Composites Science and Technology 91 (2014) 30–37

Contents lists available at ScienceDirect

Composites Science and Technology

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

Prediction of the braid pattern on arbitrary-shaped mandrels using the minimum path condition

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ARTICLE INFO

Article history:
Received 5 January 2013
Received in revised form 12 November 2013
Accepted 15 November 2013
Available online 5 December 2013

Keywords:
A. Textile composites
C. Modeling
E. Braiding
Minimum path condition

ABSTRACT

A mathematical model is developed to predict the braid pattern (by braiding process) on arbitrary-shaped mandrels considering braiding process parameters. This model includes basic requirements for the braid pattern to be formed, i.e., the braid pattern is formed at a point on the mandrel surface where the line running from the braid point to the yarn carrier on the braiding bed is tangent to the mandrel surface. Additionally, the minimum path condition is incorporated into the mathematical model to reflect braiding process parameters more rigorously. The minimum path condition requires that the braid pattern be formed at a point on the mandrel surface where the total length of the braiding yarn hanging over from the previous braiding point to the yarn carrier is minimized. The new model is implemented to simulate the braid pattern on a conical and a rectangular, acentric mandrel. The simulation results are compared with experiments, demonstrating that the current model is highly suitable for predicting the braid pattern on complex mandrels within reasonable accuracy, thereby providing an effective tool for designing braid composites.

1. Introduction

Braiding is a conventional method for fabricating three-dimensional (3D) textile preforms (e.g., rope-like products). Due to the simple, automated process and near net-shape formability, braiding technology has been used to prepare various 3D textile preforms for advanced fiber-reinforced composites [1,2]. Near net-shape preforms are strongly preferable for advanced fiber-reinforced composites, because such preforms can be converted into advanced composites without welding or joining, ensuring high damage resistance. Along with these advantages, the mass productivity and high mechanical performance of braid composites have promoted their applications to automotive parts [3–5]. There is a growing demand for an effective tool for designing braid composites. The ability to predict the braid pattern is the most fundamental and important component, because the braid pattern determines the mechanical properties of the resulting braid composite.

Over the last two decades, studies have been performed to develop mathematical models for predicting the braid pattern on various mandrel shapes. In the early years, the prediction was limited to cylindrical mandrels, the braid angle of which could be determined by the arctangent of the angular velocity over the axial velocity [6]. Hereafter, this method is denoted as the “cylinder method” throughout the manuscript because the prediction method was originally developed based on cylindrical mandrels. The cylinder method was applied to predict the braid pattern on complex-shaped mandrels [7,8] by representing them with segmented disk-like and cylindrical parts. The braid pattern of even non-circular cross-sectional mandrels (e.g., ellipsoid, cone, and pyramidal mandrels) was also simulated using this method by assuming the movement of the braiding yarn on a circular mandrel [5,9,10].

A series of differential equations have been derived to represent the movements of the braiding yarns during the braiding process and then to predict the braid pattern on arbitrarily-shaped mandrels [11–14]. In these studies, a “guide ring” was frequently introduced in the experiments to make the experimental conditions close to those used in the simulations. Although this method was developed based on axisymmetric mandrels, it was extended to cover non-axisymmetric mandrels using the surface function of a mandrel and other braiding process variables [15]. Because the governing equations were expressed by three differential equations with four unknowns (i.e., indeterminate differential equations), a numerical scheme was developed to solve them: one

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http://dx.doi.org/10.1016/j.compscitech.2013.11.012

coordinate (e.g., z coordinate) of the braid point is given by assuming a cylindrical mandrel, and then the other x and y coordinates, including the z coordinate, are iteratively determined until all three coordinates satisfy the governing equations. As such, this method is referred to as the "generalized cylinder method" throughout the manuscript, because one coordinate of the braid point was initially obtained using the cylindrical mandrel assumption.

In this study, a mathematical model was developed that can predict the braid pattern formed on a complex-shaped mandrel by a circular braiding machine. To predict the braid pattern without the rigor of solving indeterminate governing equations and with various braiding process parameters considered (the angular speed of the yarn carriers: ω; the axial velocity of the mandrel: V; the radius of the guide ring: R_g; the convergence zone length: H_c; and mandrel shape; see Fig. 1 for their detailed illustrations), we introduced a "minimum path" condition for our mathematical model. In the following, we present the governing equations derived from the minimum path condition and discuss their implementations and validations for two mandrels chosen for this study.

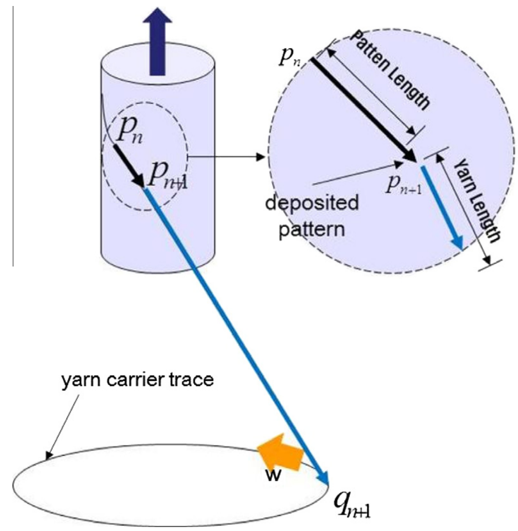

Fig. 2. Schematic diagram explaining the determination of the next braid point (p_{n+1}) after the previous braid point (p_n) formed.

2. Methods

2.1. Theoretical background

To derive the governing equations for predicting the braid pattern on arbitrarily-shaped mandrels, including non-axisymmetric and acentric shapes, the following basic assumptions are introduced.

(1) The braid pattern on the mandrel surface is differentiable.
(2) After a braiding yarn touches the mandrel surface and forms the braid pattern, the yarn sticks to the mandrel surface (no slip condition).
(3) The braiding yarn running from the braid point to the yarn carriers is straight.
(4) The braid point (and thus pattern) is formed at a point on the mandrel surface where the total length of the braiding yarn running from the previous braid point to the yarn carriers is minimized (i.e., the minimum path condition).

The first assumption simply implies that the braid patterns are formed smoothly with no dents or kinks on the mandrel surface. The second assumption excludes yarn slippage or friction on the mandrel surface, reflecting the locking of the yarn movement due

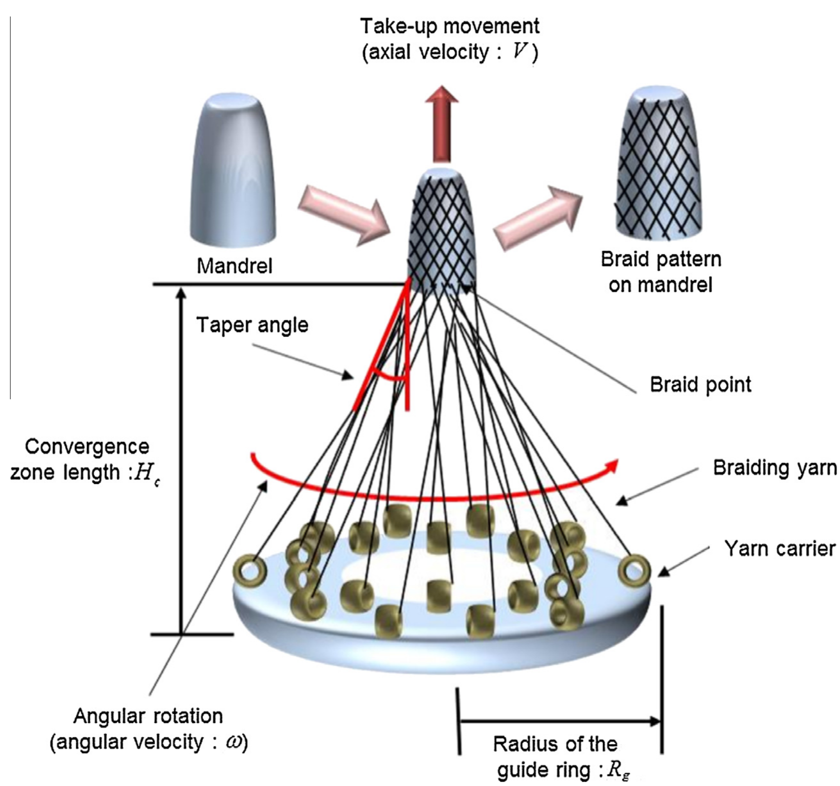

Fig. 1. Schematic diagram illustrating the braiding process and parameters.