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Yarn mobility in woven fabrics – a computational and experimental study

E. Tapie*, Y.B. Guo, V.P.W. Shim

Impact Mechanics Laboratory, Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, 117575, Singapore

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ABSTRACT

With the increasing usage of woven fabrics in various applications, an understanding of inter-yarn friction characteristics is useful for effective employment of such fabrics. Although the yarn pull-out test is a recognized method to ascertain yarn mobility within a weave, the physics governing yarn pull-out has not yet been fully examined, and previous finite element models were unable to reproduce the results of yarn pull-out tests. Consequently, fabric response involving yarn pull-out has not yet been well-understood in terms of the influence of inter-yarn friction and yarn crimp. The work undertaken provides insights into this by proposing a new yarn pull-out test procedure, which involves in-plane and out-of-plane pull-out; the latter is relevant to projectile penetration of fabric, during which yarns are often pulled out of the fabric plane. Pre-tension is also applied to fabric specimens, and its influence on the response is analyzed. The energy absorbed during out-of-plane pull-out is quantified, and yields insights into fabric performance.

A finite element model is then developed to simulate yarn pull-out tests. To characterize inter-yarn friction, a Coulombic description that considers both static and kinetic friction, is implemented. The numerical model is able to describe both in-plane and out-of-plane yarn pull-out. The model is validated and used to identify mechanisms that restrain yarn mobility during yarn pull-out and how pre-tension affects this mobility. The local fluctuations in the experimental force-displacement curves are captured by the simulation, and are found to be caused by periodic alteration of the original crimped yarn profile during pull-out. Simulation results also show that most of the energy is dissipated by friction during yarn pull-out, and that the fabric stores strain energy. Pre-tension has a significant influence on both frictional energy dissipation, and strain energy in the fabric. Strain energy is found to be more sensitive to pre-tension than frictional dissipation, indicating that excessive restraint of yarn mobility may result in premature yarn failure.

1. Introduction

From applications in civilian aircraft to parachutes and sport gear, the use of high strength polymeric fibers has increased over the past few decades. The high specific strength, stiffness and toughness of aramid fibers endow them with favorable characteristics for energy dissipation. When subjected to external loading, a fabric dissipates energy by a complex combination of several mechanisms (Parsons et al., 2010). They include mainly strain energy due to stretching of the yarns, frictional dissipation associated with inter-yarn interactions within the fabric and, in the case of dynamic loading, kinetic energy due to transfer of momentum to the yarns. Frictional dissipation is particularly important when a projectile penetrates a fabric and pulls one or several yarns out of the weave, contributing to decelerating the projectile (Shim et al., 2012), (Nilakantan and Nutt, 2014). Inter-yarn friction helps transmit stress within the fabric because of contact between yarns (Zhou et al., 2014) (Tan et al., 2005b) and restrains yarn movement due to constraints imposed by neighboring yarns (Nilakantan and Nutt, 2014).

To better characterize yarn interactions within a weave, a pull-out test was developed by (Sebastian et al. 1986) to study the effect of a softening agent on the properties of a fabric. The pull-out test involves pulling out one or several yarns out of a woven fabric subjected to varying constraints, and measuring the pull-out force. Using the same experimental setup, Kirkwood et al. (2004) proposed a theoretical model to relate the force sustained by the yarn to its displacement. Dong and Sun (2009) found that fabrics with a higher yarn count (i.e. with more yarns per unit length) necessitate a higher force to extract a yarn from the weave; they also determined experimentally the inter-fiber static coefficient of friction, and reported values ranging from 0.20 to 0.39. Bilisik (2012) found that fabric density, number of pulled yarns, and specimen size significantly affect yarn mobility, as fabric rigidity is greatly dependent on these parameters. More recently Nilakantan and Gillespie (2013), showed that pre-tension positively enhances fabric resistance to single yarn pull-out, and that the

* Corresponding author. Tel.: +65 6516 6330.
E-mail address: emmanuel.tapie@u.nus.edu (E. Tapie).

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pull-out force varies linearly with pre-tension. They also noticed that the peak pull-out load decreases with pull-out speed, which may explain why in ballistic experiments, where speeds are relatively high, yarn pull-out is often observed. However, no study on the energy dissipated during pull-out has been undertaken. Zhou et al. (2014) recently employed simulation to study the influence of friction on the ballistic performance of polymeric fabrics, and concluded that determining the appropriate friction parameter is the key to successfully modeling a weave. Their results were however not compared with experiments, and confirmed the difficulties linked to ascertaining friction characteristic of woven fabrics. Further investigations need to be undertaken to tackle this issue.

With progression of computational capability, numerical models have been developed to simulate high-strength fabrics. Due to the multi-scale structure of such fabrics, modeling is complex, and the scale of precision (Grujicic et al., 2011b) may vary depending on the main focus of the study. Some authors (Grujicic et al., 2011a) work on the atomistic structure of fibers, while others homogenize a woven fabric as a continuum plate (Parsons et al., 2010). However, for simulation of macro-scale experiments, it is reasonable to idealize each yarn as continuum material, i.e. a "yarn-level" model. Early simulations modeled the fabric as a network of pin-joint trusses (Shim et al., 1995; Tan et al., 2003; Tan et al., 2005a), but these models had difficulties in capturing the deformation of yarns, as well as their interactions with neighbors. More recently, researchers like Shahkarami and Vaziri (2007), Cuong et al. (2012) and Grujicic et al. (2008) used shell and membrane elements; such models offer a better representation of inter-yarn interactions within a fabric, as inter-yarn contact is modeled. However, the volumetric deformation or inter-yarn friction cannot be precisely reproduced due to oversimplification of the contact geometry, even though they are important parameters (Sockalingam et al., 2014). To address these issues, Shockey et al. (1999) was the first to propose a 3D yarn level model, followed by more recent studies (Nilakantan and Nutt, 2014; Grujicic et al., 2008; Gogineni et al., 2012); details regarding yarn transverse deformation or contact interaction within the fabric can be modeled. Zhu et al. (2011) and Dong and Sun (2009) were the first – and only authors so far – to the authors knowledge, to simulate yarn pull-out. Zhu et al. (2011) compared their results with experiments and showed that numerical simulation could qualitatively reproduce the trend observed in experiments, but the values obtained for the pull-out force were much too high compared to experimental data. This was attributed to the excessive artificial rigidity of simulated continuum yarns: in reality, yarns are made of hundreds of soft filaments able to slip and slide relative to one another during pull-out, giving the yarn an exceptional ability to deform by flexure without much stress. On the other hand, a simulated yarn, modeled as continuum, has a solid cross-section and a high flexural stiffness, leading inevitably to overestimation of the pull-out force. Consequently, a study proposing a finite element model able to quantitatively fit experiments has yet to be reported. The latter could prove a powerful tool to better understand the mechanisms affecting yarn mobility and pull-out in a fabric.

Two main issues are relevant: (i) during impact, the projectile pulls yarns out in a direction perpendicular to the fabric plane (out-of-plane pull-out), whereas pull-out tests are generally performed parallel to the fabric plane (in-plane pull-out); a new type of test should apply yarn pull-out in a fashion similar to that when a projectile perforates a fabric; (ii) a numerical model able to simulate qualitatively and quantitatively both modes of pull-out would provide useful insights into the physics governing yarn pull-out.

This work attempts to address these two aspects. A new experimental setup is designed to perform both in-plane and out-of-plane pull-out tests on woven fabric, this is followed by development of a finite element model which is subsequently validated. Friction characteristics of the fabric are deduced from a parametric study. Finally, the evolution of energy components during yarn pull-out is examined, and the influence of pre-tension on strain energy and friction dissipation is studied.

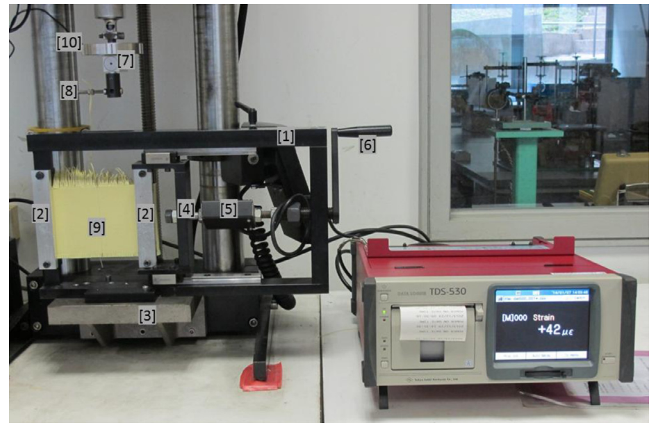

Fig. 1. Experimental setup for in-plane yarn pull-out: (1) Frame; (2) Fabric clamps; (3) Frame base attachment and Instron Universal testing machine base; (4) SEBMZ20-160 Misumi linear slider; (5) Load cell; (6) Hand crank; (7) 100 N load cell; (8) Load cell attachment; (9) Fabric specimen; (10) Instron 5500 Universal testing machine cross head.

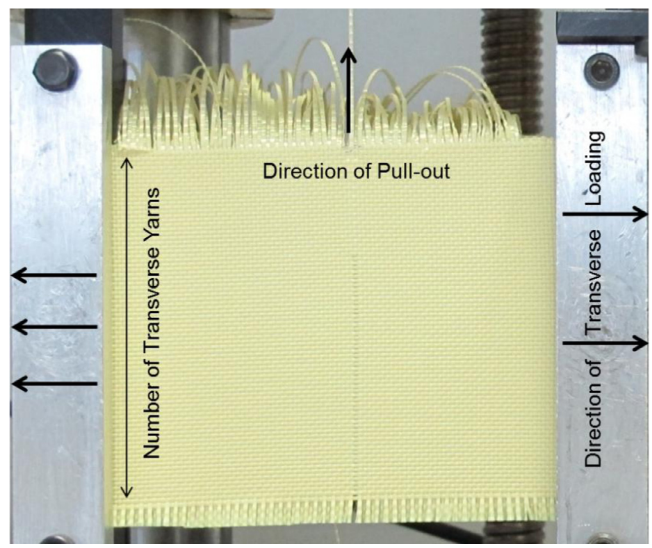

Fig. 2. Fabric specimen during in-plane pull-out.

2. In-plane pull-out

2.1. Experimental setup

The fabric studied is Twaron® T717 manufactured by Teijin Aramid®, and the test arrangement (Figs. 1 and 2) is similar to that of Nilakantan and Gillespie (2013), Dong and Sun (2009) and Zhu et al. (2011). It essentially comprises an aluminum alloy frame which holds the fabric specimen in place by means of two aluminum alloy 6061 clamping bars with rubber linings to prevent slippage of the fabric during pre-tensioning, and to protect the clamped fabric from being damaged by the sharp edges of the metal clamping plates. One of the clamps is attached to a linear slider which translates linearly by means of a manual hand-crank to apply pre-tension. Nilakantan and Gillespie (2013) highlighted that when pre-tension is applied to a fabric specimen, a "relaxation" effect takes place, whereby after application of stretching, the load exponentially decreases until it stabilizes at a lower force. To address this issue, in the present work a 1 kN