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Modeling yarn slip in woven fabric at the continuum level: Simulations of ballistic impact

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A R T I C L E I N F O

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A B S T R A C T

Woven fabric is used in a wide variety of military and commercial products—both in neat form and as the reinforcement phase of composites. In many applications, yarn slip, the relative sliding of the yarns composing the weave, is an important mode of deformation or failure. Yarn slip can significantly change the energy absorption capacity and yarn density of the fabric and also cause yarns to unravel from the weave. Virtually all existing models for woven fabric that allow yarn slip are discrete in nature. They simulate every yarn in the weave and are therefore computationally expensive and difficult to integrate with other material models. A promising alternative to discrete models is the mesostructure-based continuum technique. With this technique, homogenized continuum properties are determined from a deforming analytic model of the fabric mesostructure at each material point. Yarn-level mechanisms of deformation are thus captured without the computational cost of simulating every yarn in the fabric. However, existing mesostructure-based continuum models treat the yarns as pinned together at the cross-over points of the weave, and an operative model that allows yarn slip has not been published. Here, we introduce a mesostructure-based continuum model that permits yarn slip and use the model to simulate the ballistic impact of woven fabric. In our approach, the weave is the continuum substrate on which the model is anchored, and slip of the yarns occurs relative to the weave continuum. The cross-over points of the weave act as the material points of the continuum, and the evolution of the local weave mesostructure at each point of the continuum is represented by state variables. At the same time, slip velocity fields simulate the slip of each yarn family relative to the weave continuum and therefore control the evolution of the yarn pitch. We found that simulating yarn slip significantly improves finite element predictions of the ballistic impact of a Kevlar® woven fabric, in particular by increasing the energy absorbed at high initial projectile velocities. Further simulations elucidate the micromechanisms of deformation of ballistic impact of woven fabric with yarn slip. Our findings suggest ways to improve the performance of flexible armor and indicate that this approach has the potential to simulate many other types of woven fabric in applications in which yarn slip occurs.

1. Introduction

Valued for its flexibility, formability, and high specific strength, woven fabric is an increasingly important part of many defense and commercial systems. These systems include personal body armor, deployable structures such as air bags, sails,

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and parachutes, and restraint systems such as seat belts and head restraints. Woven fabric also reinforces polymers or ceramics in helmets, armor panels, and numerous structural applications.

Modeling woven fabric is challenging due to the complexity of the weave architecture and the multiple modes of deformation of the yarns (Lomov et al., 2001). At the mesoscale, a woven fabric consists of two orthogonal, interlaced sets of yarns, *warp* yarns and *weft* yarns, each typically composed of hundreds of continuous fibers. During weaving, the warp yarns are held taut in the loom and moved up and down by the heddles. Meanwhile, the weft yarns are pulled through the gaps by the shuttle. The resulting undulation of each yarn over and under the orthogonal yarns is described as *crimp*, and wherever the yarns cross is termed a *cross-over point*. The macroscopic deformation of woven fabric, decidedly nonlinear and anisotropic, is controlled by one or more of the following mechanisms: (1) *yarn stretch*, the elongation of the yarns; (2) *uncrimping*, the straightening of the initially undulating yarns; (3) *in-plane shear*, the relative rotation of the yarns at or between the cross-over points; (4) *locking* or "jamming," the in-plane contact of the yarns with each other; (5) *yarn slip*, the relative sliding of the yarns at the cross-over points.

Mesostructure-based continuum models have been shown to simulate accurately and efficiently the deformation of woven fabric in many circumstances (Boisse et al., 1997, 2001; Tanov and Brueggert, 2003; Ivanov and Tabiei, 2004; Nadler et al., 2006; Shahkarami and Vaziri, 2007; Hamila et al., 2009; Parsons et al., 2010b; Assidi et al., 2011; Xia et al., 2011). These models assume that at an appropriate scale, sufficiently larger than the spacing of the yarns, woven fabric deforms in an affine manner and may therefore be approximated as a continuum. At each material point, the deformation of sections of discrete yarns are simulated by the deformation of an analytic unit cell of the fabric, typically composed of pin-joined trusses or beams. The unit cell deforms with the continuum and thus tracks the orientation and, in some cases, the crimp of the yarns. The geometry of the deformed unit cell, together with the constitutive relations of the yarns, determines the stress in the continuum. As a result, the macroscopic predictions of these models derive from the actual mechanisms of deformation of the yarns. An additional benefit of this type of model is that critical yarn-level details, such as orientation, tension, areal density, shear angle and crimp amplitude, are also calculated. All the models referenced above, however, approximate the fabric as slip-free, essentially by pinning the yarns together at every cross-over point of the unit cell.

Omitted in nearly all mesostructure-based continuum models, slip of the yarns at the cross-over points is an important mode of deformation in many applications. During ballistic impact, yarn slip is initiated primarily by gradients of tension in the yarns struck by the projectile. It occurs when the differential yarn tension across a given cross-over point exceeds the friction force at that same cross-over point, causing the yarns to slide relative to one another. Yarn slip affects the energy absorbed by the fabric (Lastnik and Karageorgis, 1982; Briscoe and Motamedi, 1992; Bazhenov, 1997) and causes unraveling at the free edges of the fabric. Furthermore, yarn slip has been shown with experiments (Godfrey and Rossettos, 1998, 1999) and with micromechanical modeling (Abbott and Skelton, 1972; Popova and Iliev, 1993) to blunt the stress concentration at the tips of cuts in woven fabric. During composite forming operations, yarn slip can be caused by gradients of shear locking forces (Zhu et al., 2007) and transverse shear loads, affecting the shape and properties of the formed part as well as potentially causing the fabric to fail.

The simulation of yarn slip at the scale of an actual fabric has largely been limited to two types of discrete model, both with drawbacks compared to the mesostructure-based continuum approach. One type of model is the discrete three-dimensional approach, in which every yarn (or even fiber) is modeled in three dimensions with finite elements (Shockey et al., 1999; Duan et al., 2005, 2006a; Zhang et al., 2008; Chocron et al., 2011, among others). These finite element meshes are tedious to construct (and must be reconstructed for any change in the geometry of the fabric), computationally very expensive, and difficult to integrate with other material models for the simulation of fabric-reinforced composites. The second type of model is that of Roylance et al. (1973), in which the fabric is modeled as an array of point masses connected by massless, pin-joined trusses. Roylance et al. (1995), Termonia (2004), and Zeng et al. (2006), among others, extended this approach to include yarn slip. Although more efficient than the three-dimensional approach, the point mass models still must simulate every yarn in the fabric. In addition, with this type of model, it is difficult to include contact between layers in multi-layer simulations and to incorporate the matrix in the simulation of fabric-reinforced composites. Notably also, Boubaker et al. (2007) used somewhat of a hybrid technique, in which the undulating yarns are discretized as elastic trusses connected by rotational springs, to study the effects of inter-yarn friction on yarn extension at the meso-level.

The mesostructure-based continuum approach is more efficient and versatile than both types of discrete approach. The mesostructure of the weave can be varied without remeshing in order to optimize the design of new fabrics, and other continuum material models can be integrated easily for the simulation of composites. In the literature, to our knowledge, the only continuum-level approach for modeling yarn slip in woven fabric is that of Nadler and Steigmann (2003) and Nadler (2009). These authors proposed simulating the two yarn families as two interacting surfaces, each composed of continuously distributed yarns. The material points of surface-1 are tracked explicitly by the equations of motion. In turn, in the deformed configuration, the evolving points of surface-2 that interact with the material points of surface-1 are determined by the relative slip between the two surfaces. The efficacy of this approach is difficult to evaluate because it appears that no operative implementations or results have been published. Because this model does not explicitly track the motion of the cross-over points of the weave, using it to simulate the interactions between the yarns and to describe the evolution of the mesostructure of the weave might be challenging. Furthermore, this model does not permit yarn slip at the edges of the fabric, the locations where slip is most apt to occur if the edges are not clamped tightly. In light of the