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Optimization of elastic properties and weaving patterns of woven composites

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ABSTRACT

Predictions of geometric characteristics and elastic properties of patterns in woven fabric composites are proposed based on unit cells. This study addresses the optimization of the elastic properties within woven fabric composite unit cells with multiple designs based on periodic boundary conditions and evolutionary algorithms. Furthermore, the study permits a reliable prediction of mechanical behavior of woven fabric composites unit cells in which the weave patterns are the variables. The models are treated as a single-ply for each weave pattern embedded in a matrix pocket. The analyzed weave patterns are created by TexGen, the simulation is done with ABAQUS. At the unit cell level, effective elastic properties of the yarn were estimated from Finite Element (FE) simulations using periodic boundary conditions. An evolutionary algorithm is adopted in optimizing the elastic properties of woven fabric composites with recombination and mutation operators. We present a parameter study to investigate the effect of various geometric parameters. Those parameters include the gap length, the shape of the yarn section, the yarn thickness, the constituent materials, the fiber volume fraction and the elastic properties. By examining this optimized model through the pre-determined parameters as mentioned above, an optimal parameter set for composite's performance can be properly selected.

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1. Introduction

Textile composites have become popular due to their low material cost and labor requirements compared to traditional unidirectional prepreg composites. They also provide high strength-to-weight and stiffness-to-weight ratios compared with the use of randomly orientated reinforcements [1,2]. In order for practitioners to be able to exploit these properties it is essential to have a good understanding of their behavior. Woven fabrics generally consist of two sets of yarns that are interlaced and lie orthogonal to each other. The yarns that run along the length of the fabric are known as warp ends whilst the threads that run from one side to the other side of the fabric, are weft picks [3].

The mechanical properties of woven fabrics are governed by: (a) weave parameters such as an architecture pattern, yarn size, yarn spacing length, fiber crimp angle and volume fraction of fiber bundles, see Fig. 1 and (b) laminate parameters such as stacking orientation and overall fiber volume fraction [4]. The mechanical performance could be determined either via experimental work or simulations; the latter is a less costly approach commonly used in determining the mechanical properties of woven fabrics. Many of these models have been reviewed by Byun and Chou [5] and Tan et al. [6] for 2D and 3D textile composites, and Ayrannci and Carey [7] for 2D textile (braided) composites. Lomov et al. [8] delineated the modeling of 3D woven fabrics with the aid of Wise-Tex software [9]. On the other hand, the elastic behavior of woven fabric composites depends on a number of factors, including fiber and matrix properties, fabric architecture and relative and total fiber volume fractions (i.e. volume proportion of fibers in yarns) [10]. The reliable prediction of mechanical properties of woven fabrics is of primary importance to the success of woven fabric composites [11].

Nevertheless, textile composite models that were reported in various earlier research deal primarily with a particular structure (e.g. plain weave, a rib knit). There is a lack of generalized models of woven fabrics, that can treat the weave pattern itself as a parameter [11]. The relationships among geometric parameters have not been thoroughly investigated in most published studies to accurately determine the variation of one parameter and whether its effects are interrelated with that of other design parameters [4].

An evolutionary algorithm (EA) is a population-based stochastic meta-heuristic for optimization. Candidate solutions to the optimization problem are iteratively optimized with respect to a fitness function that measures the solution quality. The search process is

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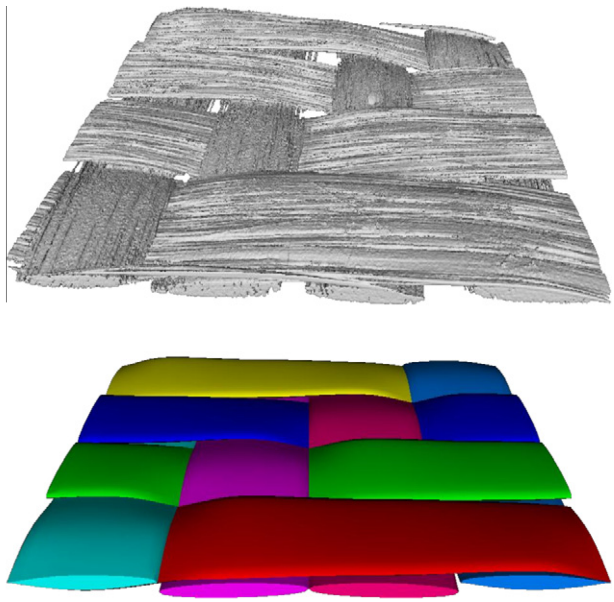

Fig. 1. Fibers in a yarn. Reproduced by [12].

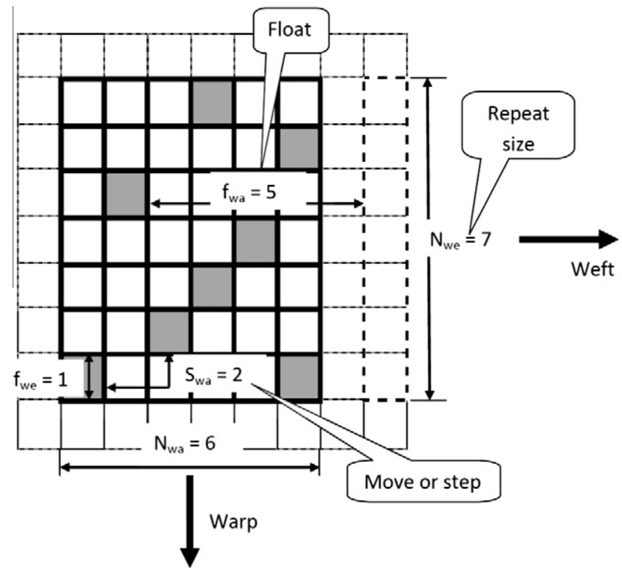

Fig. 2. Elements of a typical weave. Reproduced by [1].

based on a population of candidate solutions, which is iteratively optimized with biologically-inspired operators like recombination, mutation, and selection [13]. At each generation, a new set of solutions is created by the process of stochastically changing solutions, and selecting the one with the highest fitness. The optimization process shares similarities with the natural evolution of populations of individuals that adapt to their environment.

In light of this, the parametric study attempts to look at the development of an elastic model by emphasizing the effect of geometric parameters on the elastic characteristics of woven fabric composites. The aim is to determine the potential of these patterns in terms of strength compared to existing woven fabric composites. This idea was motivated by the performance and uniqueness of weave patterns applied commonly in Malaysian craft products such as handicrafts which are known for their resistance and quality. Thus, the weave properties of those products have a potential to be further explored and adopted for engineering related products such as membranes.

The paper is arranged as follows: Section 2 describes the geometric modeling of woven fabric composites. Section 3 explains the fundamental of elastic behavior in detail. In Section 4, the models to predict the elastic properties of woven fabric composites are derived. Section 5 defines the process used to predict the elastic properties in order to obtain the best selection of weave among weaving patterns via an evolutionary algorithm. Finally, Section 6 presents the selection that has been made and discussions based on the numerical results obtained.

2. Geometric modeling of weave patterns

In Malaysia (and other similar countries in South East Asia) weaving used to be a leisure activity of village women in rural coastal areas. Material used is ‘‘Pandanus’’ leaves or called ‘‘mengkuang’’ by the locals which after being stripped of thorns and split into strands, are soaked, dried, dyed and then woven according to the desired patterns. The patterns are inspired from nature usually from surrounding flora, fauna and carry the name of their creator [14].

In general, weave patterns are defined by a number notation such as 4X4, 5X3, and 2X2. The first number in the notation indicates the number of yarns that crossed ‘‘over’’, known as warp direction before it changes direction or known as weft direction (perpendicular yarns). A fundamental weave is made of basis weaves that served as a starting point for creating complex patterns and commonly are classified into three different basic styles: (a) Plain weave. (b) Twill weave. (c) Harness-Satin weave. A plain weave is defined as a 1X1 weave and a twill weave is defined as a set of identical number of weave both under and over such as 2X2 and 4X4 twill weaves. A Harness-Satin is referred as Harness, Satin, or Crowfoot, which refers to any number larger than 1, followed by X, and another larger number larger than 1. The most common satin harness used are Harness-Satin 8(8*HS*) and Harness-Satin 5(5*HS*).

Fig. 2 depicts elements of woven fabric composite pattern used for weave classification. The pattern is represented with black squares corresponding to crossovers where the warp yarn is on top and the minimum repetitive element is called a *repeat*. The *repeat* can have different number of warp (N_{Wa}) and weft (N_{We}) yarns. *Weft float* (f_{We}) describes the length of a weft yarn on the face of the fabric, measured in number of intersections. The *warp float* (f_{Wa}) is defined similarly since the number of white squares between black squares are equal in fundamental weaves. The distance between white and black squares, measured in number of squares is called *move or step*(s) in which this characterizes the shift of the weaving pattern between two weft insertions. They are characterized by a square repeat with $N_{Wa} = N_{Wa} = N$. Each warp/weft yarn has only one weft/warp crossing with $f = 1$ for warp/weft. The pattern of adjacent yarns is regularly shifted with s being a constant [1].

The chosen weaves are based on esthetics, complexity of curves, and the weight of the fabric needed in an application. In general, the looser the fabric, the more likely the fabric will fray at the ends and create spaces in the fabric when bent around complex curves. A loose fabric will fit around complex curves much better than a tighter weave fabric. A plain weave has the tightest criteria among the fundamental weaves. Since a plain weave is tight, it is the least likely to fray at the ends. Unlike plain weaves, a twill weave is much easier to bend around complex curves because its weave is looser. However, the Harness-Satin weave performs the best in catering for complex curves and bends compared to plain or twill weaves. This is because the fiber crimp in the geometry of Harness-Satin that allows it to cater for the complexness of the curves but it tends to fray at the ends. Normally, the plain weave will be chosen if the esthetic value is neglected. If esthetics are very important, generally a twill weave is selected, but for a sophisticated look a Harness-Satin 8 (8*HS*) is often used and it is the best choice for complex curves as well. The study has focused to the

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