Materials and Design 85 (2015) 282–295

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/jmad

Influences of weaving architectures on the impact resistance of multi-layer fabrics

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ARTICLE INFO

Article history:
Received 21 May 2015
Received in revised form 27 June 2015
Accepted 2 July 2015
Available online 7 July 2015

Keywords:
Fabric architecture
Composite textile
Woven fabric
Ballistic impact

ABSTRACT

Fabrics constructed from different weaving architectures such as plain, basket, twill and satin provide varying flexibility and durability when applied on surfaces of complex structures for protective applications. They also affect the manufacturing processes and mechanical properties of both fabrics and composite structures in various applications such as soft armours, helmets, aircraft engine cowlings or automobile monocoques. In this work, the influences of weaving architectures on the ballistic resistance and energy absorption of both single and multi-layer Twaron® fabrics are investigated. A mesoscale yarn model is constructed, validated experimentally, and analytical. Finite element fabric models of different fabric structures are then developed and their firmness is quantified using interlacing factors. Numerical models for plain weave are validated against experimental results from single-ply ballistic tests. The evolutions of kinetic, strain, and friction energy components, normalised with areal mass, are presented to demonstrate the better ballistic protection of the plain weave compared with other weaving architectures. Further investigations on multi-ply systems illustrate the energy absorption capacities for different types of woven fabrics and the associated ballistic resistances. The research results indicate that weaving architectures and fabric firmness are less influential on the overall ballistic protection of multi-ply systems compared to the single-ply cases.

1. Introduction

The impact resistance and flexible geometry of high-strength textile fabrics have made them favourable materials for both military and civil protective applications, such as personal armour clothing, helmets, and automobile monocoque structures. Other applications include their use as protective layers for aircraft engine cowlings against fragments during service, and use in composite materials for marine structure hulls to protect against underwater blast impulse [1–3], as well as use in military vehicles operating in landmine-risk areas. Widely used fibres for ballistic impact resistance include aramids such as Twaron® (Teijin), Kevlar® (DuPont), PBO fibres such as Zylon® (Toyobo), and ultra-heavy molecular weight polyethylene (UHMWPE) such as Spectra® (Allied Signal) [4]. These fibres are characterised by their stiffness and strength-to-weight ratios, and when woven together into a fabric structure, they provide a strength and toughness that substantially surpasses those of individual strands. This impact resistance of the fabrics is generally attributed to various factors, including its woven architecture, yarn crimp, and several mechanisms of energy absorption and dissipation of the fabric [5,6].

To achieve ballistic protection, the aramid fabrics are often designed into either multilayer woven fabrics or composites. While the energy absorption mechanism of the latter case is primarily based on the debonding or delamination of fabric/matrix layers, the energy absorbed by multilayer dry fabrics depends largely on the strength of aramid materials, as well as the interactions between the interlacing yarns [7,8]. Among the various mechanisms influencing the impact resistance of fabrics, weaving architecture is identified as one of the major factors influencing the mechanical performance and energy absorption of fabrics. In particular, the woven fabric composites provide more balance in strength, stiffness and toughness when compared with other textile fabrics [9]. Their simple fabrication process lowers the manufacturing cost, particularly for components with complex shapes in structural design. Various choices of weaving patterns such as plain, basket, satin and twill, however, introduce further complexities within the class of woven textile. The ballistic performance of woven fabrics is known to be the collective contribution of numerous factors such as fibril materials, weave types, areal mass, yarn counts and fabric, as well as projectile sizes. Permeability, wave speed [10], tensile and tear strength [5] are among the fundamental parameters of fabrics, measured experimentally and subjected to considerable variations for difference weaving architectures. Identifying the influencing factors of impact energy absorption is quite challenging due to the complicated contacts between the interlacing yarns [11]. There is, however, limited work to investigate the influences of individual factor for single and multi-layer textile structure [12].

The influences of weaving architectures in ballistic resistance have been emphasised by various authors [12,13]. One of the earliest ballistic experiments conducted by Cunniff [13] investigated the ballistic performance of Spectra®, Kevlar® 29, and nylon fabrics, and showed superior energy absorption capability of the Kevlar® 29 fabrics compared with

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http://dx.doi.org/10.1016/j.matdes.2015.07.014
0264-1275/

the other two counterparts for different weave type, yarn denier, areal density, and yarn count. Separate research by Chu and Chen [14] compared the limit velocity (V_{50}) and dissipated energies of six different Kevlar® 29 fabrics. These fabrics had identical denier and yarn counts, and similar fabric areal densities. They were subjected to impacts from 5.1 g steel-cored bullets, 8 g full metal jacket (FMJ) bullets, and 7.62 mm Fragment Simulating Projectiles (FSPs). Impacts on single-layer fabrics have indicated that twill weaves absorbed 70% less energy than the plain weaves with bullet projectiles, while this difference is greatly reduced to 3% when impacted by FSPs. Zhou and Chen [15] constructed a series of finite element models simulating fabrics of various weaving structures. By using identical settings for yarn materials, yarn denier, and yarn counts, the results have shown that plain weave absorbs 34% more energy than the lowest seven-end-satin weave. While the effect of each individual weaving parameter remains an area to be further investigated, finite element simulation has demonstrated the capability to provide a cost-effective approach to analyse fabric impact resistance.

Simulation of the impact responses of fabrics that are woven or knitted from continuous filament yarns still remains a challenging task due to their complex multi-scale structures and the material interactions from fibre to filament, yarn and fabric-levels. Fibre-level numerical approach [16,17] have been also developed and utilised to model the ballistic resistance of Kevlar® KM2. Such model could be, however, computational intensive to simulate the multilayer systems. Several analytical, numerical and hybrid approaches [18–22] have been explored to model the ballistic impacts of woven fabrics. Numerical models at different scales were developed, including the macro-scale that simulates fabric layer as homogenised membranes, the mesoscale that constructs the fabrics from anisotropic continuum yarn, and the microscale focusing on the fibre level [16,17]. Ha-Minh et al. [19] have implemented a multi-scale model, which is a combination between macroscopic and mesoscopic finite element models to investigate the ballistic impact on 2D KM2® plain weave fabrics. Mesoscale fabric model is based on modelling individual continuum yarn at millimetre length-scale [23]. By this way, detailed mechanisms of the yarn interactions, such as friction and failures, could be captured enabling the model to provide in-depth understandings of damage evolution and energy transfer during ballistic impact [24,25]. The above computational studies focus mostly on the impact of single layer plain-woven fabric systems, while similar studies on other weaving structures and the associated multilayer systems have not been performed.

This research aims to investigate the evolution of energy absorption during impact in both single and multi-layer fabric structure via both physical and numerical analysis. Experimental studies on the ballistic performance of plain woven fabrics are performed to provide evidences regarding the failure mechanisms and deformations. The schematic and actual setups of the gas gun experiments are presented and discussed. Mesoscale models are then developed and validated to investigate the ballistic resistance of plain woven structures, and used as the benchmark for comparison. Material models of aramid yarns (Twaron®) are built employing the mechanical properties obtained from both literature and experiments. Single and multilayer fabric models of the four different woven structures: plain, twill, satin, and basket are then constructed using the finite element software LS-DYNA R971.

2. Firmness factor of the woven fabric structures

Considerable efforts have been devoted to quantify the firmness of woven fabrics, in order to develop analytical references in evaluating the performance of the fabrics. These techniques are mostly based on geometric calculations of yarn interlacement in a weave structure. In particular, the coverage percentage and distributions of cross-overs, interlacements, and spaces between the warp and weft yarns are attributed to the tightness of the fabric against tension, bending and permeability [26]. There is, however, no direct study to correlate the firmness factor and the ballistic resistance of a woven architecture, which requires some modifications to the calculation to address the importance of the contact area between yarns. In a recent study, Morino et al. [27] proposed to correlate the cross-over firmness factor (*CFF*) and floating yarn factor (*FYF*), which are calculated based on the interlacements and floats of warp and weft yarns to the mechanical properties of the fabric. The *CFF* and *FYF* parameters are defined as:

$$CFF = \frac{Number\ \ of\ \ cross{-}over\ \ lines\ \ in\ \ a\ \ complete\ \ repeat}{Number\ \ of\ \ interlacing\ \ points\ \ in\ \ a\ \ complete\ \ repeat}, \tag{1}$$

$$FYF = \frac{\text{Number of floating segments in a complete repeat}}{\text{Number of interlacing points in complete repeat}}, \tag{2}$$

where the cross-over line is defined as the place at which the warp/weft yarn changes from over to under the weft/warp yarn. The floating, or free segment, corresponds to a part of the yarn that lies between two uniform contact segments (on the same side of the contact plane). This original approach has been pointed out by Milašius et al. [28] to be cumbersome and non-intuitive. Skliannikov [29] has proposed a new way to comprehensively present the fabric's woven setting to include contact (c), interlacing (i), free (f), and space (s) fields, as illustrated in Fig. 1. The contact field is defined by the contact regions between the warp and weft threads. Interlacement zones correspond to the cross-over regions of warp yarns from one plane to another with respect to the weft yarn, and vice versa. The free fields are similar to the floating segments defined above, and the space field is the part of the fabric without warp or weft yarn coverage.

Based on the new weave setting notation, Padaki et al. [30] have proposed modifications to Eqs. (1) and (2), replacing the *CFF* and *FYF* parameters with an interlacement index (I) and float index (F), as follows:

$$I = \left(\frac{i_{wp} + i_{wf}}{R_{wp}.R_{wf}}\right), \quad F = \left(\frac{f_{wp} + f_{wf}}{R_{wp}.R_{wf}}\right), \tag{3}$$

where the interlacement index is defined as the ratio of the total number of interlacements in warp (i_{wp}) and weft (i_{wf}) in a given weave unit cell, to that of a maximum number of possible contact fields. The product of warp repeat (R_{wp}) and weft repeat (R_{wf}) of a woven design gives the maximum possible number of contact fields. Similarly, the float index is defined by the ratio of the number of free fields to the maximum possible floats in the warp and weft threads. For the plain weave, R_{wp} and R_{wf} are both equal to two, while the twill weave unit cell illustrated in Fig. 1 corresponds to a value of three for both R_{wp} and R_{wf}. As fabric tensile strength has shown strong dependence to I in the past literature [30], further investigation into its influence on ballistic protection forms part of the objective of this study. Based on Eq. (3), the values of interlacement index for plain, 2/2 twill, 2/2 basket and 4-harness satin have been calculated as 2.0, 1.0, 1.0 and 1.0, respectively. The values of factor I suggest the highest firmness of plain weaves.

In another approach to consider the weave factor, Skliannikov [29] proposed a weave-tenseness factor, C, for the entire fabric, which was modified later by Milašius et al. [31] to address the firmness in warp and weft directions separately:

$$P_{wp(wf)} = \sqrt{\frac{3R_{wp}R_{wf}}{3R_{wp}R_{wf} - \left(2n_{f.wp(wf)} + \sum_{i=1}^{6} K_i n^i_{fi.wp(wf)}\right)}}, \tag{4}$$

where n_f is the number of free fields; n_{fi} is the number of free fields belonging to group i (Skliannikov [29] categorised all free fields into six groups according to their relations with space fields); K_i is the elimination factor of group i; and subscripts *wp* or *wf* correspond to warp or weft yarns. In this definition, the smaller the value of $P_{wp(wf)}$, the firmer the fabric with respect to the warp and weft directions. In particular, the