Composites: Part A 86 (2016) 87–96

Contents lists available at ScienceDirect

Composites: Part A

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

Creep compaction behavior of 3D carbon interlock fabrics with lubrication and temperature

Joffrey Renaud [a,*], Nicolas Vernet [b], Edu Ruiz [a], Louis Laberge Lebel [a]

[a] NSERC-Safran Chair on 3D Composites for Aerospace, Polytechnique Montréal, Department of Mechanical Engineering, C.P. 6079, Station Centre-ville, Montréal QC H3C 3A7, Canada
[b] Safran Group, 75015 Paris, France

ARTICLE INFO

Article history:
Received 4 February 2016
Received in revised form 11 April 2016
Accepted 16 April 2016
Available online 19 April 2016

Keywords:
A. Carbon fibers
A. 3-Dimensional reinforcement
B. Creep
B. High-temperature properties

ABSTRACT

This study aims at understanding and improving the compaction of 3D carbon interlock fabrics with water lubrication, high temperature and a combination of them. The creep compaction behavior was characterized in a mechanical testing machine under different lubrication and temperature conditions. Three different interlock fabrics were studied at high temperature in order to assess the influence of the weaving pattern on the creep compaction behavior. Finally, an experimental study was carried out to point the impact of fiber sizing on the creep compaction behavior and its evolution with temperature. The results of this work demonstrate the strong impact of temperature and lubrication on the compaction ability of 3D interlock fabrics and its link to the fiber sizing.

1. Introduction

Composite materials are now widely used in aircraft structures [1]. These composite parts can be manufactured using Liquid Composite Molding (LCM) processes where dry reinforcement fabrics are placed in a mold and subsequently injected with resin. These processes involve a compaction of the reinforcement at different steps of the fabrication. Therefore, understanding the compaction behavior of composite textile fabrics is of great industrial relevance. It allows, for example, determining the force required to compact a fabric at a certain thickness or fiber volume content (V_f). Moreover, when manufacturing large composite parts, reducing the required compaction force of the reinforcement has a direct effect on mold size and associated costs. In the past decades, researchers have estimated the compaction behavior of fabrics used for liquid composite molding [2–4]. However, previous studies mainly focused on traditional 2D woven fabrics.

3D woven fabrics for composite manufacturing have been in development for decades now [5] and have been used in specific industrial applications in recent years. They differ from 2D fabrics because the weaving has an out-of-plane direction allowing the attachment of several layers together. The 3D interlock, shown in Fig. 1, differs from orthogonal architectures by the absence of tows in the through-thickness direction. The superposed weft tows are linked together by warp tows at consecutive upper or lower layers (see Fig. 1). Consequently, warp tows present a certain out-of-plane waviness that is called through-thickness crimp. The compaction behavior of 3D woven fabrics has been recently studied [6–8] but not as widely as for 2D fabrics.

Textile fabrics have a viscoelastic behavior in compaction [4,9]. When the fabric is compacted and maintained at a certain thickness, the compaction force decreases with time until a stabilization is reached (i.e. relaxation). When a constant force is applied on the reinforcement, its thickness reduces with time (i.e. creep). Debnath et al. have shown that the compaction creep tend to follow a logarithmic decrease of thickness against time [10]. Analog logarithmic evolution of the compaction force with time is observed for the case of relaxation. To simplify the discussion in the rest of the document, the notion of compaction ability will be used. The higher the compaction ability of a fabric, the lower the relaxation force engaged to reach a certain thickness and the lower the crept thickness at a given compaction pressure.

To get a better understanding of fabric compaction behavior, researchers have focused on studying the main phenomena that govern it. Van Wyk first identified fiber bending as the main mechanism that governs the compaction of a bundle of randomly orientated wool fibers [11]. Later, Gutowski studied the compaction of a bundle of lubricated aligned fibers and drew similar conclusions [12,13]. He observed that the transverse stiffness of a bundle of aligned fibers was very low compared to the stiffness of a single fiber. According to him, each fiber has a certain waviness and acts as a beam in bending when compacted. Based on this principle, he

* Corresponding author.
E-mail addresses: joffrey.renaud@polymtl.ca (J. Renaud), nicolas.vernet@safran.fr (N. Vernet), edu.ruiz@polymtl.ca (E. Ruiz), lll@polymtl.ca (L.L. Lebel).

http://dx.doi.org/10.1016/j.compositesa.2016.04.017

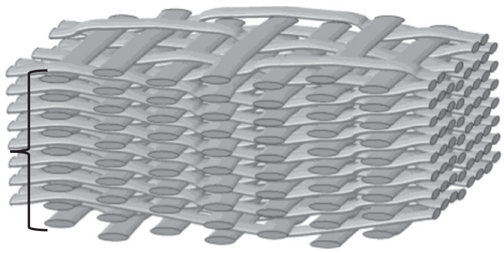

Fig. 1. Example of a 3D interlock fabric (from [34]).

developed an elastic model to predict the transverse compaction force of the bundle. This model has been improved by other authors to model the compaction of woven fabrics [8,14,15]. For the single layer case, authors identified tow flattening and tow bending as the components of the total compaction force [15,16]. These components are illustrated in Fig. 2, showing that tow flattening tend to change its cross section to a more elliptical shape. Tow bending reduces tow waviness and lengthen it. For the multi-layer case, the sliding between layers (nesting) appeared as the third component dominating compaction behavior [14,17]. This approach of compaction analysis was extended to 3D interlock fabrics by Vernet and Trochu [8]. They considered that compaction behavior is mainly governed by tow flattening and bending and developed a model to estimate the total compaction force of a fabric depending on weaving parameters. The estimated compaction force was compared to experimental results on five different 3D interlock fabrics with good accuracy.

It is possible to increase the compaction ability of a fabric by using different techniques. For example, repeated compaction at the same thickness is a well-known technique that allows to progressively reduce the required compaction force [18,19]. Using this idea, authors studied fabric compaction assisted with vibration and found good results for different ranges of frequencies [17,20,21]. Lubrication with water, oil and resins was also proven to be an efficient way to increase the compaction ability of a fabric [4,22–25]. According to the authors, the lubricant reduces the friction between fibers and facilitates reorganization during compaction. Pure water is a commonly used lubricant due to its ease of removal by evaporation.

Results on the compaction ability of lubricated fabrics showed that this behavior is governed by friction between fibers at different scales. Authors studied the friction between fibers [26], tows [27,28] and fabrics [27,29]. Cornelissen et al. have shown that the relative humidity had a significant effect on the friction coefficient between two parallel carbon tows [28]. This tends to confirm the results of the impact of lubrication on fabrics compaction behavior. Moreover, the coefficient of friction between fibers is influenced by their surface finish. Roselman and Tabor have shown

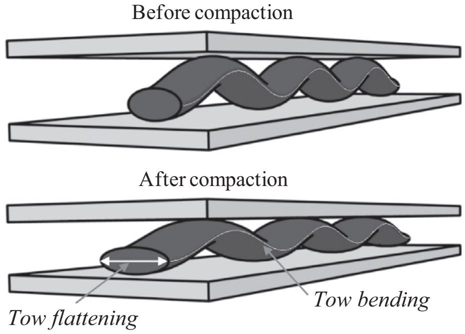

Fig. 2. Illustration of tow flattening and tow bending during fabric compaction.

that oxidative treatments on carbon fibers tend to increase the friction between them. According to the authors, the oxidative treatment created edge planes on the fiber surface that increased roughness and the friction coefficient [26]. Cornelissen et al. investigated the impact of the presence of sizing on the friction between carbon fiber tows. It was observed that friction behavior at room temperature was not significantly modified by the sizing [28]. In composite applications, sizing is used to protect fibers during weaving and also to enhance adhesion between resin and fibers by increasing their chemical compatibility [30]. The sizing used for composite fibers is mainly constituted of polymer resins chemically compatible with the molding resin (e.g. epoxy). Thus, its viscosity and physical state are likely to change with temperature. If sizing becomes liquid enough to act as a lubricant, then it may modify the compaction behavior of a fabric. In the same line of thoughts, authors studied the effect of temperature on the compaction behavior of fabrics with a thermoplastic binder inserted between layers [31–33]. They observed that fabric compaction ability increased with temperature because the physical state of the binder changed from solid to viscous and then acted as a lubricant.

The results reviewed above indicate two approaches that could enhance the compaction ability of 3D carbon interlock fabrics. Firstly, water could be used as a lubricant. Secondly, fiber sizing viscosity could be reduced by heat and therefore amplifying its lubrication role. The following objectives were then defined for the present study. First, to demonstrate that it is possible to maximize the compaction of a 3D carbon interlock fabric using water lubrication, high temperature and a combination of both. Then, to study the relationship between compaction behavior, temperature and fiber sizing. Classical methods will be used for the characterization of fabric compaction behavior except that creep will be studied instead of relaxation that is characterized in the majority of existing studies. The results of this study will enhance an already large knowledge on composite fabric's compaction behavior by adding the effects of lubrication and temperature on 3D carbon interlock fabrics. To the best of author's knowledge, the effect of temperature on creep has not been studied even on other kinds of fabrics, so it constitutes the greatest novelty of this paper.

2. Materials and experimental setup

2.1. Description of the 3D interlock fabrics

The three-dimensional interlock fabrics studied in this work were all woven with carbon fibers (IM7, Hexcel), covered with a proprietary epoxy sizing. According to the manufacturer, the sizing weight ratio was between 0.8% and 1.2%. The weaving parameters of the three fabrics used in this study are described in Table 1. The warp/weft ratio represents the distribution of fibers in the warp direction versus the weft direction. The number of interlock layers corresponds to the number of stacked weft tows in the thickness direction. In the case of fabric A, this number alternates between 7 and 8 at every fabric plait. Consequently, the number of interlock layers is specified as 7–8. Two different weaving patterns were studied and are identified as 1 or 2 in Table 1.

Table 1
Description of the weaving parameters of the three fabrics used in this study.

	Fabric A	Fabric B	Fabric C
Areal density (g/m^2)	9958	14,587	11,831
Warp/weft ratio	70/30	50/50	60/40
Number of fibers per tow	48K/48K	48K/48K	48K/72K
Thickness at V_f = 58% (mm)	9.65	14.13	11.46
Number of interlock layers	7–8	8	8
Weaving pattern	1	2	2