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# Influence of phase shift on the responses of woven laminated composites

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ABSTRACT

This paper focuses on understanding the influence of phase shift on the responses of woven laminates under uniaxial compression, uniaxial tension, biaxial compression, biaxial tension, and in-plane shear. Laminates in this paper have the same constituent microstructures in each layer of lamina. Fiber tows are modeled as transversely isotropic materials. Matrix is modeled as isotropic material before yielding and modeled as perfectly plastic material after yielding. All simulations are subject to periodic boundary conditions in the *x* and *y* direction whereas *z* direction, the through-thickness direction, is not subject to periodic boundary conditions. The results show that phase shift has significant influence on the homogenized tangential stiffness and the failure strength particularly under uniaxial compression. Under uniaxial compression, the laminate without phase shift has the lowest maximum strength and tangential stiffness and the laminates with 4 mm phase shift has the highest maximum strength and the highest tangential strength. Under biaxial compression, the laminate with 4 mm phase shift also has the highest maximum strength but the laminate with 2 mm phase shift has the lowest maximum strength. However, the tangential modulus do not change during the deformation under biaxial compression. The results show that by optimally arranging phase shift, the maximum strength for a laminate under uniaxial compression and biaxial compression can be reached.



## 1. Introduction

Over the past several decades, polymer composites have become increasingly important. The percentage of composites being used in primary structures gradually increases in aerospace industry such as more composites used in commercial aircrafts of Boeing 787, Airbus A350XWB, and Bombardier C series. The same trend also occurs in car industry such as higher percentage of composites being used in BMW i3. Amongst many types of composites, polymer textile fiber composites (TFC) prove to be attractive and cost effective compared to conventional continuous fiber composites. Detailed introduction to TFC can be seen in [1,2]. Textile fiber composites are flexible to be tailored to different microstructural configurations for attaining the desired mechanical properties. Woven textile composites can be manufactured in plain, satin, basket, mock leno, and etc in Fig. 1. Laminated textile composites have been used in adaptive wind turbine blades [3] and in the automobile [4]. It is expected that applications of textile composites will be prevalent in the future.

For engineers, the information of stiffness is of great interest to design textile composites. A direct way to get stiffness is to conduct experiments. Another way is to identify the microstructures and conduct simulations assuming that the material properties of microstructures are known. Many methods have been used in the literature to get the information of stiffness from microstructures. An approximation method, called mosaic method [5], uses different piecewise rectangular blocks to simplify complex microstructures and the authors point out that the modified mosaic parallel model fails to describe composites with large interlaced regions. Instead of using the mosaic method which approximates regions of microstructures, the authors use detailed description of fiber undulation and continuity along both the warp and weft directions and the authors get fairly good results [6]. Another method, analytical model, is used for the calculation of the effective linear elastic stiffness of a 2D triaxial flat braided composite (2DTBC). Unintended imperfection in the fiber tow is also included in that analytical model [7]. The influence of various parameters such as braid angle, waviness ratio, material properties, and cross-sectional shape on the effective engineering properties of the braided composites is discussed in [8].

Besides stiffness, the ultimate strength and the failure mechanisms are also of interest to engineers. Comparing damage mechanisms of various weave composites[9], the authors indicate that the weave architecture has significant influence on the progressive

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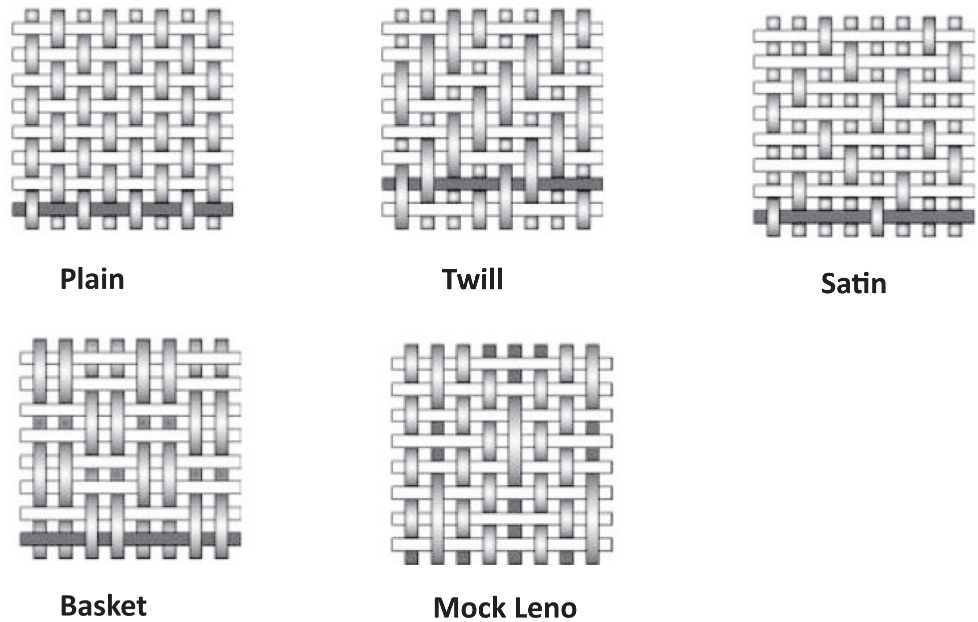


**Fig. 1.** Different configurations of woven composites.

failure behaviors even if the composites have the same overall fiber volume fraction, tow waviness, and tow cross-section. Weave architecture and internal geometry affect location and morphology of the damage initiation [10]. The weave architecture needs to be considered to capture the physics of the compressive failure of 2D woven composites, both at lamina and laminate level. The performance of 2D woven composites under low impact is studied and compared with 3D woven composites and the authors conclude that 3D woven composites have better impact resistance than 2D woven composites[11]. Different sizes of representative unit cells are used to study progressive failure on textile composites [12]. The influence of parameters such as yarn size, yarn spacing, yarn crimp, braid angle, and overall fiber volume fraction on the strength of textile composites is studied [13]. These papers mentioned above indicate the importance of microstructure arrangement on the responses of composites.

Although it is desirable to include microstructure information as much as possible, in the progressive failure analysis at the structural level, it is not practical to do so due to expensive cost on computation. It is practical to use homogenized material properties of a representative unit cell if such periodicity of a unit cell can be found. For example, one layer of plain weave lamina in Fig. 1 can be approximated as a homogenized orthotropic material. This is because the angle between fiber tows in the local principal direction and another local principal direction is 90 degree in a unit cell. If one were to conduct simulations on a laminated composite made from the several layers of the same lamina, one could treat the whole composite as homogeneous orthotropic materials. However, by doing so, one would neglect the influence of phase shift between different layers of laminae due to rich microstructure variation in the $z$ direction. In the following, phase shift and nesting are defined separately to not confuse readers. In our definition, phase shift is defined as two layers of laminae have the same microstructures in each layer being stacked in the $z$ direction but are shifted relatively in the $x$–$y$ plane. The volume fraction of fibers and matrix in different layers of laminae is the same. The definition of nesting in the literature refers to the change of microstructures within the representative unit cell. This usually comes with the change of volume fraction of constituents in a unit cell. The influence of phase shift on laminated woven composites using 2D models is studied in [14]. The influence of nesting, such as flatness of the yarns, tightness and balance of the fabric, fabric weaving, braiding, knitted pattern, number of layers and degree of shear has been studied by [15]. Particularly, the authors point out nesting effect becomes more pronounced with the decrease of the fabric tightness and the decrease of the float length in the weave. When nesting is introduced, the stiffness for the in-phase and out-of-phase configuration of the layers differs by 10%–20%. This change roughly corresponds to the change in fiber volume fraction caused by the nesting [16]. The influence of phase shift has rarely got attention in the community. To save computation cost, one has to use unit cell to conduct progressive failure analysis. The motivation of this research is to investigate the influence of phase shift among different layers of laminae on this unit cell as opposed to treat every layer of lamina with the same homogenized modulus. This paper is organized as follows: How two-layer laminated woven composites with different phase shift are created is explained first. This is followed by how the finite elements analysis is being conducted in the commercially available software, ABAQUS. Results of laminated composites under in-plane uniaxial compression, in-plane uniaxial tension, in-plane biaxial compression, in-plane biaxial tension, and in-plane shear are presented and discussed. Finally, the conclusions are made.

## 2. Representative unit cell with phase shift and without phase shift

The representative unit cell (RUC) of woven laminated composites used in this study consists of two layers of laminae. Each layer of lamina has a dimension of 10 mm in the $x$ and $y$ (in-plane) direction and 1.5 mm in the $z$ (through-thickness) direction in Fig. 2. Each lamina has four fiber tows, two are undulated along the $x$ direction and two are undulated along the $y$ direction. Each fiber tow is described by a sinusoidal function with an elliptical cross section whose major axis, $a$, is 4 mm and minor axis, $b$, is 0.4 mm. The volume fraction of fiber tows is 46 %. The undulated sinusoidal curve and the elliptical cross section is based on the microstructures of a woven composites specimen in Fig. 3. In order