shown in Fig. 3 [22]. During the hot pressing process the epoxy resin available in bidirectional Cycom 934 prepreg carbon fiber mat melts and wets the carbon as well as ramie fibers resulting in a well bonded carbon/ramie fiber reinforced epoxy hybrid composite as shown in Fig. 4. The fabricated carbon/ramie fiber reinforced epoxy hybrid composite plates identified by specimens codes were measured and calculated for parameters like mass, thickness, weight percentage of fiber/matrix, density as presented in Table 4.

2.3. Quasi-static indentation test

The knowledge of indentation resistance and energy absorption characteristics of fabricated carbon/ramie fiber reinforced epoxy hybrid composites can be understood from quasi-static indentation test [23]. The damages incurred in carbon/ramie fiber reinforced epoxy hybrid composites during the quasi-static indentation test also reveals few inferences. The quasi-static indentation test was conducted as per ASTM D6264/6264-17 standard at ambient temperature and standard laboratory conditions [24]. All the carbon/ramie fiber reinforced epoxy hybrid composite specimens with varied fiber stacking sequence and ramie fiber orientation with named specimens codes for identification were sized to

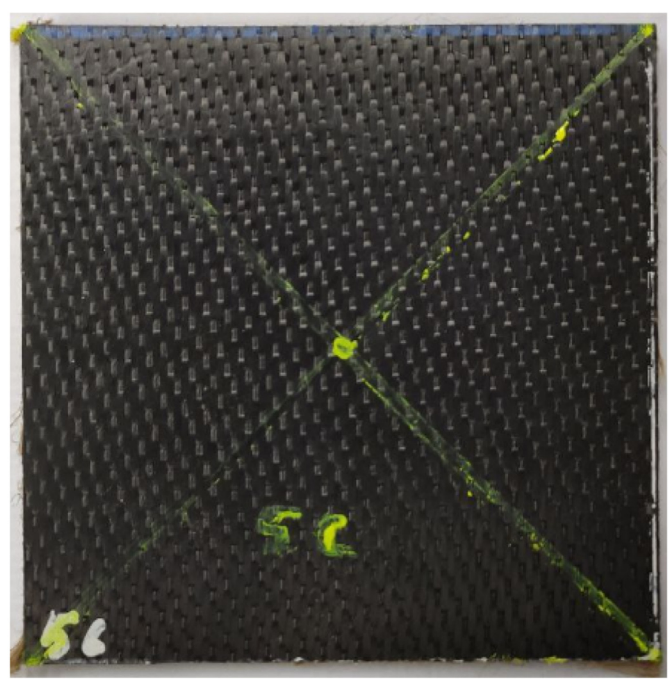


Fig. 4. Fabricated carbon/ramie fiber reinforced epoxy hybrid composite.

100 mm × 100 mm using dremel cutter as shown in Fig. 5 to carry out quasi-static indentation test.

The quasi-static indentation test was carried out in Instron 600Dx-600 KN universal testing machine (Fig. 6) using hemispherical indenter made

Table 4
Physico-mechanical properties of carbon/ramie fiber reinforced epoxy hybrid composites plates of size 300 mm × 300 mm.

Specimens name	Mass (g)	Thickness (mm)	Ramie Fiber Weight (wt.%)	Carbon fiber (wt.%)	Epoxy Weight (wt.%)	Density (kg/m^3)
CR1	151.530	1.46	44.28	33.47	22.25	1153.2
CR2	289.285	2.98	46.32	32.21	21.41	1078.6
CR3	385.714	4.12	52.11	28.73	19.16	1040.2
CR4	523.469	5.70	51.20	29.28	19.52	1020.4
CR5	697.959	7.66	48.00	31.20	20.80	1012.4

of steel as shown in Fig. 7(a). The purpose of selecting this indenter is that the literature reveals among the same category of indenters hemispherical indenter incur maximum internal damage to composites during quasi-static indentation test [24]. The fixture shown in Fig. 7(b) is used to support carbon/ramie fiber reinforced epoxy hybrid composites specimens during quasi-static indentation test. The center of carbon/ramie fiber reinforced epoxy hybrid composite specimens is marked before fixing the hybrid composite specimen into the fixture for quasi-static indentation test as shown in Fig. 8. This is to ensure that the indentation force is applied exactly in the center of hybrid composite specimen. Later, the hemispherical indenter was aligned with center of carbon/ramie fiber reinforced epoxy hybrid composite specimen (Fig. 9) loaded on fixture and quasi-static indentation test was carried out with indenter displacement speed of 10, 20 and 30 mm/min designated as A, B and C respectively for easy identification and interpretation of results. The required data was recorded at the rate of 0.02 s for all carbon/ramie fiber reinforced epoxy hybrid composite specimens. The hybrid composite specimens undergone quasi-static indentation test were cut along the cross-section undergone damage using dremel cutter to assess the damage.

2.4. Energy absorption study

The data recorded from the experimentation of quasi-static indentation test does not reveal all the parameter required for assessing the quality of carbon/ramie fiber reinforced epoxy hybrid composites. The available energy (E) at the given hemispherical indenter displacement (δ) is important to be known since the available energy at hemispherical indenter is being transferred to the carbon/ramie fiber reinforced epoxy hybrid composite specimen during indentation test [25]. Registering positive value as downward displacement of hemispherical indenter and applying numerical integration algorithm the available energy at hemispherical indenter displacement (δ) is given by the equation (1).

$$E = E(\delta) = \int_{\delta_o}^{\delta} F(\delta)d\delta \tag{1}$$

Where δ_o is the hemispherical indenter displacement when hemispherical indenter contacts the carbon/ramie fiber reinforced epoxy hybrid composite specimen in m and F is the recorded contact force at hemispherical indenter displacement (δ) in N. The maximum energy (E_{max}) consumed by the hemispherical indenter to displace to its maximum value is represented by the equation (2).

$$E_{max} = E(\delta_{max}) = \int_{\delta_o}^{\delta_{max}} F(\delta)d\delta \tag{2}$$

Where δ_{max} denote the maximum extension of hemispherical indenter in m. The energy absorbed (E_a) by the carbon/ramie fiber reinforced epoxy hybrid composite specimens during the maximum loading in quasi-static indentation test was represented by the equation (3).

$$E_a = E(\delta_f) = \int_{\delta_o}^{\delta_f} F(\delta)d\delta \tag{3}$$

Where δ_f, is the displacement of hemispherical indenter at the end of last cycle in m.

3. Results and discussion

3.1. Quasi-static indentation analysis

The performed quasi-static indentation test on carbon/ramie fiber reinforced epoxy hybrid composite specimens reveal the data related to indentation force, hemispherical indenter displacement and maximum indentation force at displacement of hemispherical indenter [26]. Fig. 10 represents the variation of indentation force exerted by hemispherical indenter on carbon/ramie fiber reinforced epoxy hybrid composite specimens for different hemispherical indenter displacement of 10, 20 and 30 mm/min. The observations on the force displacement curve of quasi-static indentation test show cases three distinct regions namely penetration, indentation and friction region. Similar observations were reported in literature for hybrid composite specimens during quasi-static

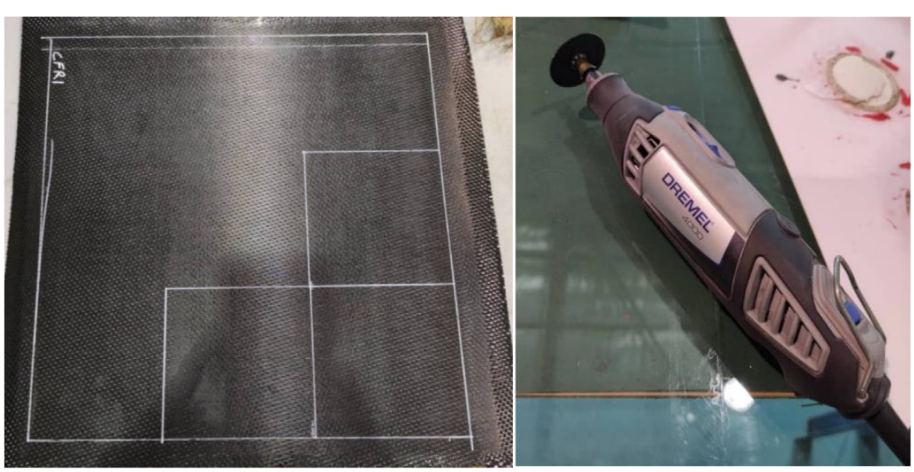
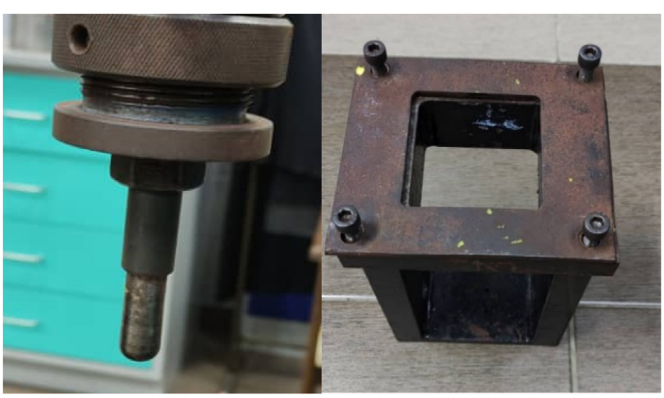


Fig. 5. Specimens preparation for quasi-static indentation test (a) Carbon/ramie fiber reinforced epoxy hybrid composite marked for sizing 100 mm × 100 mm (b) Dremel cutter used for cutting composites.

Fig. 6. Universal testing machine used to carry out quasi-static indentation test.



(a) (b)

Fig. 7. Fixture and indenter used for carrying out quasi-static indentation test (a) Hemispherical Indenter and (b) Support Fixture.

indentation test [27].

In the penetration region hemispherical indenter approaches the top surface of loaded carbon/ramie fiber reinforced epoxy hybrid composite specimen and causes initial damage to the top loaded surface of hybrid composites. This results in inception of indentation and elastic displacement of carbon/ramie fiber reinforced epoxy hybrid composite specimen due to the indentation force will initiate matrix cracking and delamination in hybrid composite specimen [28]. The carbon/ramie fiber reinforced epoxy hybrid composite specimens CR1 and CR2 incurred more damage in penetration region due to its less thickness and inability to resist penetration compared to CR3, CR4 and CR5. Considerable variations in damage in this region was not observed for change in displacement rate of indenter.

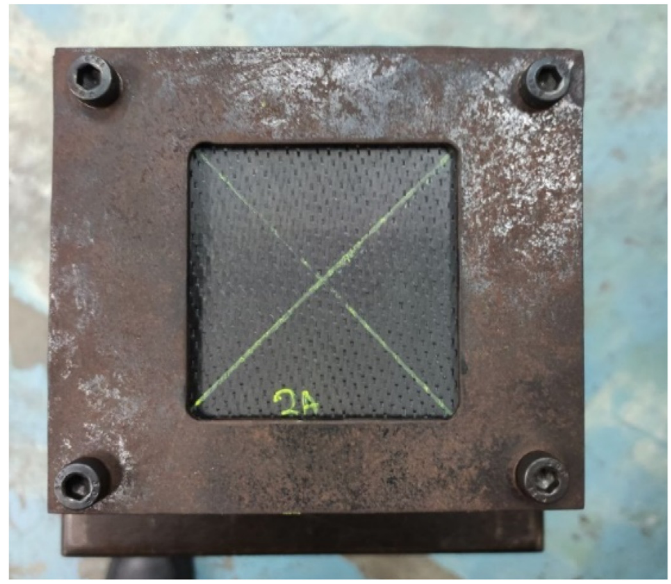


Fig. 8. Carbon/ramie fiber reinforced epoxy hybrid composite with center marked and clamped to fixture.

In the indentation region, fluctuation in indentation force is observed in all carbon/ramie fiber reinforced epoxy hybrid composite specimens and different rates of hemispherical indenter displacements. The fluctuation in indentation force is due to penetration of hemispherical indenter through the thickness of carbon/ramie fiber reinforced epoxy hybrid composite specimen dislocating fibers and damaging the matrix [29]. This fluctuation in indentation force is less in CR1 and CR2 compared to CR3, CR4 and CR5 since lesser layer of carbon/ramie fiber reinforced epoxy hybrid composite specimens will offer minimum resistance for the hemispherical indenter to diffuse into hybrid composites.

The penetration of hemispherical indenter into carbon/ramie fiber reinforced epoxy hybrid composites in the indentation region breaks the fibers and damage the bonding between the fiber and the matrix which is revealed by instantaneous spikes in the indentation force shown in force displacement curves [30]. These peaks are not much dominant in Fig. 10(c) since at higher indenter displacement rate of 30 mm/min the instantaneous force required to break the fiber is less compared to lesser indenter displacement rates. Then the indentation force starts to decrease indicating the failure of carbon/ramie fiber reinforced epoxy hybrid composite specimens due to the penetration of hemispherical indenter [31]. In the friction region, the indentation force continuously tend to decline representing the residual force of friction in hemispherical indenter.

Fig. 11 presents the plot of maximum indentation force at maximum displacement of hemispherical indenter. The observations from the plot reveals that carbon/ramie fiber reinforced epoxy hybrid composite specimen undergone indentation test CR5-B exhibit maximum indentation force of 12.891 N at maximum displacement of 8929.62 mm. This ensures that the carbon/ramie fiber reinforced epoxy hybrid composite specimen CR5 which is subjected to indentation test at hemispherical indenter displacement rate of 20 mm/min possess maximum strain energy to failure property among the other hybrid composite specimens [32].

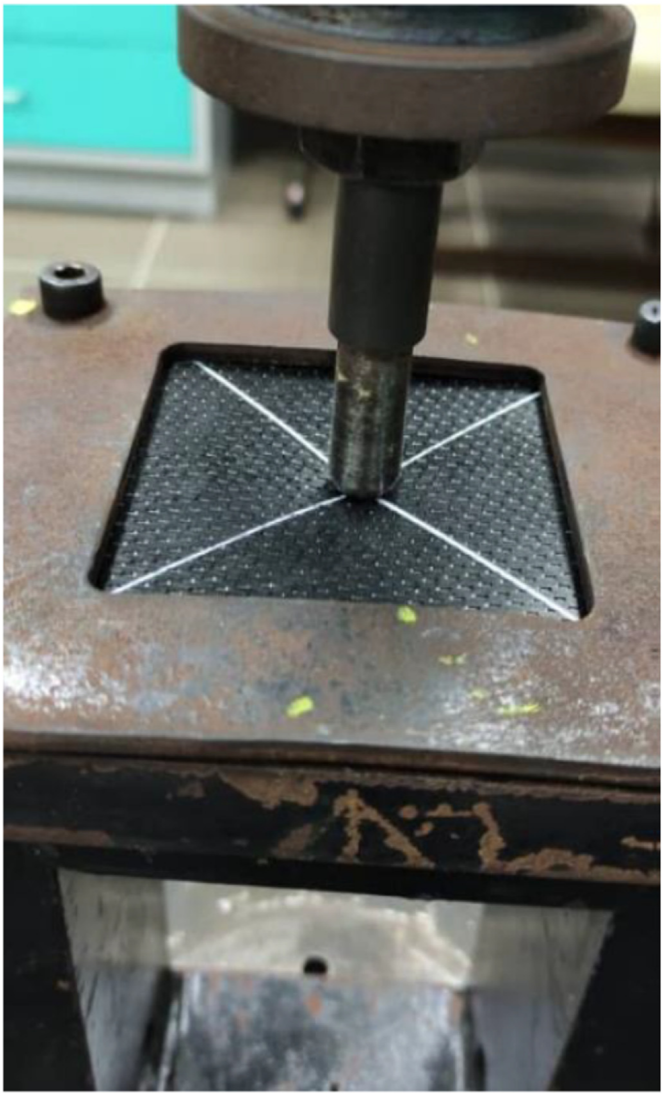


Fig. 9. Hemispherical indenter aligned with center of carbon/ramie fiber reinforced epoxy hybrid composite loaded to fixture.

3.2. Energy absorption analysis

The area under curve in the plot of indentation force against the displacement of hemispherical indenter represents the indentation energy and its proportional to the capability of carbon/ramie fiber reinforced epoxy hybrid composites to absorb energy [33]. Fig. 12 presents the absorbed energy and specific absorbed energy of carbon/ramie fiber reinforced epoxy hybrid composite specimens undergone indentation test at different hemispherical displacement rates. It is observed from the plot that absorbed energy and specific absorbed energy of carbon/ramie fiber reinforced epoxy hybrid composites exhibit the same trend of variation pattern from specimen to specimen and hemispherical indenter displacement rates [34]. The maximum absorbed energy of 114.926 J and specific absorbed energy of 1481.94 J/kg is witnessed for CR5-B at the hemispherical indenter displacement rate of 20 mm/min. The maximum value of strain energy, absorbed energy and specific absorbed energy of CR5 reveals its better indentation resistance compared to other carbon/ramie fiber reinforced epoxy hybrid composites [35]. The more number of carbon and ramie fiber layer and optimum hemispherical indenter displacement rate of 20 mm/min presents better indentation resistance and damping capability to the hybrid composites. Further increase in hemispherical indenter displacement rate reduces the indentation resistance of the carbon/ramie fiber reinforced epoxy hybrid composites.

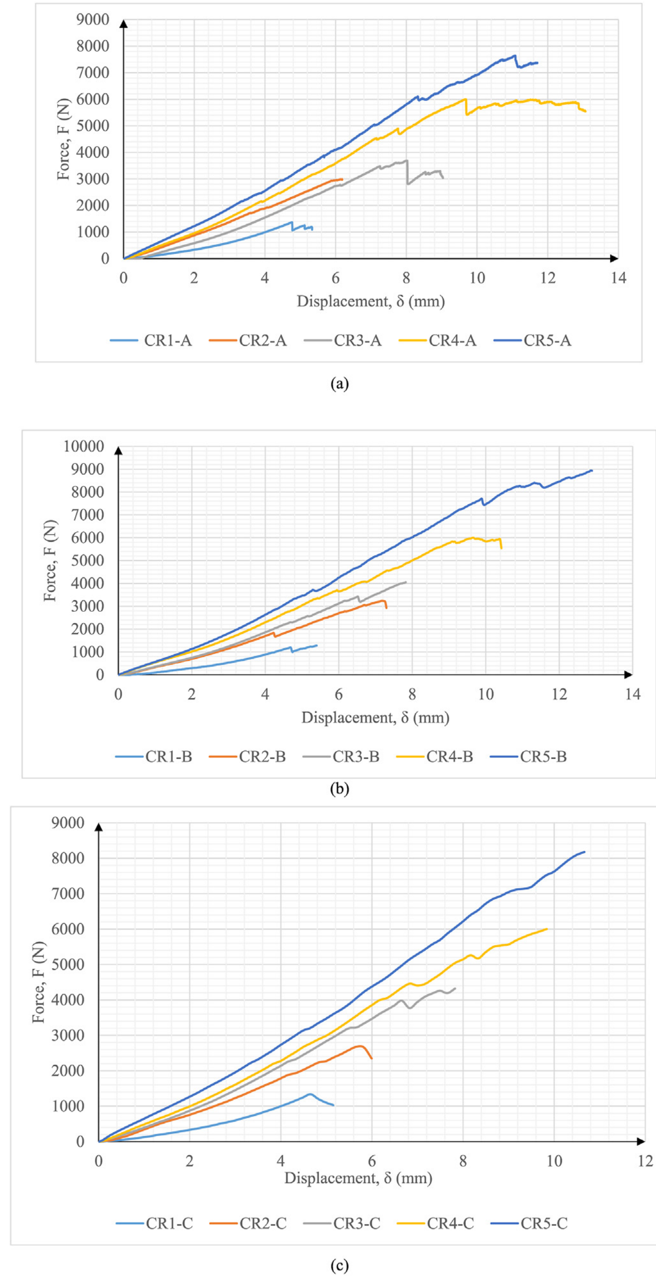


Fig. 10. Variation of indenter force with displacement of hemispherical indenter at displacement rate (a) 10 mm/min (b) 20 mm/min (c) 30 mm/min.

3.3. Displacement rate effect on energy availability

The effect of energy availability on hemispherical indenter during quasi-static indentation test of carbon/ramie fiber reinforced epoxy hybrid composites at different hemispherical indenter displacement rates is shown in Fig. 13. A non-linear parabolic behavior is observed in the variation of energy availability on hemispherical indenter along with its displacement [36,37]. It is also revealed that as the hemispherical indenter advances into carbon/ramie fiber reinforced epoxy hybrid composites the availability of energy in hemispherical indenter increases.

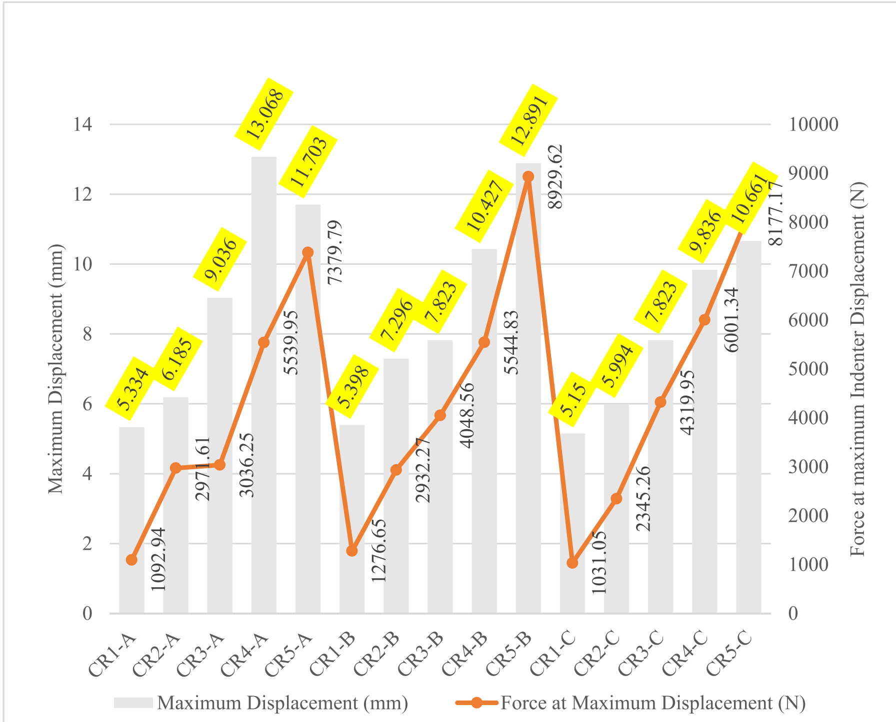


Fig. 11. Maximum indentation force at maximum displacement of hemispherical indenter.

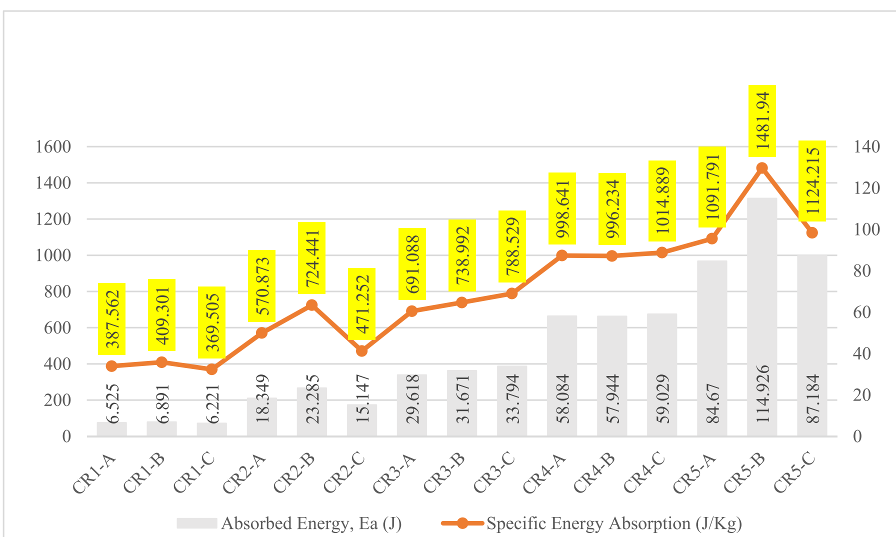


Fig. 12. Absorbed energy and specific absorbed energy calculated for carbon/ramie fiber reinforced epoxy hybrid composites with different indenter displacement rates.

The plots in Fig. 13 (a) to (c) showcases that at less number of carbon and ramie fiber layers the hemispherical indenter displacement rate of 20 mm/min exhibit minimum energy in the hemispherical indenter for penetration into carbon/ramie fiber reinforced epoxy hybrid composites. But with increase in number of carbon and ramie fiber layers the same hemispherical indenter displacement rate of 20 mm/min exhibit maximum energy in hemispherical indenter for penetration into carbon/ramie fiber reinforced epoxy hybrid composites as shown in Fig. 13 (d) and (e). This supports the better indentation resistance of CR5 carbon/ramie fiber reinforced epoxy hybrid composite specimen as discussed.

3.4. Damage assessment analysis

The cross-section view of carbon/ramie fiber reinforced epoxy hybrid composites CR5-B undergone quasi-static indentation test is shown in Fig. 14 (b). The top and bottom surface of carbon/ramie fiber reinforced epoxy hybrid composites CR5-B undergone quasi-static indentation test show a punctured surface with delamination and dent visible in bottom surface [38]. Moreover, delamination between carbon and ramie fiber is also observed in the damaged CR5-B specimen as shown in Fig. 14 (b). The cross-section of undamaged CR5-B carbon/ramie fiber reinforced epoxy hybrid composite specimen is also shown in Fig. 14 (a) for

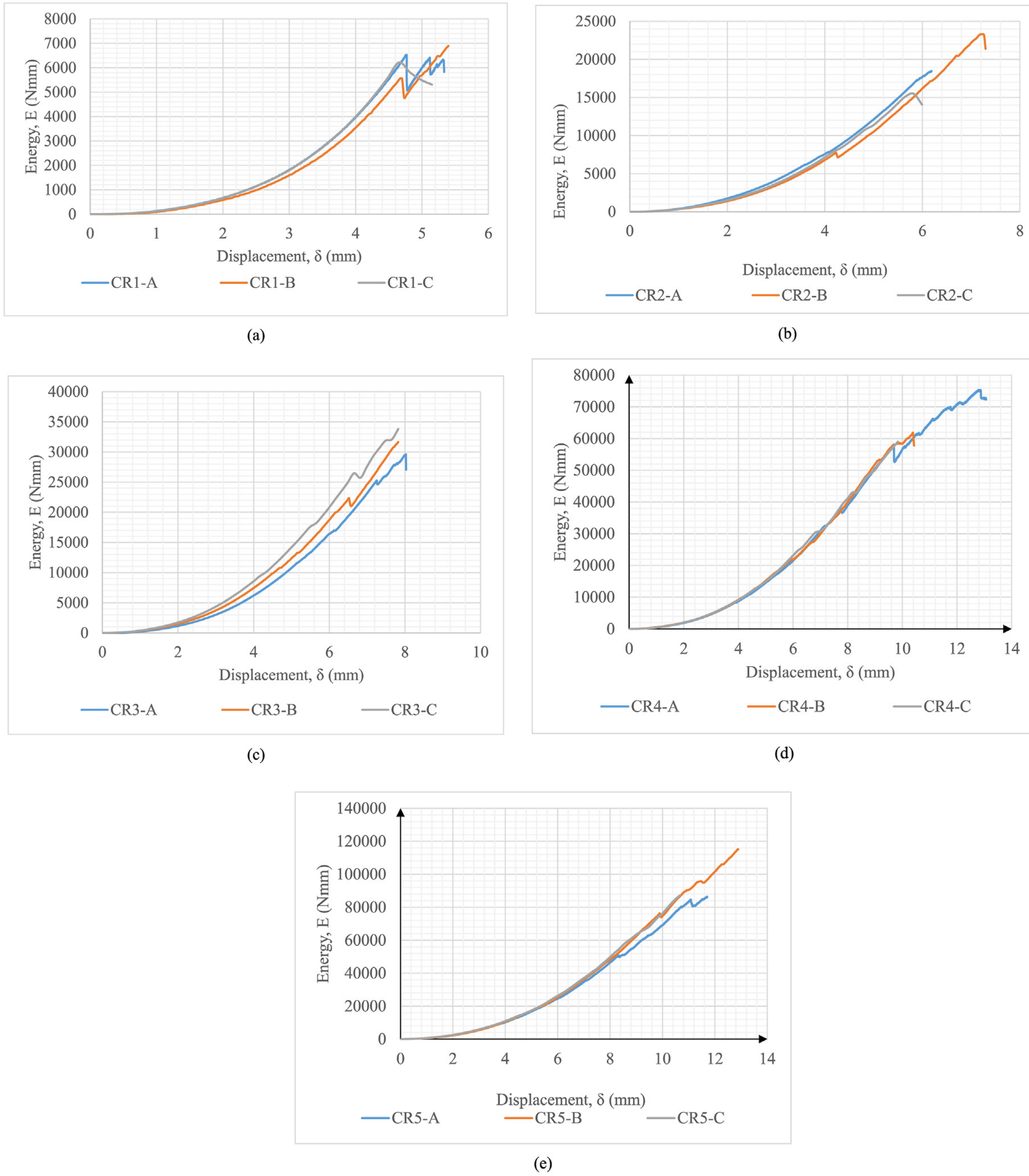


Fig. 13. Variation of Energy with displacement of hemispherical indenter (a) CR1 (b) CR2 (c) CR3 (d) CR4 and (e) CR5.

comparison and reference. The keen observation on sectional views of carbon/ramie fiber reinforced epoxy hybrid composites also reveal that displacement rate of hemispherical indenter does not influence the deformation of hybrid composite specimens during quasi-static indentation test [39]. The other observed damages include matrix cracking, fiber breakage, debonding between epoxy matrix and carbon/ramie fibers.

As the hemispherical indenter penetrates through carbon/ramie fiber reinforced epoxy hybrid composites fiber breakage occurs with is indicated by the sharp rise in indentation force before failure of composites [40]. In the case of CR5 hybrid composites, during the quasi-static indentation test CR5 gave maximum resistance to penetration of hemispherical indenter due to a greater number of carbon and ramie fiber layers and the bonding strength between the epoxy matrix and the carbon/ramie fibers. Hence, the indentation force required to damage CR5 hybrid composite specimen is also substantially high compared to other composite specimens. This ensures the better indentation resistance of CR5 carbon/ramie fiber reinforced epoxy hybrid composites.

4. Conclusions

In this investigation, indentation resistance as well as damage assessment of the carbon/ramie fiber reinforced epoxy hybrid polymer composites for different stacking sequence of carbon/ramie fibers and orientation of ramie fiber were done and the conclusions arrived were summarized below.

➢ Force-displacement curve of indentation curve indicate several indentation force peaks indicating fiber breakage in carbon/ramie fiber reinforced epoxy hybrid polymer composites.

(a) (b)

Fig. 14. Comparison between (a) undamaged (b) damaged cross-section of the carbon/ramie fiber reinforced epoxy hybrid composite CR5-B.

- ➢ Indentation force at failure for CR5 hybrid composite specimen was always found to be maximum in all indenter displacement rates in the range of 7700 to 9000 N.
- ➢ CR5 hybrid composite exhibited maximum energy absorption capability of 114.926 J due to a greater number of ramie fiber layers and is independent of orientation of ramie fiber.
- ➢ Energy available at indenter increased with increase in number of carbon/ramie fiber layers in the hybrid composites.
- ➢ Assessment of damaged portion of carbon/ramie fiber reinforced epoxy hybrid composites shows a smaller number of minor cracks revealing the ductile nature of hybrid composites.

The results of above investigation reveal that CR5 carbon/ramie fiber reinforced epoxy hybrid polymer composite is best suited and can be employed in low velocity impact loading applications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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