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Short communication

Effect of twist on transverse impact response of ballistic fiber yarns

Bo Song [a, *], Wei-Yang Lu [b]

[a] Sandia National Laboratories, Albuquerque, NM 87185, USA
[b] Sandia National Laboratories, Livermore, CA 94550, USA

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ABSTRACT

A Hopkinson bar was employed to conduct transverse impact testing of twisted Kevlar KM2 fiber yarns at the same impact speed. The speed of Euler transverse wave generated by the impact was measured utilizing a high speed digital camera. The study included fiber yarns twisted by different amounts. The Euler transverse wave speed was observed to increase with increasing amount of twist of the fiber yarn, within the range of this investigation. The higher transverse wave speeds in the more twisted fiber yarns indicate better ballistic performance in soft body armors for personal protection.

1. Introduction

Effective and efficient soft body armor employed against ballistic or blast impact depends on the mechanical properties of the fiber yarns used in the fabric, and on the fabrication process. Ballistic performance of fiber yarns and fabrics has been investigated through theoretical analysis, numerical simulation, and experiments [1–4]. When a fiber yarn or fabric is subjected to external impact, a transverse wave is produced and propagates in the yarn or fabric. The speed of transverse wave has been found to be critical to their ballistic performance [5]. A faster transverse wave speed is desired to dissipate the impact energy more quickly [5]. The transverse wave speed has been shown to depend on the external impact speed and the longitudinal wave speed that is usually a material constant of the fiber yarn [6].

When an aligned fiber yarn is subjected to transverse impact, the individual fibers in the yarn are impacted progressively along the thickness direction within the first several microseconds [6]. Fig. 1 shows a high-speed image at the very early stage of a Kevlar® KM2 fiber yarn being impacted. As shown in Fig. 1, only the first half of fibers in the yarn were impacted and deformed at this moment while the other half of fibers kept staying free. This image reveals that not all fibers have been impacted simultaneously, which may result in progressive premature failure of the fiber yarn when subjected to high speed impact. In this case, the fiber yarn behaves simply as a group of individual fibers instead of a solid component bundling all individual fibers, which possibly downgrades the global ballistic performance. It is therefore reasonable to characterize the transverse impact response of twisted fiber yarns. In addition, the angle shown in Fig. 1 might represent the transverse wave propagation in the portion of the compressed fibers instead of the whole fiber yarn. The impact wedge was shaped but might still affect the shape of the deformed fibers at very early stage of impact loading.

Twisting a fiber yarn has been explored to address the deficit in the mechanical response discussed above. Twist more effectively holds all individual fibers in a fiber yarn without significant change in density. For example, twist can improve the interactions among individual fibers in terms of friction forces such that the fibers are capable of bearing load even after some individual fibers are broken [7]. The mechanical properties of twisted fiber yarns have been investigated in Refs. [8–10]. Both modulus and tensile strength change after a fiber yarn is twisted. In general, the tensile strength increases when the fiber yarn is slightly twisted. However, the change in modulus has been observed to depend on the amount of twist. For example, Im et al. [10] found the tensile strength increased after the poly (paraphenylene benzobisoxazole) or PBO fiber yarn was twisted. The tensile strength kept increasing with increased twist level up to 6 turns per inch. When the fiber yarn was twisted more, the tensile strength decreased. The Young's

* Corresponding author.
E-mail address: bsong@sandia.gov (B. Song).

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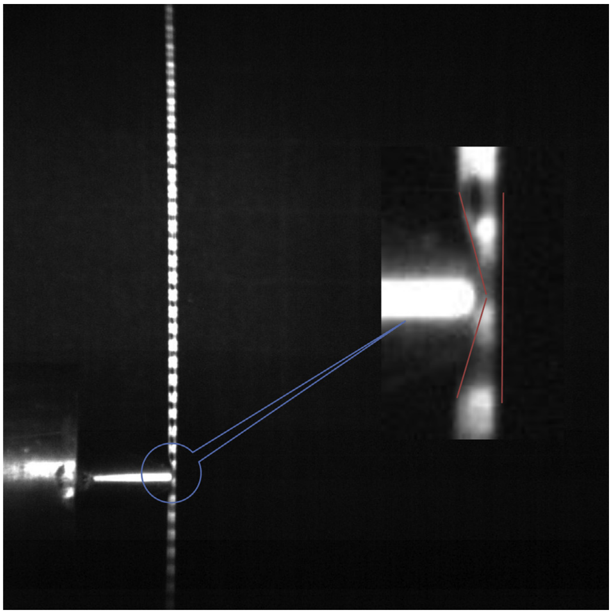

Fig. 1. Non-uniformly transverse impact on the non-twisted fiber yarn.

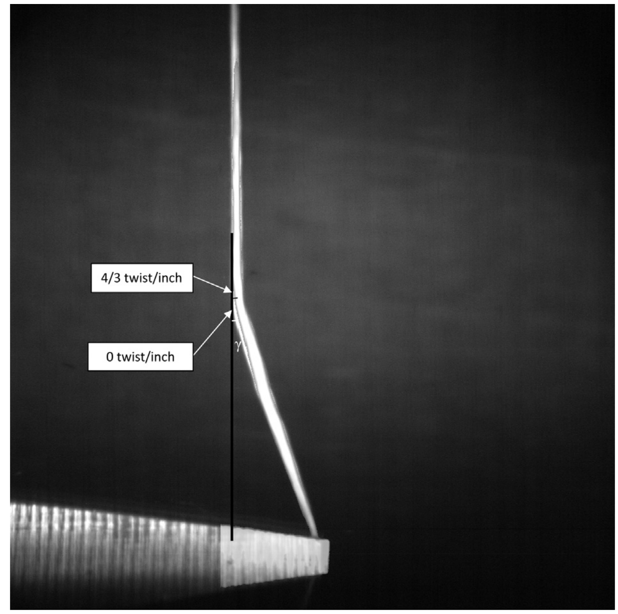

Fig. 3. Comparison of Euler transverse wave propagation in non-twisted and twisted fiber yarns.

modulus had little change when the fiber yarn was twisted by 6 twists per inch or under. However, when the fiber yarn was twisted more, the Young's modulus significantly decreased. Therefore, the twist level is a critical parameter that affects the mechanical properties of the fiber yarn.

There has been little to document the twist effect on the transverse wave speed produced in a fiber yarn subjected to transverse impact. In this paper, we report the transverse wave speed produced in twisted fiber yarns by different amount of twist to determine the effect of twist on the transverse wave speed and thus the ballistic performance.

2. Experiment and results

The experimental procedure of the transverse impact on a fiber yarn has been documented in Ref. [6]. The schematic of this modified Hopkinson bar setup is shown in Fig. 2. In this study, the fiber yarn used was 450 denier Kevlar KM2 taken from a 0/90 plain woven fabric, which is the same as the fiber yarn in Ref. [6]. As shown in Fig. 2, the fiber yarn was set perpendicular to the pressure bar axis. The initial load on the fiber yarn was set to be nearly zero (<0.3 N) measured with a load cell attached to the bottom. A Cordin 550 high speed digital camera was used to take the images of the fiber deformation during transverse impact. In this study, we performed transverse impact on the fiber yarns at the same speed, $V = 53$ m/s. The fiber yarns were twisted by different amounts: 0 (no twist), 1/3, 2/3, 4/3, and 8/3 turns per inch, before transverse impact.

The transverse impact experimental results show that all twisted fiber yarns displayed a very similar characteristic of deformation: an isosceles triangle shape was formed. With increasing time (or the bar end displacement), the triangle area became larger and both sides moved outwards along the non-deformed fiber yarn [6]. The movement of the sides along the fiber yarn represents the propagation of Euler transverse wave. Since the impact velocity of the pressure bar end was constant while deflecting the fiber yarn, there was little change in the internal angle of the isosceles triangle. There is a relationship between the angle, γ, marked in Fig. 3, and the Euler transverse wave speed, c_s, [6].

$$c_s = \frac{V_0}{\tan \gamma} \tag{1}$$

where V_0 is the impact velocity of the bar end. It is noted that, the velocity of the bar end is the same as the striker speed in this study where the resistance of the fiber yarn to the bar-end movement is negligible. We measured the angle for each test of the fiber yarns with different amount of twist and found that the angle was dependent on the twist amount. In other words, the twist amount influenced the transverse wave speed according to Eq. (1). The high-speed images for the fiber yarns, without twist and with a twist of 4/3 turns per inch, were overlapped to compare the

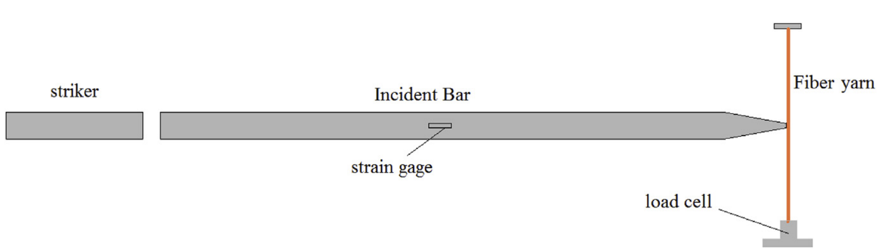

Fig. 2. Schematic of the Hopkinson bar for transverse impact testing of fiber yarns.