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Finite element analysis of pre-stretch effects on ballistic impact performance of woven fabrics

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ABSTRACT

Pre-stretch effects on ballistic impact performance of woven fabrics that made of Kevlar KM2 is investigated with finite element simulation. Individual yarns of the fabrics are modeled with truss elements incorporated with equivalent material properties of real fiber yarns. Before the projectile is issued, a fabric panel that has a rectangular configuration is pre-stretched by directly applying displacement boundary conditions. This two-step loading condition is realized through results transferring capability offered by the commercial software ABAQUS. Simulation results reveal that pre-stretch can significantly influence the fabric's ballistic response such as ballistic limit, energy absorption and wave propagation. The fabric with higher pre-stretch absorbs more energy, however fails earlier than the fabric with lower pre-stretch. Parametric studies show that with the increase of pre-stretch, the deformation contour evolves from a pyramid shape that is conventionally observed in non-pre-stretched fabrics into a conical shape.

1. Introduction

Woven fabrics that made of high strength aramid fibers such as Kevlar have attracted great attention in applications such as soft body armor and bulletproof vest. In these applications, the fabrics are required to provide ballistic resistance against the incident high speed projectiles. To continuously improving the protection performance and comfortability of the protective apparels, extensive studies have been conducted on the ballistic impact behavior of woven fabrics, from experimental characterization to numerical simulation, in the past several decades [1–3]. In Cheeseman's [4] review paper, seven factors were outlined that influence the ballistic performance of woven fabrics: material properties, fabric structure, projectile geometry, impact velocity, multiple ply interaction, far field boundary conditions and friction [5,6]. These factors can be further categorized into intrinsic factors like material properties and extrinsic factors like impact velocity. Extrinsic factors are often related to experimental method used, such as projectile geometry and clamp designing. Another extrinsic factor that exerts a great influence on the fabric response however has rarely been studied is fabric pre-stretch that arises from clamping during experiment [7]. For example, in Ref. [8], it was reported that the fabric was slightly pre-stretched before been fired upon. However, it is not known how much pre-stretch was applied and it is not well understood how the pre-stretch precisely affects the fabric deformation and its impact performance.

Although many different clamping configurations have been studied [9,10], it is tacitly assumed that the pre-stretch is zero in these configurations. In reality, pre-stretch can be generated intentionally or unintentionally when griping the fabric into a test machine. One of the most obvious effects of pre-stretch is to diminish or eliminate initial fiber crimp that arises from the elegant woven structures of fabrics. For a single yarn, de-crimping generates a zero force with no initial strain, while further stretch induces a pre-strain in fiber yarns. Shin et al. [11] observed that yarn pre-tension in a fabric serves to induce failure at an earlier instance and also reduce the cut energy of the fabric. Furthermore, while it is well known that friction improves the ballistic response by maintaining the integrity of woven pattern, pretension has a significant effect on friction. For example, in a quasi-static test, it was found that the peak pull-out force of a fabric yarn increases with the increase of pre-load magnitudes [12]. Under impact, to eliminate crimp and consequently keep the fiber yarn straight, a slight pre-load is inevitably introduced [13]. On the other hand, even though for a fiber reinforced composites rather than a dry fabric, many studies have been conducted on pre-load effects and it is found that pre-load has significant effects on their deformation, energy absorption and damage property [14,15], there is actually very few literature reports on such effects on woven fabrics under impact [16]. Since different researchers stretch their fabric targets to a different degree before shooting, it is highly critical to investigate the pre-stretch effect when comparing the experimental results from different studies.

The challenge in studying the pre-stretch effects lies in the precise controlling of the clamp to produce a determined pre-stretch. Also, the

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fabric targets usually slip at its edges when projected upon [17], making it extremely difficult to isolate the individual effect of these factors. In contrast to experimental study, numerical simulation has substantial advantage in overcoming these deficiencies. The most prominent advantage of numerical simulation is it can isolate each individual mechanism and eliminate unwanted variables that would couple to affect the impact behavior. It also allows parametric studies of the individual effect where the dominant parameter can be meticulously controlled. Over the past two decades, finite element has gained great attention in modeling fabric impact behavior due to the exceptional advantages. Finite element models across different scales require different computational efforts. In the continuum level, the entire fabric is modeled as a shell or membrane and anisotropic behavior is incorporated with material constitutive models [18,19]. This approach is computationally efficient and can model the global behavior of fabric response, however ignores important fabric behavior such as yarn sliding and yarn-yarn friction. To capture the individual yarn behavior, meso-scale model has been developed [5,6,9,20,21]. In the meso-scale approach, fabric yarns are explicitly modeled as solid elements and the material properties are set to dominant in a principal direction. This approach has been widely used in the study of the effect of friction, material properties, clamping configurations. However, the computation cost is extremely high. Another disadvantage is that stability becomes an important consideration when setting the orthotropic material properties to a single yarn, i.e., the transverse stiffness should never be too small as required to mimic an ideal yarn, which leads to excessive bending stiffness for a fabric thus distracts the impact behavior. A more simplified technique is to use truss elements to model fabric yarns. Tan et al. [1] and Sanhita et al. [22] fall into this category. Truss element model significantly reduces the element numbers and is thus more computationally efficient. However, it loses important fabric information such as yarn cross-sectional area.

The goal of this paper is to investigate pre-stretch effects on ballistic impact performance of woven fabrics. To achieve the goal, a finite element model is constructed at the yarn level with truss element. It differs from the conventional truss element method in that equivalent material properties are used thus single yarn behavior is well captured. Pre-stretch effects on a single yarn impact is first studied and validated against analytical solutions. Fabric response is then validated against experimental results. The pre-stretch effect is studied for rectangular shaped woven fabrics with four edges fixed boundary conditions. The fabrics were first stretched by directly applying displacement boundary conditions at its edges and then shot by a spherical projectile. This two-step simulation is achieved by results transferring capability provided by the commercial software ABAQUS [23]. The effect on ballistic performance such as V50 velocity, energy dissipating mechanism and deformation shape is studied and compared against that of non-pre-stretched fabrics.

2. Pre-stretch effects on a single yarn impact

2.1. Yarn model and material properties

In reality, a single fabric yarn consists of hundreds of fiber filaments and thus is a very complex material [24]. The fiber material used in this study is Kevlar KM2, which has a Young's modulus of 82.6 GPa and a fiber volumetric density of 1.44 g/cm^3 [25]. Since a single yarn has little resistance to bending, it is modeled with truss element provided in commercial software ABAQUS. The truss element assumes a homogenous material and a linear elastic material model is used to characterize its behavior. An important consideration in modelling a single yarn is its cross-sectional areal, which is usually set to be 0.051 mm^2, including the area of Kevlar fiber and void space in a 600 denier yarn [26]. In the truss model, the radius of the truss element is set to be 0.05 mm to preserve a thickness of 0.2 mm for a single-ply plain woven fabric. However, this radius gives out a cross-sectional area of 0.00785 mm^2. This means it loses its accuracy in modeling the area of a real yarn. Thus the mechanical response of a single yarn, and therefore a woven fabric, would not have been captured if the physical Kevlar KM2 properties were used. To account for this cross-sectional area effect, an equivalent elastic modulus is introduced for the truss element such that it is equivalent to its fiber yarn counterpart in the sense of strain energy. In this way, the equivalent elastic modulus for the truss model is obtained through scaling that of the fiber yarn by its area ratio. To conserve the mass of a truss element with respect to a real yarn, the volumetric density of which is scaled in the same manner. This process gives out an equivalent elastic modulus of 536.6 GPa and an equivalent density of 9.355 g/cm^3. In this manner, the sound speed of the material is also retained and calculated as $\sqrt{E/\rho} = 7.57$ km/s. Furthermore, in accordance with experimental results as reported in Ref. [25], a tensile failure strain, implemented through the user subroutine VUSDFLD in ABAQUS, is set to be 4.7% for a single yarn, which corresponds to a failure stress of 3.88 GPa. These equivalent material properties are listed in Table 1 and will be used in the simulations hereafter. In addition, the yarn path is determined by following the procedure described in Ref. [5]. A single yarn geometry created in this way is shown in Fig. 1a. The mechanical response of a single yarn predicted by the FE model is shown in Fig. 1b. Here stretch ratio, which is defined as the ratio between applied displacement and the initial distance between the two fiber ends, is used rather than strain because initially the yarn strain is zero due to crimp. As can be readily seen from Fig. 1b, the force is initially very small and close to zero, which represents the crimp stage that is usually found in a yarn directly extracted from a fabric. The amount of yarn crimp accounts for approximately 1.2% of its stretch ratio. After the yarn straightens out, a force is developed in the yarn and increases linearly until it reaches the peak value determined by its failure strain. This exactly reproduce the behavior of a physical yarn that has an elastic modulus of 82.6 GPa.

Table 1
Material properties of fabric yarns.

	Density (g/cm^3)	Elastic modulus (GPa)	Failure strain (%)
Kevlar KM2	1.44	82.6	4.7
Truss element	9.355	536.6	4.7

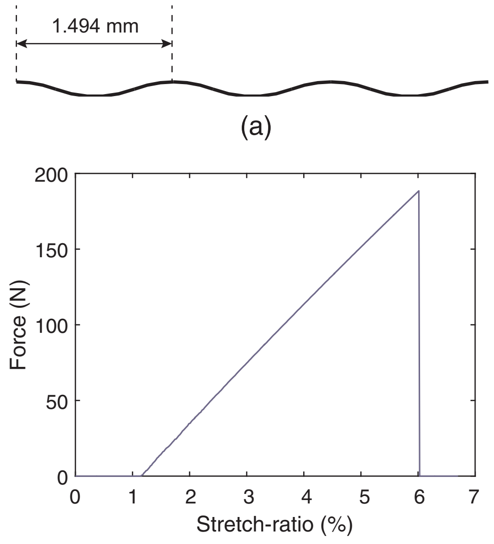

Fig. 1. Single yarn, (a) a path diagram and (b) its force-stretch ratio relationship.