Composites Part B 148 (2018) 81–92

Contents lists available at ScienceDirect

Composites Part B

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

Prediction of mechanical properties of knitted fabrics under tensile and shear loading: Mesoscale analysis using representative unit cells and its validation

T.D. Dinh[a,b,*], O. Weeger[a,**], S. Kaijima[a], S.-K. Yeung[a]

[a] Singapore University of Technology and Design, SUTD Digital Manufacturing and Design Center, 8 Somapah Road, Singapore, 487372, Singapore
[b] Department of Materials, Textiles and Chemical Engineering (MaTCh), Faculty of Engineering and Architecture, Ghent University, Tech Lane Ghent Science Park-Campus A, Technologiepark-Zwijnaarde 903, B-9052, Belgium

ARTICLE INFO

Keywords:
Knitted fabrics
Multiscale analysis
Numerical homogenization method
Periodic boundary conditions

ABSTRACT

This article presents a numerical framework to predict the mechanical behavior of knitted fabrics from their discrete structure at the fabric yarn level, *i.e.*, the mesostructure, utilizing the hierarchical multiscale method. Due to the regular distribution of yarn loops in a knitted structure, the homogenization theory for periodic materials can be employed. Thus, instead of considering the whole fabric sample under loading, a significantly less computationally demanding analysis can be done on a repeated unit cell (RUC). This RUC is created based on simple structural parameters of knitted yarn loops and its fabric yarns are assumed to behave transversely isotropic. Nonlinear finite element analyses are performed to determine the stress fields in the RUC under tensile and shear loading. During this analysis, contact friction among yarns is considered as well as the periodic boundary conditions are employed. The macroscopic stresses then can be derived from the stress fields in the RUC by means of the numerical homogenization scheme. The physical fidelity of the proposed framework is shown by the good agreement between the predicted mechanical properties of knitted fabrics and corresponding experimental data.

1. Introduction

There has been increasing interest in the mechanical behavior of fabric materials, due to the wide range of applications they can be utilized in. Especially textile composite materials, where fabric structures are utilized as preforms, are gaining more and more attention, beyond the traditional textile industries, *i.e.*, apparel and fashion. Indeed, textile composite materials can now be found in domains such as aerospace, automotive and submarines industries, as well as architecture and civil engineering, *e.g.*, tension membrane structures [1]. Furthermore, so-called functional, technical or smart textiles are utilized in biomedical applications, defense and flexible electronics [2].

In general, woven, non-woven, braided and knitted fabrics can be distinguished according to their method of fabrication. Among them, knitted fabrics, which are produced by intermeshing loops of yarns using knitting needles, have so far the most modest percentage for usage in technical applications [3], even though they are widely utilized for outerwear, such as dresses and sportswear due to their excellent formability [4].

However, due to the advancement in knitting technology as well as the availability of high performance fibers such as carbon, glass and aramid, knitted fabrics are gaining more and more interest in different innovative applications. For example, smart fibers are used as the base material for active knitted actuators [5] or shape memory alloy (SMA) fibers are knitted into garments to create the shape changing cloths [6]. In addition, knitted textiles are also the materials of choice in biomaterials because of their high flexibility and low tendency to fray [7]. Moreover, in the composite materials industry, the utilization of knitted fabrics as preforms was considered skeptically because of their relatively low stiffness and strength originating from their low fiber volume fraction. Nevertheless, the curved nature of the knitted loops manifests itself in the outstanding drapability of the resultant knitted fabrics, which catches the attention of composite materials engineers. This special property enables knitted fabric to be utilized in forming complex and deeply curved composite components [8].

Additionally, changing fiber/yarn materials and knitting pattern of preforms will vary the mechanical properties of the knitted fabric composites. Therefore, with the currently available fiber materials and

* Corresponding author. Singapore University of Technology and Design, SUTD Digital Manufacturing and Design Center, 8 Somapah Road, Singapore, 487372, Singapore.
** Corresponding author.
E-mail addresses: Tiendung.Dinh@UGent.be (T.D. Dinh), Oliver_Weeger@sutd.edu.sg (O. Weeger).

https://doi.org/10.1016/j.compositesb.2018.04.052
Received 21 January 2018; Received in revised form 12 April 2018; Accepted 24 April 2018
Available online 28 April 2018
1359-8368/

various knitting patterns, which can be formed from modern knitting machines, composite engineers indeed have more options to tailor the mechanical properties of knitted composites in such a way that they can fit a particular application. Especially, knitted fabrics can be utilized to create 3D preforms with several types of fiber and various local knitting patterns. As a consequence, various local thicknesses and properties preforms can be achieved [8]. This advantage has for instance been exploited to create auxetic fabrics and auxetic composites, which have negative Poisson's ratio [9].

From production point of view, compared to other kinds of fabrics, knitted fabrics do have several advantages such as mass productivity, low fabrication cost and quick set-up of the knitting machines [3,8]. It is noteworthy that the stiffness and strength of knitted fabrics can be improved by introducing straight yarns as described in Ref. [10].

It was experimentally validated that the mechanical properties of dry fabric preforms have a strong effect on the mechanical properties of the resultant textile composites [8,11]. In order to fully exploit the advantages as well as to identify the limitation of knitted fabrics, a better understanding of the mechanical properties of this kind of materials is needed, not only in composite industry but also in other industries, such as computer graphics [4], apparel and industrial applications [12]. Fibrous materials in general and knitted fabrics in particular exhibit high level of anisotropy and nonlinearity in mechanical properties due to the heterogeneous nature of their meso/micro structures [13]. The macroscopic mechanical behavior of knitted fabrics is mainly governed by the properties of the constituent fibers and the intricate interactions among fibers, *i.e.*, intra-yarn contact as well as among yarns, *i.e.*, inter-yarn contract [14]. Thus, modeling and simulation of knitted fabrics is a very challenging task.

The outline of this manuscript is as follows: in the next section, a detailed literature review of knitted fabrics modeling is conducted, including both geometrical and mechanical modeling aspects. Afterward, the ingredients of our proposed model, *viz.*, the geometrical model of the plain knitted unit cell, as well as the mechanical material properties of the fabric yarn are presented. Subsequently, the elements of the Repeated Unit Cell (RUC)-based homogenization technique and their implementation in ABAQUS/Standard are mentioned. This section is followed by numerical results, including the successful validation of our computational approach against experimental references. The manuscript ends with some concluding remarks.

2. Literature study on knitted fabrics modeling

During last few decades, the research in textile composites and dry fabric materials has been very active. However, most of the efforts have been focusing on woven fabrics, while significantly less references exist on the investigation of material behavior of knitted fabrics. As a whole, mechanical properties of knitted fabrics are significantly different from those of woven fabrics. The main reason is that woven fabrics are made by interlacing slightly crimped fibers orthogonally. As a consequence, they possess very little stretchability [15]. On the other hand, knitted fabrics are produced by looping the yarn through itself to make a chain of stitches that are subsequently connected together. The curvature of the yarn in the knitting pattern is the source of stretchability of knitted fabrics, even in case they are made of high modulus fibers [16]. In fact, knitted fabrics possess a hierarchical multiscale nature. The fabric is composed of the yarn and the yarn is composed of the fibers. Therefore, modeling of knitted fabrics can be addressed at three different scales, *viz.*, macroscale or fabric scale, mesoscale or yarn scale, and microscale or fiber scale. Hitherto, most of the works in modeling knitted fabrics have been proposed at mesoscale [10,17–19]. To model knitted fabrics at mesoscale level, we need to define a realistic geometry model of the repeated unit cell (RUC), which is the smallest pattern used to represent the whole fabric by several translations, a material constitutive law for the fabric yarn, which can reflect its fibrous nature [17], as well as frictional contact among the yarns, and appropriate boundary conditions.

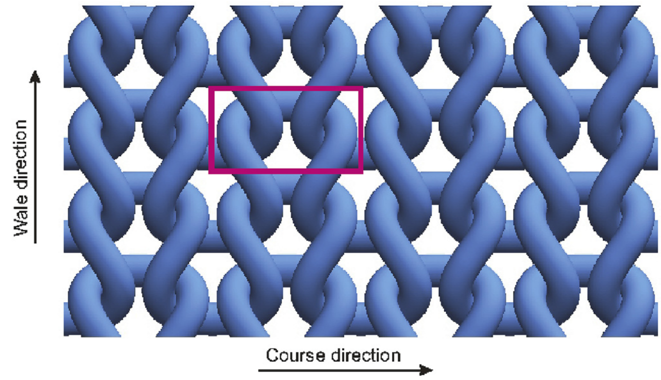

Fig. 1. Plain weft-knitted structure and its RUC bounded by the rectangle.

2.1. Geometrical models

In the literature, a couple of geometrical models were proposed for knitted fabrics, mainly aiming at plain weft knitted fabrics. In a plain weft knitted structure, rows are referred to as courses, which run across the width of the fabric, and columns are referred to as wales, which run along the length of fabric (*cf.* Fig. 1). According to Gravas et al. [20], the first two-dimensional geometrical model for knitted fabrics was proposed by Tompkins [21] more than a hundred years ago. A few years later, Chamberlain [22] proposed another two-dimensional model. That model presented a projection of the yarn loop of a plain weft knitted fabric, which is composed of circular arcs and straight lines. The first three-dimensional model for plain knitted fabric was proposed by Peirce [23]. In that model, Peirce assumed that the heart line of the course yarn is composed of circular arcs and straight lines. Additionally, he assumed that this heart line lies on a circular cylindrical surface. It was pointed out in the paper of Leaf and Glaskin [24] that the geometrical model of the fabric yarn of Peirce caused discontinuities in torsion that occur at material points in the loop. Thus, they proposed another model [24] to fix that defect. In that proposed model, Leaf and Glaskin assumed that the projection of the heart line of the yarn is composed of only circular arcs. That model was later utilized in Ref. [25] to model knitted fabric reinforced composites.

Recently, Vassiliadis [26] proposed a more complex geometrical model for plain weft knitted fabrics using B-Splines. The inputs of this model are the main structural parameters of a single jersey fabric, *viz.*, the course space, the wale space and the thickness of the yarn. This geometrical model was utilized in mesostructural analyses by the same author [18]. Moreover, the model was also employed in the analyses presented in Refs. [27,28]. Furthermore, based on that model Abghary et al. [10] have proposed a novel geometrical model for 1×1 rib knitted fabrics. Recently, McKee et al. [15] have utilized trigonometric functions to describe the heart line of the knitted yarn. The parameters in that model were calibrated with X-ray tomographic images. It is noteworthy that all of the geometrical models mentioned thus far were aimed for relaxed knitted fabrics. Therefore, the residual stresses originated from the knitting process mentioned in Ref. [29] can be neglected.

2.2. Mechanical models

There have been various approaches to simulate the mechanical behavior of knitted fabrics. As mentioned in Ref. [29], during the course of loading the main deformation modes of knitted yarns are inter-yarn slip, inter-yarn shear, yarn bending, yarn buckling, intra-yarn slip, yarn stretching, yarn compression and yarn twist. These deformation mechanisms can indeed be captured at the yarn level, *i.e.*, the