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Ballistic impact response of Kevlar® reinforced thermoplastic composite armors

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ABSTRACT

The ballistic impact response of thermoplastic-based composite armors made from Kevlar® fabric and polypropylene (PP) matrix has been investigated against ballistic test standard NIJ-STD 0106.01 Type IIIA. Kevlar® fabrics of different architectures, namely 2D plain woven, 3D orthogonal and 3D angle interlock fabrics, were produced and used as reinforcements to fabricate composite armor panels, using compression molding technology. Interfacial property between PP and Kevlar® was improved by adding a coupling agent called maleic anhydride grafted PP. Reduced density was observed in Kevlar® thermoplastic-based composites as compared to that of the thermoset-based laminates. Ballistic impact tests were imparted with 9 mm full metal jacket (FMJ) on armor panels having different fabric architecture. Ballistic test results revealed that 2D armor was 2.4–7% more susceptible to damage than 3D armors. Hydrocode simulations were carried out using ANSYS AUTODYN v. 14.0 to obtain an estimate for the ballistic limit velocity and simulate failure modes. Post-impact damage patterns obtained from the simulations were compared with the experimental results to assess the performance of the simulations. Good correlation between the hydrocode simulations and experiments was found, both in terms of failure modes and damage patterns. 3D composite armors were able to confront the 9 mm FMJ projectile; however, the 2D plain woven armors failed. The increase in the ballistic limit from 2D plain woven armor to 3D orthogonal and 3D angle interlock armors was 16.44% and 20%, respectively, indicating the effect of fabric architecture.

1. Introduction

With the requirement of light weight body armors, the need for performance improved fiber reinforced composites is significantly increasing. The architecture of the fabric plays a significant role in the protection against ballistic impact and provides a unique ballistic penetration resistance for varied orientations. The main structural parameters of the fabric, which shows the effect on the ballistic performance, are type of weave (with a twist in the yarns), yarn crimp, fabric structure, projectile geometry, impact velocity and friction [1–5].

The ballistic impact response of thermoset-based composite laminates, such as S2 glass/polyester [6], E-glass/epoxy [7,8], S2 glass/epoxy [9,10], Kevlar® 29/Vinylester [11] and Kevlar®/epoxy [12], was investigated by several researchers through experiments, numerical simulations, and analytical models. Silva et al. [11] investigated the ballistic impact response of Kevlar® 29/Vinylester panels impacted with a fragment simulating projectile (FSP) (320–360 m/s). Numerical simulations were carried out using AUTODYN commercial software. Post-impact damage patterns obtained from the simulations were in good agreement with the experimental results. Further, simulations were extended to obtain ballistic limit velocity and residual velocity. Similarly, hydrocode simulations were carried out using AUTODYN to investigate the ballistic response of a Kevlar® helmet by Tham et al. [12]. The response of the helmet from simulations was compared with the ballistic impact test results in terms of post-impact damage. Further, simulations were extended to assess the ballistic resistance of helmet against NIJ-STD-0106.01 Type II (9 mm FMJ) and 1.1 g FSP. It was found that the helmet was able to stop both the projectiles. Grujicic et al. [13] developed a material model based on the unit cell method and integrated with ANSYS/AUTODYN as a user defined subroutine. Different stages of armor penetration such as shearing of the filament, delamination, and stretching of the filament on the back face of the target were observed. Kevlar® fabric was also used as a hybrid layer

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in hybrid composites with other laminates reinforced with carbon and glass fibers [14–17].

Designing of body armors based solely on the experimental data requires huge material and manpower, which is time consuming and also uneconomical. Recent advances concerning the ballistic impact response of composite laminates offer the possibility of preventing tests by using numerical simulations such as hydrocodes [11–14,17] that can reduce the expenses incurred in designing of the body armors. Due to the continuous development of numerical algorithms and material models, the accuracy and the applicability of simulation results are increasing.

All the above discussed studies have been concentrated on the ballistic impact behavior of thermoset-based composite laminates. Though thermosets were extensively used as matrix materials, the use of these matrices is limited due to a few shortcomings, namely, the need for low temperature storage and a long curing process. Thermoplastic-based composites, on the other hand, are an alternative to thermoset-based composites due to their long shelf life, short processing time, sufficiently tough, chemical resistant melt-processability, and an ability to be recycled [18,19]. Also, thermoplastic composites have relatively low brittleness transition temperatures, which allow potential improvements in terms of greater ballistic resistance, higher mechanical toughness, and faster manufacturing cycles [20,21]. Studies of Walsh et al. [20,21] reported that the thermoplastic aramid based composites exhibit improved ballistic performance at a much lighter weight. Song [22] studied the influence of microscopic and macroscopic characteristics on the ballistic impact response of thermoplastic composites made of Kevlar® 29/nylon 66, Kevlar® 29/polyetheretherketone (PEEK), Kevlar® 29 /polycarbonate, Kevlar® 29/Polysulfone, Kevlar® KM2/Polysulfone, and Kevlar® KM2 fiber/linear low-density polyethylene (LLDPE) laminates. The characteristics, like processing temperature, cooling rate, fabric configuration, fiber wetting, polymer morphology, and stiffness of the laminate, significantly affected the ballistic performance of the composite armor. The major energy absorbing mechanisms observed were fiber breakage, fiber straining, matrix cracking, and delamination. The review work of Kulkarni et al. [19] stated that the thermoplastics have lower tensile strength than thermosets; as a result, ballistic performance was reduced. Therefore, thermoplastics are used with high ductile fibers like Kevlar® to enhance the matrix stiffness. Carrillo et al. [23] has studied the ballistic response of Kevlar® 129/PP laminates through experimental studies. The addition of PP matrix to aramid fabrics showed improved impact resistance. However, low adhesion was reported between Kevlar® fabrics and PP matrix, suggesting for improvements in the interfacial property. Further, it was reported that numerical modeling is required to validate the results obtained through experiments.

After a thorough literature review, it is observed that the ballistic impact behavior of thermoset two dimensional (2D) Kevlar® composite laminates was investigated with woven or unidirectional fabrics. The laminates with 2D plain woven fabrics evidence the presence of crimp, exhibit poor in-plane stiffness, and suffer more damage due to delamination. On the other hand, in 3D fabrics, warp and fill tows do not have any crimp, and yarns in *z*-direction play a vital role in holding all warp and fill yarns together. The 3D structure of fabric provides increased areal density, thus increasing the amount of specific energy absorption [24].

Studies on Kevlar®/PP composite laminates are not conclusive due to low adhesion problem between aramid and PP [23,25,26]. Further studies are required in terms of enhancing the interfacial property between Kevlar® fabric and PP matrix. Also, numerical validation is necessary to confirm the experimental results [23]. Ballistic impact resistance of thermoplastic-based body armors reinforced with 3D fabrics was also not reported in the open literature. To the author's knowledge, there is no literature available to investigate the ballistic impact response of Kevlar® thermoplastic laminates according to NIJ-STD-0106.01 Type IIIA [27].

In the present study, Kevlar® 29 yarns were woven to get fabrics with three different architectures, namely 2D plain woven (2D-P), 3D orthogonal (3D-O), and 3D angle interlock (3D-A). Composite armor panels were fabricated with PP matrix reinforced with the above three types of fabrics using vacuum assisted compression molding machine. The interfacial property between the Kevlar® and PP was improved by adding a coupling agent called maleic anhydride grafted (MAg)-PP. The objectives of the present work were dual. The first objective was to perform a ballistic impact test on Kevlar®/MAg-PP (K-MPP) composite armor panels for their perforation capability against the ballistic test standard NIJ-STD-0106.01 Type IIIA when impacted by a 9 mm FMJ projectile. The response obtained from the ballistic test was used as a benchmark for later comparison with that obtained from hydrocode simulations. Post-impact damage patterns of the armors were acquired to determine the extent of damage due to different failure modes and fabric structures. The second objective was to study the influence of fabric architecture on the ballistic impact response of K-MPP laminates. For the same mass and geometry of the projectile, ballistic limit velocity and energy absorbed by the target were compared for the three types of thermoplastic-based Kevlar® armor panels, and new findings on their ballistic impact response were reported.

2. Experimental

2.1. Materials

The high performance aramid (Kevlar® 29) fiber tow was considered with a linear density of 1000 Denier. Fabrics with three solid woven structures viz. 2D-plain woven (2D-P), 3D-orthogonal (3D-O) and 3D-angle interlock (3D-A) were prepared using CCI sample weaving machine with rapier weft insertion mechanism. Physical parameters of the fabric are given in Table 1a and Table 1b. Microscopic views of the woven structure are shown in Fig. 1. These fabrics were produced with two warp beams, one containing the binding yarns and the other containing the ground yarns.

PP sheets were produced with two different grades, namely, MI3530 and CO15EG, using in-house extrusion facility with nitrogen gas at a pressure of 150 bar.

2.2. Fabrication of laminates

The vacuum assisted compression molding technique was used for the consolidation of stacked fabrics and resins. The specimens were cured at 200 °C. Fiber weight fractions obtained for 2D-P, 3D-O and 3D-A were 60.2%, 64%, and 64%, respectively. Three types of specimen were prepared: first, sixteen layer 2D-P laminate; second, eight

Table 1
(a) Physical parameters of Kevlar® 29 fabrics. (b) Properties of constituent materials.

(a)

Property	2D-P	3D-A	3D-O
Warp yarns/inch	40	40	40
Weft yarns/inch	32	120	120
Areal density (g/m^2)	363.75	745.86	780.36
Thickness (mm)	0.64	1.17	1.24

(b)

Property	Tenacity (gpd)	Strain (%)	Modulus (gpd)
Kevlar® yarn	14.91 (6.13)[a]	2.99 (5.18)	547.30 (10.11)
Polypropylene sheet	17.93 (14.23)	4.08 (14.20)	98.14 (19.18)

[a] Value enclosed in parentheses indicates the coefficient of variance of corresponding 15 readings for each sample.