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Experimental investigation of ballistic limit and energy absorption in hybrid composites made of Kevlar and Innegra fibers

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Abstract

In this research, the effect of high velocity impact on Kevlar/Innegra hybrid composites and the effect of adding Innegra fibers on the ballistic properties of Kevlar/epoxy samples have been studied experimentally. For this purpose, 6 sets of samples with different configurations of Kevlar and Innegra fabric fibers were made in 5 layers. Then, the high velocity impact test (gas gun) was performed on the samples at two velocities of 103 and 136 m/s (higher than the ballistic limit speed) and at the energy level of 37 and 64 joules, respectively, by the projectile of conical head cylinders. To find the most optimal configuration; With the help of energy relationships, the ballistic limit and energy absorption rate were calculated for each sample separately and it was observed that the use of Innegra fibers with IKIKI configuration increased energy absorption by 50.57% compared to the Kevlar/epoxy sample. Further, due to the non-uniformity of thickness and mass among the manufactured samples, the specific energy absorption rate was calculated for Kevlar/Innegra hybrids, and the values obtained for KIKIK and IKIKI samples show an increase of 61.5% and 23%, respectively. The above results show the high effect of using Innegra fibers in increasing the energy absorption of the Kevlar/epoxy sample.

Keywords: Hybrid composite; Ballistic limit; Specific energy absorption; Kevlar; Innegra

1. Introduction

Kevlar fibers exhibit lower compressive strength compared to tensile strength, making them susceptible to bending under compressive loads [1]. The brittleness of epoxy resin (post-curing) reduces impact resistance and ballistic performance in Kevlar/epoxy composites [2]. Additionally, the high cost of Kevlar fibers makes their use economically unfeasible. The difference in longitudinal and transverse tensile strengths of Kevlar fibers necessitates their replacement with fibers offering higher elasticity and strength [3].

This study aims to improve the ballistic performance of Kevlar/epoxy composites by hybridizing them with Innegra fibers. Cost-effectiveness is a critical factor in material selection, especially given the high import costs of Kevlar. Hybridizing Kevlar with Innegra fibers not only addresses Kevlar's weaknesses and enhances energy absorption but also reduces production costs, making it highly suitable for defense and military applications. Additionally, the impact of thickness and mass variations on the performance of Kevlar/Innegra hybrids is analyzed to guide material selection for protective applications.

2. Materials and Fabrication

The materials used include:

- Kevlar Fabric (trade name 100D-P60): Plain weave, sourced from China.
- Innegra Fabric: Satin weave, sourced from Australia.
- Epoxy Resin (PC-105) and Hardener: Sourced from South Korea, was used with a 20% hardener ratio.

The composite samples in this study were prepared using the hand lay-up method in 6 different configurations with dimensions of 10 × 30 cm. To achieve the required laboratory dimensions (7 × 7 cm), a laser cutting machine was employed, minimizing cutting errors. It should be noted that 9 samples were prepared for each configuration of the monolithic and hybrid composites made from Kevlar and Innegra fibers.

3. Energy Parameters and Ballistic Limit

The most common method for determining the energy absorption of composite laminates involves measuring the kinetic energy loss after a projectile penetrates and exits the sample. Theoretically, the energy absorption of the composite can be calculated as the difference between the initial energy of the projectile and its residual energy.

Weight is a critical parameter in designing composite samples for protective applications. A structure with high energy absorption capabilities but excessive weight becomes impractical and counterproductive. To optimize the balance between energy absorption and weight, Specific Energy Absorption (SEA[1]) is evaluated [4]. This parameter is calculated as the absorbed energy per unit mass of the sample, with units of Joules per gram (J/g). The average impact results for hybrid and non-hybrid Innegra/Kevlar composites are summarized in Table 1.

Table 1. Average Impact Results for Hybrid and Non-Hybrid Composites.

Configuration	Impact Velocity (m/s)	Output Velocity (m/s)	Absorbed Energy (J)
	136	126.5	8.72
KKKKK	103	82	13.58
	56	0	11.23
	136	104	26.86
IIIII	103	49.5	28.78
	89	0	27.73
	136	114	19.24
KIKIK	103	71.5	19.02
	74	0	20.58
	136	113.5	19.63
IKIKI	103	56	27.37
	80	0	22.72
	136	121.5	13.05
KKIKK	103	74.5	17.70
	66	0	15.49
	136	116	17.60
IIKII	103	54.5	26.73
	78	0	21.73

The estimated ballistic limit speed for the Innegra/epoxy sample (89 meters per second) compared to the Kevlar/epoxy sample (56 meters per second) leads to the conclusion that the Innegra/epoxy sample demonstrates desirable ballistic performance. Additionally, the Innegra/epoxy sample has a wider permissible impact speed range compared to the Kevlar/epoxy sample. Utilizing it for the production of Kevlar/Innegra hybrids can enhance ballistic performance and reduce costs compared to the Kevlar/epoxy sample, making it a highly suitable option for military and defense industries.

The highest specific energy absorption (energy absorption relative to weight) corresponds to the sample with the KIKIK configuration, which shows an increase of 61.5% and 42.29% in specific energy absorption compared to the Kevlar/epoxy and Innegra/epoxy samples, respectively. For the sample with the IKIKI configuration, the increases are 23% and 8%, respectively. This indicates that the use of Innegra fibers leads to increased energy absorption compared to the standalone Kevlar sample, and their combination with Kevlar fibers will enhance impact strength in Kevlar/Innegra hybrids.

4. Microscopic Fracture Analysis

In Figures 1 and 2, the extent and nature of the damage for samples with KIKIK and IKIKI configurations, along with the estimated ballistic limit velocity, are shown. When Kevlar fibers are placed in the first and last layers, the damage is more localized, whereas, with Innegra fibers placed in the first layer, interlayer delamination occurs around the impact point. This interlayer delamination is more noticeable for the sample with the IKIKI configuration at velocities near the ballistic limit. The difference in failure modes leads to a change in ballistic performance, highlighting the crucial role of the first layer in absorbing the projectile's energy.

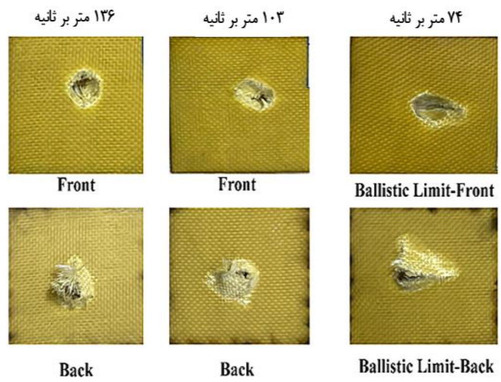

Figure 1 - Impact of a projectile on a Kevlar/Innegra hybrid with KIKIK configuration.

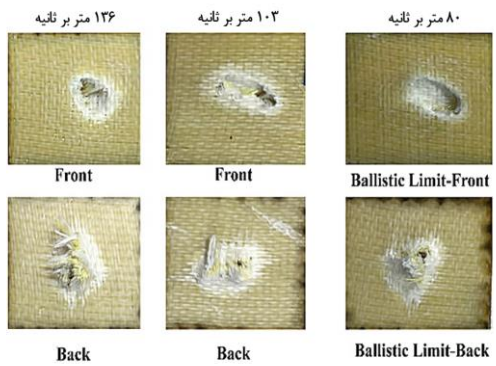

Figure 2 - Impact of a projectile on a Kevlar/Innegra hybrid with IKIKI configuration.

The dominant failure mechanism in the KIKIK sample (Figure 1) is fiber breakage and the expulsion of fibers from the matrix. It is noteworthy that due to the Innegra

[1] Specific Energy Absorption

fibers being positioned in the middle of the KIKIK sample, as the projectile reaches the middle layer (Innegra fibers), it reduces the projectile's energy level and causes rotation on the sample surface, resulting in a conical surface on the back of the sample.

Furthermore, the failure mechanisms in the IKIKI hybrid sample (Figure 2) include matrix crushing and fiber breakage on the top layers, and fiber breakage with fiber expulsion from the matrix in the lower layers, ultimately leading to interlayer delamination.

The shear hole created by projectile penetration and the increased failure surface in the IKIKI hybrid sample compared to the KIKIK sample indicate maximal stretching of the Innegra fibers in the direction of projectile exit. Additionally, the fiber splitting of the Innegra fibers during fracture enhances ballistic performance and completely blocks the shear hole, thereby boosting the ballistic performance of the IKIKI sample.

5. Conclusions

1. The suitable ballistic performance of the Innegra/epoxy sample compared to the Kevlar/epoxy sample demonstrates the high capability of Innegra fibers to absorb energy and reduce the kinetic energy of the projectile. The use of Innegra fibers in the construction of Kevlar/epoxy composites and its hybridization with Kevlar fibers has led to an increase in energy absorption in Kevlar/Innegra composites.

2. Considering the non-uniform thickness among the manufactured samples, it can be stated that the composite formed from 5 layers of Innegra is more economically feasible than the composite made from 5 layers of Kevlar, due to the imported nature of Kevlar fibers. Therefore, its use in energy absorbers is economically justified. In other words, given the high cost of Kevlar fibers and their imported status, the energy absorption capability in 5-layer Kevlar/epoxy composites can be improved by using Innegra fibers.

3. The highest energy absorption per weight corresponds to the KIKIK sample, followed by the sample with the IKIKI configuration, which recorded values of 23.3 and 46.2 joules per gram, respectively.

4. In the fully Kevlar/epoxy sample and the KIKIK sample, due to the thinness of the samples, better membrane deformation was observed compared to samples containing Innegra fibers. The primary contribution to projectile absorption comes from the bending and tensile behavior of the layers, while the remaining absorbed energy is attributed to fiber failure and shear failure of the constituent layers.

5. In samples where Innegra fibers are positioned in the first and last layers, the resistance to compression is greater than that to tension for the sample, and the stress wave upon reaching the last layer during projectile exit is tensile. This leads to fiber pull-out and petalling phenomena in the IKIKI sample.

6. References

[1] Safri, S. N. A., Sultan, M. T. H., Jawaid, M., & Jayakrishna, K. (2018). Impact behaviour of hybrid composites for structural applications: A review. *Composites Part B: Engineering, 133, 112-121*.

[2] Liu, A., Chen, Y., Hu, J., Wang, B., & Ma, L. (2022). Low-velocity impact damage and compression after impact behavior of CF/PEEK thermoplastic composite laminates. *Polymer Composites, 43(11), 8136-8151*.

[3] Da Silva Junior, J. E. L., Paciornik, S., & d'Almeida, J. R. M. (2004). Evaluation of the effect of the ballistic damaged area on the residual impact strength and tensile stiffness of glass-fabric composite materials. *Composite Structures, 64(1), 123-127*.

[4] Zimmermann, N., & Wang, P. H. (2020). A review of failure modes and fracture analysis of aircraft composite materials. *Engineering failure analysis, 115, 10469*.