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ORIGINAL RESEARCH

Plain Kevlar and a CNT-reinforced Kevlar epoxy polymer composite: Comparative study of its mechanical, low velocity and ballistic impact properties

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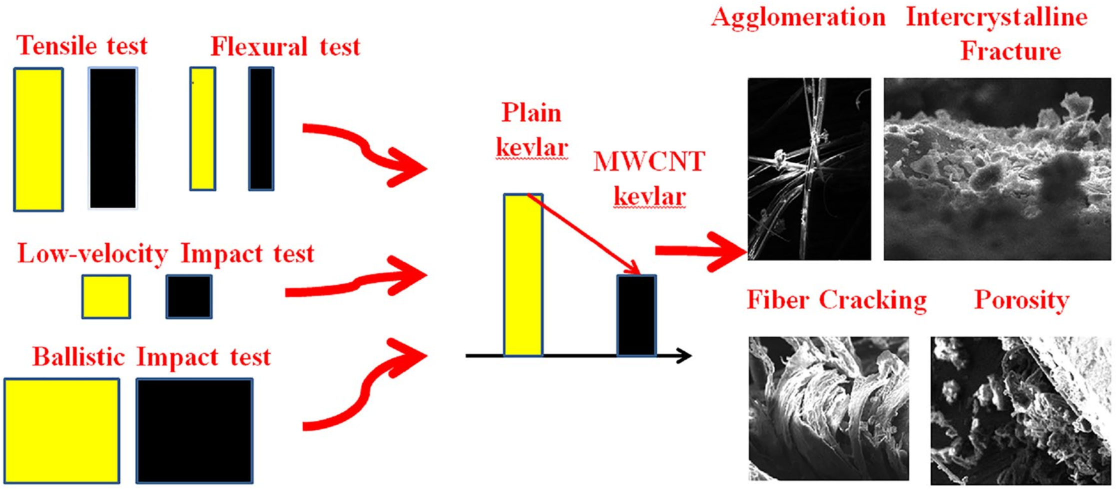
Abstract

This study focuses on the development of an advanced material using Kevlar-reinforced polymer epoxy composites reinforced with 1% carbon nanotubes for armor application. The tensile strength, flexural strength, low-velocity impact strength, and ballistic impact strength were analyzed for plain Kevlar reinforced epoxy composite and multi-walled carbon nanotubes reinforced polymer composite. The sonification method was employed in the current research to acquire a uniform mixture of multi-walled carbon nanotubes in epoxy resin for fabricating multi-walled carbon nanotubes reinforced Kevlar epoxy composites. All the tests were conducted under standard test conditions. The results showed the addition of 1% multi-walled carbon nanotubes in Kevlar epoxy polymer composites has decreased the tensile strength, flexural strength, low-velocity impact resistance, and ballistic impact resistance. The common reason for the decrease in properties of the composite is the increased agglomeration of multi-walled carbon nanotubes in the epoxy matrix, which allows an increase in porosity of the multi-walled nanotubes reinforced Kevlar epoxy composite compared to plain Kevlar epoxy composite. Maximum tensile strength is 197.10 MPa and maximum flexural strength is 131.98 MPa for plain Kevlar epoxy polymer composite. The common failure mechanisms observed during testing were deformation, fiber cracking, matrix cracking, intercrystalline fracture, and agglomeration.

Graphical Abstract



Keywords Polymer · Kevlar · Nanotubes · Composite · Characterization · Impact

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Introduction

Composites are a special class of man-made materials that are designed and suitable for various applications from automotive to space applications and used in various forms, such as particle, fiber, and whisker reinforcement. There is a demand for a lightweight material with excellent tensile strength, flexural strength, and high impact resistance property for armor application and ballistic impact resistance application. The proposed solution for material with excellent properties is advanced fiber reinforced polymer composite material. Polymer composite is a good contender for lightweight material with better mechanical properties. Adding reinforcement in the form of fibers and particles increases the mechanical strength of composites. Kevlar [1–3], also known as poly(*p*-phenylene terephthalamide), is a heat-resistant, light-weight, strong fiber that is primarily utilized in ballistic [4–6] armour applications in the form of cloth or as reinforcement [7, 8] in epoxy polymer composites. It is also used in a variety of disciplines, including industrial safety gloves, heavy-duty ropes, and a variety of other things. Although Kevlar is a tough material that is well-suited for armour applications. The current research focuses on improving the properties of Kevlar epoxy polymer composites by reinforcing them with carbon nanotubes [9, 10], namely, tensile strength, flexural strength [11], low velocity [12], and ballistic impact resistance. Those properties were measured and compared with the plain Kevlar epoxy polymer composite. To obtain a uniform mixture of carbon nanotubes in Kevlar epoxy composite [13, 14] ultrasonication method was employed.

Suresha et al. [15] observed that an increase in multi-walled carbon nanotubes by above 0.5% results in agglomeration and decreases the tensile strength of the aramid epoxy composite. The tensile strength of the composite highly depends upon the efficient load transfer between the fiber and matrix. Sharma et al. [16] investigated the behavior of multi-walled carbon nanotubes epoxy composite. They observed the addition of multi-walled carbon nanotubes beyond 200 weight fraction does not change the mechanical properties of the composite. Hiremath et al. [17] reported adding 0.1% carbon nanotubes in recycled glass fiber reinforced composite to increase the tensile strength by 37.92% and tensile modulus by 18.09%.

Kumar et al. [18] carried out the flexural test in a three-point bending test with a crosshead speed of 1 mm/min. Matrix cracking, fiber cracking, and delamination were the failure mechanisms observed during the testing of pineapple leaf and flax fiber reinforced composite. Bilisik et al. [19] studied the effect of stitched carbon cloth on the bending properties of carbon fiber reinforced epoxy composites. They reported that stitching of carbon fabric decreases the flexural strength of the composite due to fiber breaking and induced irregularities in the fabric. Rangaswamy et al. [20] reported an increase in multi-walled carbon nanotubes beyond 0.6% which results in agglomeration. Furthermore, they added agglomeration is due to the Van der Waals attraction between the multi-walled carbon nanotubes and increase the porosity of the composite.

David-West et al. [21] investigated the effect of surface orientation on low-velocity impact properties of carbon fiber reinforced polymer composite. They reported the orientation of the laminate affects the impact resistance property of the composite. Tasyurek et al. [22] reported that the addition of carbon nanotubes in glass fiber epoxy composite improved the adhesion between the fiber and matrix. It also increased interlaminar fracture during a low-velocity impact tests. Ranjbar et al. [23] reported that the addition of multi-walled carbon nanotubes increased the low-velocity impact strength of glass fiber reinforced epoxy composite.

Braga et al. [24] have reported that the use of epoxy matrix as a backing plate in "multilayered ballistic armor system" acts as an additional mechanism of energy dissipation during the ballistic impact. Stephen et al. [25] reported that a 3-layer Kevlar-reinforced epoxy composite has better energy absorption compared to a 3-layer glass fiber reinforced epoxy composite and a 3-layer carbon fiber reinforced epoxy composite. The total impact energy of Kevlar-reinforced polymer composites was reported by Kang et al. [26]. This is divided into 4 categories, membrane energy, detachment energy, bending energy, repulsion energy. Talib et al. [27] reported that the addition of Al_2O_3 as a reinforcement into a Kevlar 29 fiber reinforced polymer composite has increased the ballistic impact of the composite. Taraghi et al. [28] stated that the addition of 0.5% MWCNT by weight increases the absorbed energy by 35% and bending stiffness by 15% at ambient temperature.

From the literature review, we can refer that most of the Kevlar reinforced polymer composites include epoxy resin as the matrix as it offers superior properties compared to other resins. Researchers are interested in using MWCNTs to improve the tensile strength [29], flexural strength [30–32], low-velocity impact [33] strength, and ballistic impact [34–36] strength of the Kevlar hybrid [37, 38] composite. Very little research was reported on adding multi-walled carbon nanotubes to more than 0.6%. Therefore, the current research focuses on investigating the effect of 1% by weight MWCNTs to improve the tensile strength, flexural strength, low-velocity impact strength, and ballistic impact strength of Kevlar reinforced epoxy composites.

Experimental

Specimen preparation

Kevlar 49 fiber bi-directionally [39] oriented in 0° in the warp direction and 90° in the weft direction was used. Kevlar grade of 400 g/m^2 (grams per square meter) grade was utilized to make the test specimen. Epoxy [40] resin of CT/E-120 grade and hardener of CT/AH-60 grade obtained from "Composite Tomorrow in Gujarat" were used for fabricating the composite. Adnano Technologies, India, provided multi-walled carbon nanotubes (MWCNT) [41–43] of 10–15 nm diameter and 5 µm length, prepared through the catalytic carbon vapor deposition process, was employed in the current research. The examples were made of 300 mm × 300 mm dimensions using the hand-layup process, followed with the mixture rule of 50%:50% (by weight). Kevlar sheet was stacked in three layers and epoxy resin is applied to Sample 1. Sample 2 is manufactured by adding 1% CNT to epoxy resin by weight, stacking three layers of Kevlar sheets in order, and curing it, as shown in Fig. 1. The samples are made by hand-layup technique. At Crescent Institute of Science and Technology, the samples are made by hand-layup method, which involves in order layering of the composites. To acquire a uniform mixture, the epoxy resin was added with multi-walled carbon nanotubes in an ultrasonic bath. The stirring of epoxy resin and multi-walled carbon nanotubes mixture, using in a ratio 99:1 by weight, was done in 30 °C at 50 Hz for 10 min to obtain a uniform mixture. The epoxy resin and hardener were mixed in a 10:1 ratio. Three samples for plain reinforced Kevlar epoxy composite and tensile test, flexural test, low-velocity impact, and ballistic impact were tested for each three samples. The mechanical properties of epoxy resin, Kevlar fabric and multi-walled carbon nanotubes are listed in Table 1.

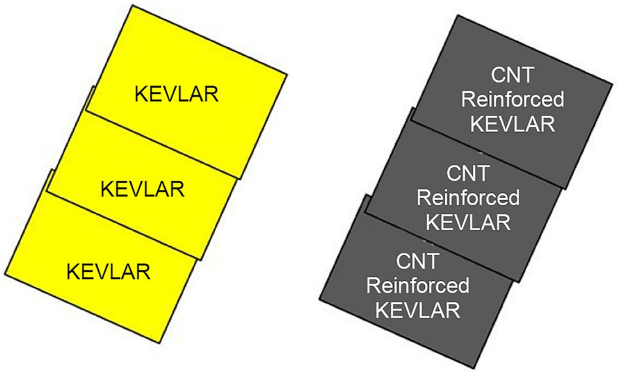

Fig. 1 Stacking sequence arrangements for plain and CNT reinforced Kevlar epoxy polymer composite

Table 1 Material property

Mechanical properties	Epoxy resin	Kevlar fabric	Multi-walled carbon nanotubes
Tensile strength	55–70 MPa	3600 MPa	10–60 GPa
Tensile modulus	2.5–4.0 GPa	60 GPa	–
Flexural strength	120–140 MPa	43 MPa	–
Flexural modulus	3.2–3.6 GPa	1322 MPa	–
Density	1.1–1.2 g/cc	1.45 g/cc	2.1 g/cc

Tensile test

The tensile test was carried out in Instron 3382 testing machine in accordance with ASTM D-3039 standard at the Central Institute of Plastic Engineering and Technology, Chennai. The specimen was cut to a size of 150 mm × 25 mm using an abrasive water jet machine for testing. During the tensile test, the specimen was clamped at the ends by a specimen holder and the test was carried out at a speed of 5 mm/min.

Flexural test

The flexural test was carried out in Instron 3382 testing machine using a three-point bend test setup and in accordance with ASTM D-790 standard. The test specimens were cut to a size of 127 mm × 12.7 mm for testing by an abrasive water jet machine for the better surface finish at the edges. The test was carried out at a speed of 5 mm/min. The flexural strength of the composite sample is calculated using the formula stated below:

$$\text{Flexural strength}\ \sigma_{\mathrm{f}} = \frac{3\rho l}{bd^2}$$

p force measured, l length of the sample, b breadth of the sample, d thickness of the sample.

Low-velocity impact test

The CEAST fractovis drop weight impact tower was used for the impact test. It used a hemispherical striker with a 25 mm diameter and 1.926 kg weight. To prevent lateral movement of the specimen, it was clamped with a 50 N force in a 79 mm diameter circular enclosure. Different Kevlar specimens were subjected to impact tests at speeds of 2.8 m/s, 3.96 m/s, and 4.85 m/s. A data acquisition system was used to capture the impact force, impact energy, deformation, the time during the impact, and rebounding. For this, the energy absorbed and the force produced during impact were recorded using a built-in piezoelectric sensor

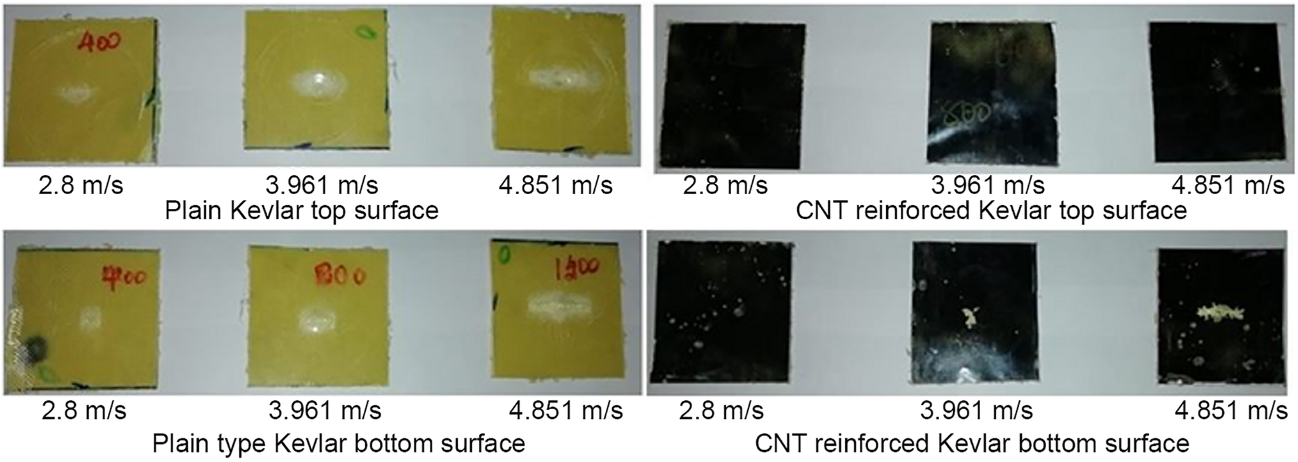

Fig. 2 Low velocity impact test samples

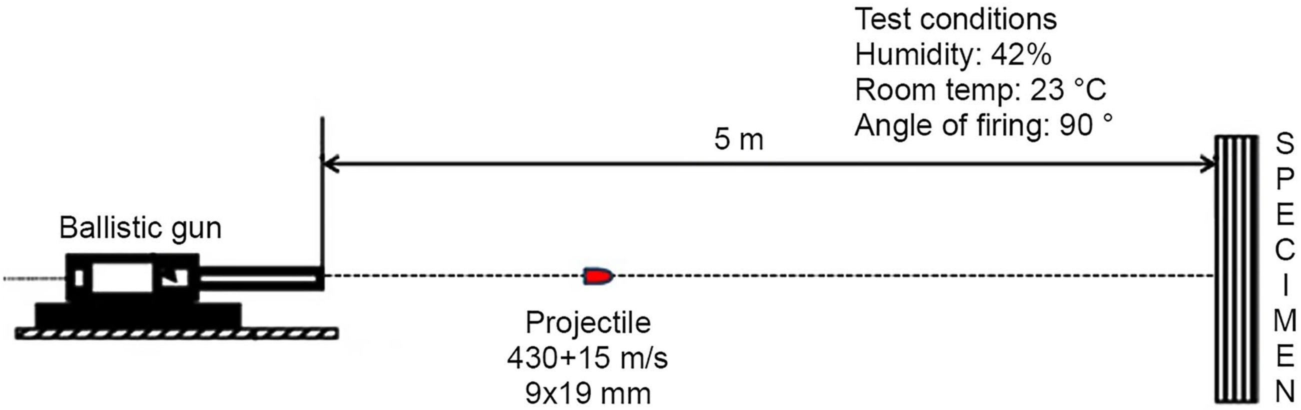

Fig. 3 Ballistic impact test set up

inside the striker. The samples were tested using a common ASTM D5628-D standard. The specimens were prepared with a size of 90 mm × 90 mm using an abrasive water jet machine, as shown in Fig. 2.

Ballistic impact test

The National Forensic Sciences University in Gujarat's Ballistic Research Centre and Testing Range hosted the ballistic impact test. At 430 m/s, the ballistic impact test was carried out accordance with NIJ Level IIIA, as shown in Fig. 3. The sample was made to a size of 300 mm by 300 mm and the target panel was mounted on a fixture. The test bullet had a length of 9 mm and a diameter of 19 mm; it was fired from a distance of 5 m at a 90° angle. The findings of the test on three samples of plain Kevlar reinforced polymer composite and SMA sheet reinforced Kevlar epoxy composite are discussed below.

Table 2 Tensile strength and flexural strength of the specimens

Specimen	Tensile strength (MPa)	Flexural strength (MPa)
Plain Kevlar reinforced polymer composites	197.10	131.98
CNT reinforced Kevlar polymer composites	92.70	123.96

Results and discussion

The tensile and flexural tests were carried out and the readings obtained during the tensile test and flexural test are listed in Table 2.

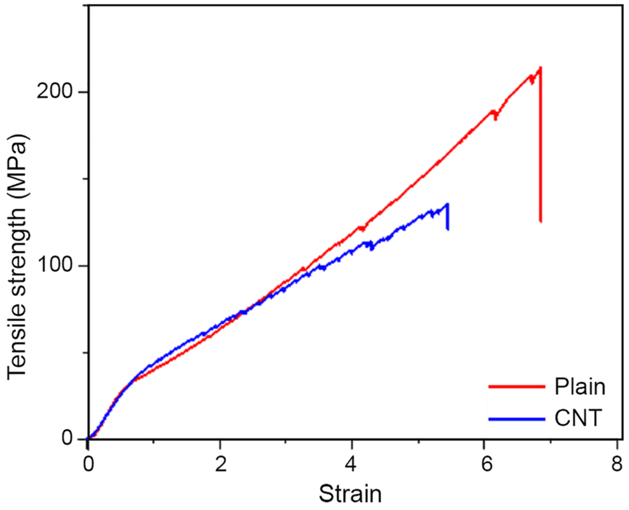

Fig. 4 Tensile strength vs. strain graph

Tensile test

The tensile test was carried out on different specimens, and the tensile test was carried out on all four specimens. From Fig. 4, it could be observed, that the addition of carbon nanotubes in plain Kevlar epoxy polymer composite decreased the tensile strength of the composite by 52.97%. A similar effect is observed by Rangaswamy et al. by adding 0.9% carbon nanotubes by weight in glass Kevlar epoxy hybrid composite due to agglomeration of carbon nanotubes. The agglomeration of carbon nanotubes has led to brittle fracture, which is observed in the matrix part of carbon nanotubes reinforced with plain Kevlar epoxy polymer composite.

Flexural test

During the flexural test, the top layer of the specimen experiences compressive stress and the bottom-most surface experiences tensile stress for both test specimens. In flexural tests the multi-walled carbon nanotubes reinforced Kevlar epoxy polymer composite, of the flexural strength is found to be high compared to plain Kevlar epoxy polymer composite due to the resistance offered by the carbon nanotubes used as reinforcement. From Fig. 5, the maximum flexural strength of 131.98 N is observed in plain Kevlar epoxy polymer composite which is 6.47% higher than carbon nanotubes reinforced Kevlar epoxy polymer composite. The reason for the decrease in flexural strength for carbon nanotubes reinforced Kevlar epoxy composite can be observed by Chang et al. (). They showed that the addition of carbon nanotube 0.4% by weight contributes to lower flexural strength and modulus of fiber reinforced polymer composites.

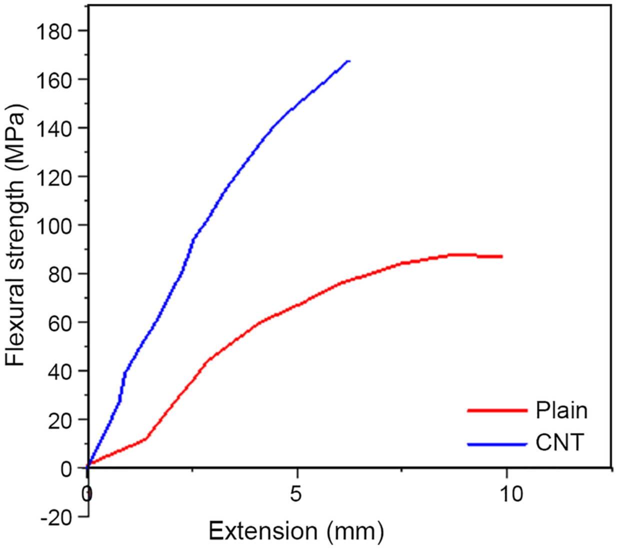

Fig. 5 Flexural test graph for the specimens

Impact test

The impact test was conducted at Madras Institute of Technology, Anna University, Chennai, using a CEAST Fractovis drop weight impact tower. It uses a hemispherical striker with a diameter of 25 mm and a weight of 1.926 kg. To prevent lateral movement, the specimen was clamped in a circular enclosure with a diameter of 79 mm and a clamping force of 50 N. At velocities of 2.8 m/s, 3.961 m/s and 4.851 m/s, impact tests were performed on several Kevlar specimens. The impact force, impact energy, deformation, the time during the impact, and rebounding were all recorded using a Data Acquisition system. A piezoelectric sensor and many other sensors are integrated into the striker to record the energy absorbed and force created during impact, as well as the time and deformation of the specimen. The graphs of force vs. time, force vs. deformation, energy vs. deformation, deformation vs. time, and energy vs. time are presented in the given titles. The results of low speed impact tests are tabulated in Table 3.

Impact force vs. time

The graph depicts the material's force or impact resistance during a drop weight impact from different impact velocities, as shown in Fig. 6. The tests were conducted on several specimens, with the force being recorded using data gathering equipment. When comparing plain Kevlar reinforced polymer composites with CNT-reinforced Kevlar epoxy polymer composites, it is obvious that plain Kevlar reinforced polymer composites generate significantly more force. At varied impact speeds of 2.8 m/s, 3.96 m/s, and 4.85 m/s, a single peak force is obtained for CNT reinforced

Kevlar epoxy polymer composite. The peak impact force is increased by 0.22% and 3.53% for impact velocities of 3.96 m/s and 4.85 m/s, respectively, by adding carbon nanotubes in plain Kevlar epoxy polymer composite. In comparison to other specimens, the impact force is absorbed in a short amount of time. The increase in impact force is due the internal resistance offered by multi-walled carbon nanotubes, which offer resistance to deformation.

Impact force vs. deformation

The graph depicts the link identified between the impact force created when the drop hammer weight makes contact with the specimen and the impact force generated when the drop hammer weight makes contact with the specimen, as shown in Fig. 7. For all the impact velocities a closed hysteresis curve is observed for plain and carbon nanotubes reinforced Kevlar epoxy polymer composite. It means no penetration was observed during the testing of the specimen.

Absorbed energy vs. deformation

The graph shows the relationship between energy and deformation rate for several specimens. We may deduce from the graph that the plain Kevlar polymer composite has the most energy and the carbon nanotubes reinforced polymer

Table 3 Low-velocity impact test results

Specimens at different impact velocities	Peak impact force (N)	Peak impact energy (J)	Maximum deformation (mm)	Damaged area (mm^2)
Plain Kevlar reinforced polymer composites				
2.80 m/s	2356	7.55	4.38	223.417
3.96 m/s	2183	15.86	6.85	437.558
4.85 m/s	2523	22.47	10.43	909.022
CNT reinforced Kevlar polymer composites				
2.80 m/s	2068	7.53	4.35	140.32
3.96 m/s	2188	14.71	7.29	237.13
4.85 m/s	2612	22.58	11.18	467.92

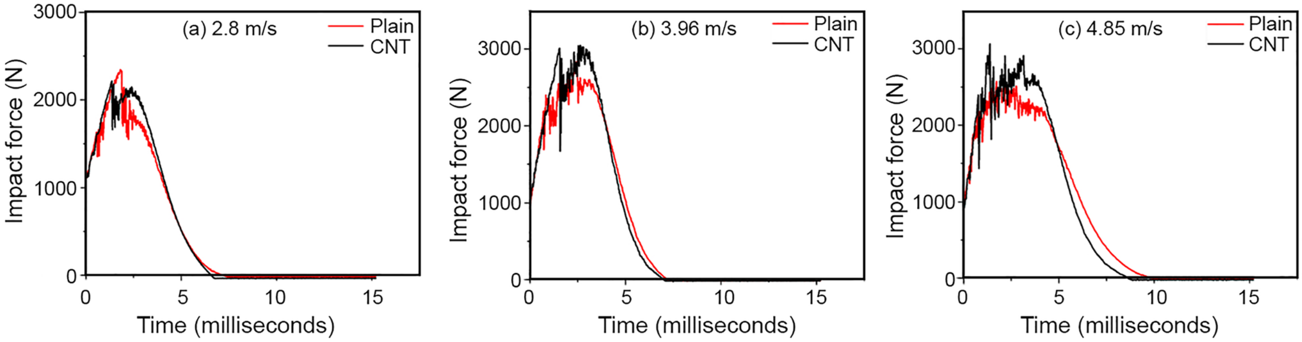

Fig. 6 Impact force vs. time interaction for impact velocity of: **a** 2.8 m/s, **b** 3.96 m/s, and **c** 4.851 m/s

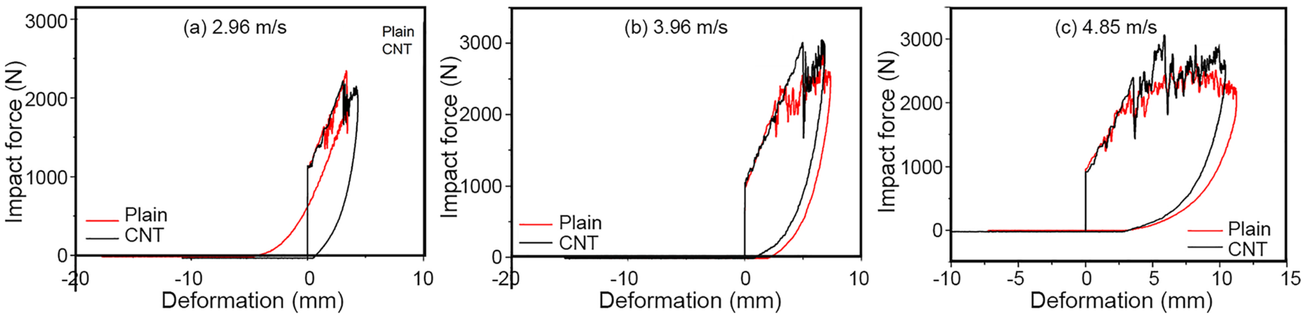

Fig. 7 Impact force vs. deformation interaction for impact velocity of: **a** 2.8 m/s, **b** 3.96 m/s, and **c** 4.851 m/s

composite has the lowest, as shown in Fig. 8. We can see from the graph that the energy generated during impact is quite low. By adding carbon nanotubes in plain Kevlar epoxy polymer composite the peak impact energy is decreased by 0.22–7.25%. With further increase in impact velocity to 4.85 m/s, the peak impact energy is increased by 0.48% compared to plain Kevlar epoxy polymer composite.

Absorbed energy vs. time

The energy recorded during the impact of various specimens at different impact velocities is displayed in the graph, and the energy depicted in the graph shows the amount of energy generated after the specimen has absorbed the energy, as shown in Fig. 9. Initially plain Kevlar polymer composite has the maximum amount of absorbed energy compared to carbon nanotubes reinforced Kevlar epoxy polymer composite during the initial low test velocity of 2.80 m/s by 1.50%. For an increase in impact test velocity by 3.96 m/s–4.85 m/s the absorbed energy increased by 2.73–1.26%. A similar increase in absorbed energy by 35% was observed by Carey et al. [44], by adding 0.5% carbon nanotubes in a glass Kevlar hybrid composite. The decrease in the absorbed energy compared to Carey et al., was due to the agglomeration of carbon nanotubes in the carbon nanotubes reinforced Kevlar epoxy polymer composite.

Deformation vs. time

From the graphs, it can be inferred that plain Kevlar epoxy polymer composite has minimum deformation and performs better than carbon nanotubes reinforced Kevlar epoxy polymer composite for all three velocities, as shown in Fig. 10. Furthermore, the addition of carbon nanotubes by 1% in plain Kevlar epoxy composite slightly increases the deformation of the composite by 8.27%, 8.03%, and 8.97% for impact velocities of 2.8 m/s, 3.96 m/s and 4.85 m/s. The time taken for regaining its original shape for plain and CNT-reinforced Kevlar epoxy polymer composite was almost the same.

Ballistic impact test

Damage absorbing mechanisms

During a ballistic impact, the bullet's incident kinetic energy is delivered to the test specimen, and this energy is absorbed in a variety of ways. The energy absorption would continue until the specimen absorbed all the kinetic energy from the

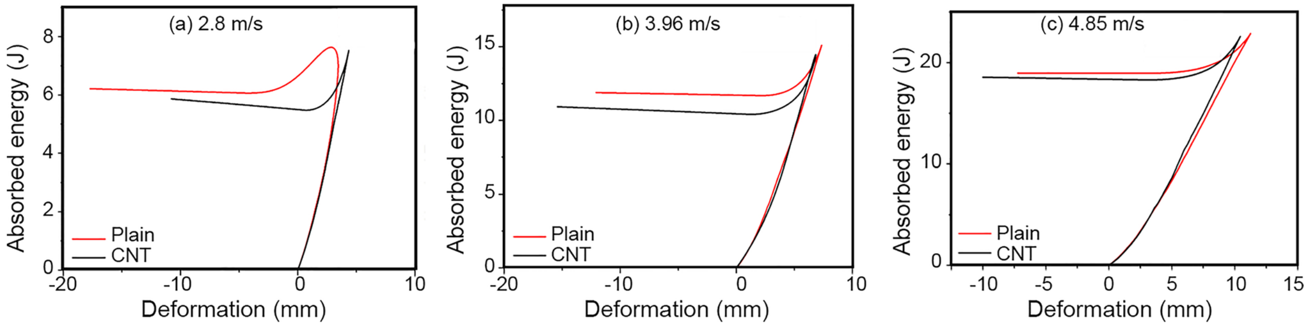

Fig. 8 Absorbed energy vs. deformation interaction for impact velocity of: **a** 2.8 m/s, **b** 3.96 m/s, and **c** 4.85 m/s

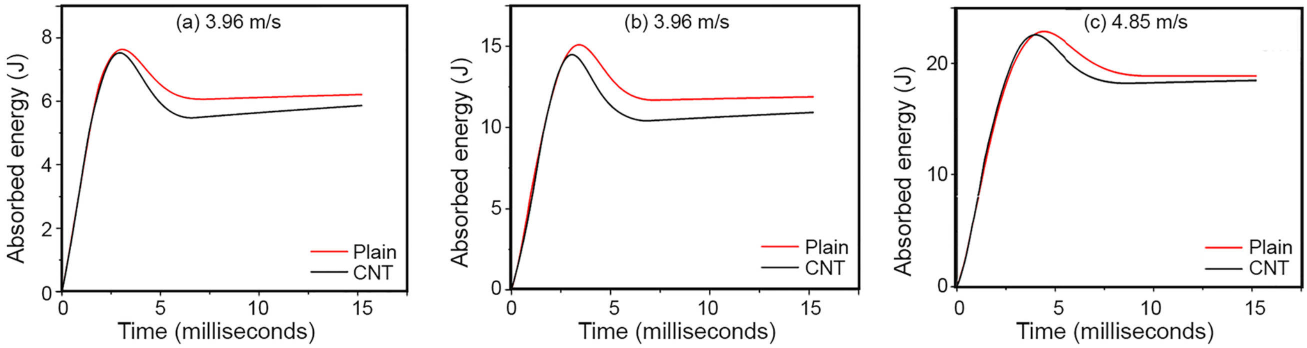

Fig. 9 Absorbed energy vs. time interaction for impact velocity of: **a** 2.8 m/s, **b** 3.96 m/s, and **c** 4.851 m/s

bullet, and indentation would develop in the specimen with various failure sources. If the bullet's initial kinetic energy is greater than the energy absorbed by the specimen, the bullet will penetrate. Primary and secondary yarn stretching and deformation, shear plugging, matrix cracking, delamination, and conical shape distortion at the test specimen's back face are all common failure modes. The damaged area measured using Image J software is tabulated in Table 4.

Damage area analysis

The sample had some penetration during the ballistic impact of a plain kevlar reinforced epoxy polymer composite, as illustrated in Fig. 11a, b, respectively. There was damage of 157.72 mm^2 on the impact surface and 567.73 mm^2 on the backside of the impact region. The sample had some penetration during the ballistic impact of CNT reinforced Kevlar epoxy polymer composite and the damaged area in the impact surface was 241.74 mm^2 and the damaged area on the backside of the impact area was 1037.10 mm^2, as shown in

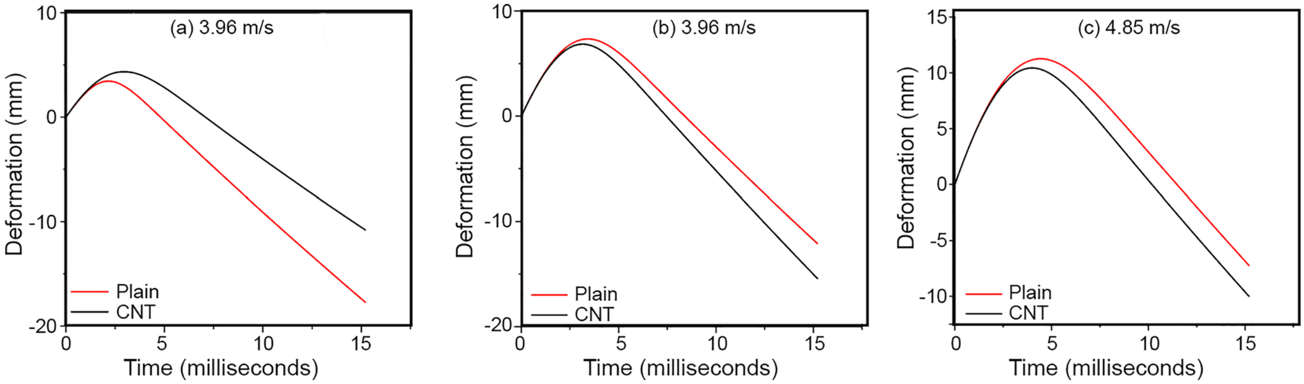

Fig. 10 Deformation vs. time interaction for impact velocity of: **a** 2.8 m/s, **b** 3.96 m/s, and **c** 4.851 m/s

Table 4 Damaged area analysis for plain and CNT reinforced Kevlar epoxy polymer composite

Specimen type	Front damaged area (mm^2)	Front damaged area average (mm^2)	Back damaged area (mm^2)	Back damaged area average (mm^2)
Plain type	160.60		564.56	
	153.46	157.72	569.12	567.73
	159.10		569.51	
CNT reinforced Kevlar composite	245.91		1036.43	
	237.33	241.74	1016.12	1037.10
	241.98		1058.76	

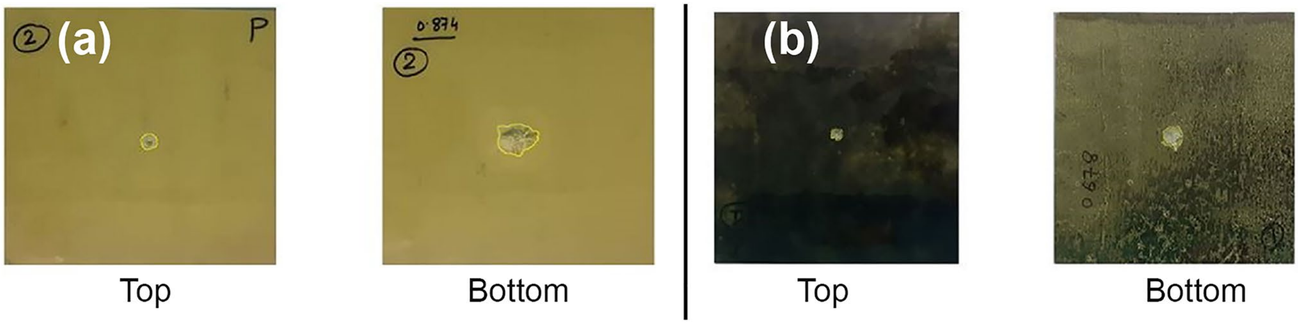

Fig. 11 **a** Damaged area of plain Kevlar reinforced epoxy polymer composite and **b** damaged area of CNT reinforced Kevlar epoxy polymer composite

Fig. 11b. The front damaged area was increased by 53.27% and the back side damaged area was increased by 82.67% reinforcing carbon nanotubes in plain Kevlar epoxy polymer composite. Similar effect was observed by Bigdilou et al. [45], for Kevlar fiber reinforced ultra-high molecular weight polyethylene composite added with 0.9% carbon nanotubes decreases the impact resistance. The reason for increase in damage area is due to agglomeration which causes increase in porosity of the multi-walled carbon nanotubes reinforced Kevlar epoxy polymer composite.

SEM analysis

For SEM analysis the samples were cut using abrasive water jet cutting and specimens were coated with gold to obtain SEM images. All the specimens were analyzed using Scanning Electron Microscope at different magnification levels. Most commonly for all the specimens the failure is observed as a crack [46] on the epoxy surface, as shown in Fig. 12a, and penetrates to another side due to the application of load. In Fig. 12b, few epoxy matrix is observed over the fiber with CNT bonded to the fabric which shows the CNT has adhered well to the Kevlar fabric and improved the mechanical properties of the CNT specimen. Figure 12c shows the deformed fiber after failure and it shows the CNT, Kevlar fiber, and resin are adhered well together and increase the mechanical properties [47] of the CNT composite. Similar adhesion [48, 49] was observed in other specimens also. In addition, Fig. 12d depicts the intercrystalline fracture observed in the epoxy matrix during the failure due to applied tensile load. Figure 12e represents the agglomeration in multi-walled carbon nanotubes reinforced Kevlar epoxy composite resulting in a decrease in tensile strength, flexural strength, low-velocity impact resistance, and ballistic impact resistance. The agglomeration of multi-walled carbon nanotubes induces porosity in the multi-walled carbon nanotubes reinforced Kevlar epoxy composite. The porosity in the composite is shown in Fig. 12f.

Conclusion

In this work, plain Kevlar epoxy polymer composite, and multi-walled carbon nanotubes reinforced Kevlar epoxy polymer composite (uniform mixture of multi-walled carbon nanotubes and epoxy resin made by sonification method)

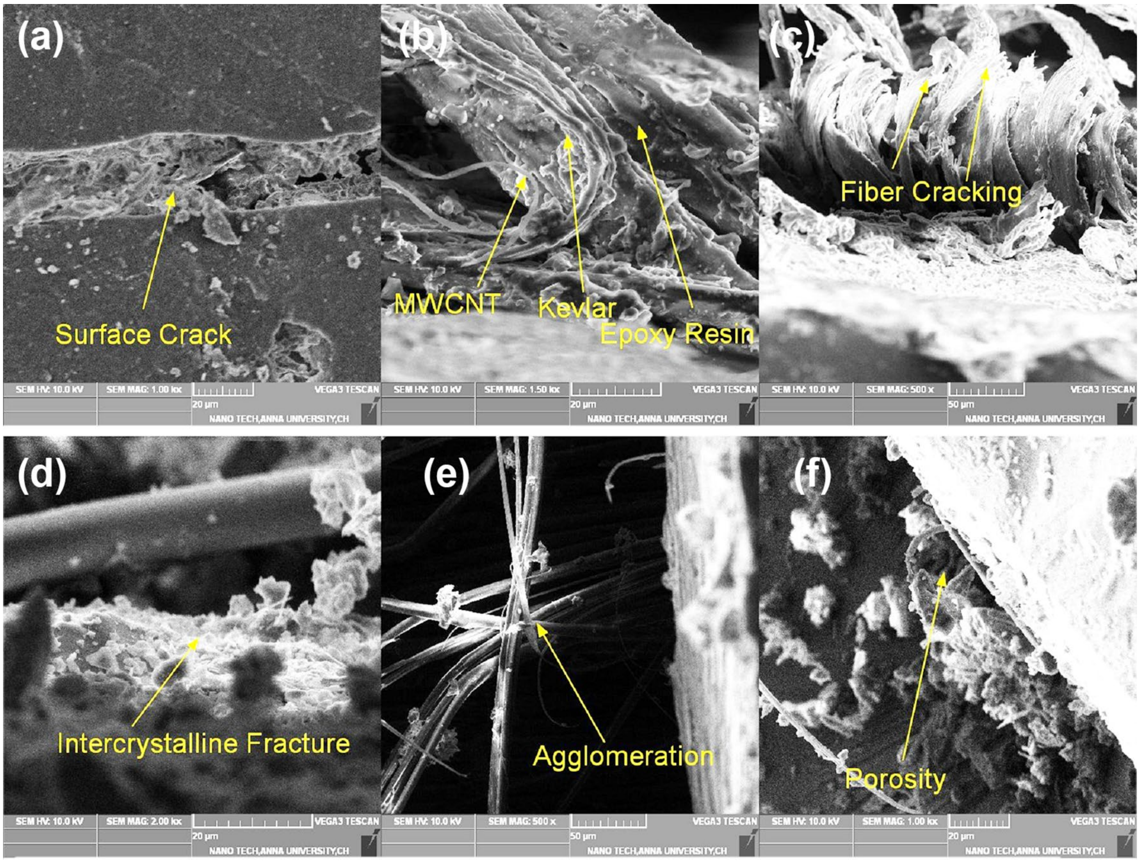

Fig. 12 **a** Surface crack at the epoxy matrix, **b** bonding of epoxy resin, Kevlar fiber, and carbon nanotubes, **c** fiber cracking at the ends of Kevlar fabric, **d** intercrystalline fracture in epoxy matrix, **e** agglomeration of carbon nanotubes, and **f** porosity in the epoxy matrix

were manufactured by hand-layup method. Furthermore, tensile test, flexural test, low-velocity impact test, and ballistic impact test on plain Kevlar epoxy polymer composite and multi-walled carbon nanotubes reinforced Kevlar epoxy polymer composite were investigated. The results of the testing are listed below.

- The tensile strength of the composite was decreased by 52.97% and the flexural strength of the composite was decreased by 6.08%.
- During the low velocity impact strength the damaged area is increased by 8.27%, 8.03%, and 8.97% for impact velocities of 2.8 m/s, 3.96 m/s and 4.85 m/s.
- Also during the ballistic impact test on adding 1% multi-walled carbon nanotubes in Kevlar epoxy composite, the damaged area is increased by 53.27–82.67% in the front face and back face, respectively.
- The reason for the decrease in tensile strength, flexural strength, low-velocity impact strength and ballistic impact resistance was mainly due to the brittle nature of the epoxy resin and the agglomeration of multi-walled carbon nanotubes in the composite.
- The failure modes observed during these testing were matrix cracking, deformation, fiber cracking, intercrystalline fracture and agglomeration.

Author contributions All authors read and approved the final manuscript.

Declarations

Competing interests The authors declare that they have no competing interests.

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