Abstract

In this study, various kinds of woven composites, its applications and fabricating methods have been reviewed. Few investigations have only been performed on anti-plane loaded woven composites. In most of them the solutions have been limited to finite element analysis, so, less pure theoretical works have been done until now. In final part of this study, an analytical model has been presented to investigate the behavior of woven fabric composites under anti-plane loading (bending), so that each of the woven yarns has been simulated to an elastic straight beam which has a concentrated load on one of the intersections of the yarns. In the analysis consider that the resin has bonded each of the yarn pairs rigidly and so the deflection of the resin is almost zero. The supports are also rigid and simply supported. Euler-Bernoulli beam theory has been considered here and slipping and shear effects haven’t been regarded here.

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Keywords: Woven composite; Anti-plane loading; Fibers; Euler-Bernoulli beam; compatibility equation.

1. INTRODUCTION

The textile fabric preforms such as two- and three-dimensional woven fabrics, braided fabrics, stitched fabrics and knitted fabrics, are gaining importance as reinforcements in the production of advanced composites (Fujita et al. 1993). For example, the composite materials reinforced with woven preforms have been considered for potential structural applications in the aircraft and automotive industries (Xu et al. 2006). The fabric materials can be applied in structural components with complex shapes. Because of
two reasons, these textiles are strengthened. First, during warps and wefts weaving, a force is produced between them and second, maybe some kind of resin has been used between warp and wefts. The main factors to weigh in deciding whether to use a textile composite or a conventional tape laminate are mechanical properties and the ease and cost of manufacture. Generally speaking, textiles are somewhat inferior in stiffness and strength for sheet applications; superior in any application, including sheet applications, requiring high strain to failure, high work of fracture, or damage or impact tolerance; and superior when triaxial loads must be carried. Their relative cost depends very much on the state to which applicable textile technologies have been developed for the particular application. If parts can be manufactured automatically to net shape, or the number of joints reduced by forming integral structures, or robotic manufacture substituted for manual set-up and handling, then textiles become increasingly cost competitive. In short, whether textiles are the better choice depends strongly on the application and the class of textile chosen (Cox and Flanagan 1997). For the commercial reasons, the application of these composites has not been reported anywhere. But in this study, a brief review on them has been done. Before using these composites under anti-plane loading we need an analytical model to investigate their behavior. Of course to survey their behavior in bending conditions some finite element models had been presented up to now (Li et al. 2008; Soykasap 2005). In the last part of this study, the analytical model has been presented.

2. WOVEN FABRICS

A woven fabric is produced by interlacing warp and weft yarns. In most of the fabrics, warps and wefts have the same materials. Hybrid fabrics are the ones that warp and wefts have different materials. Fabrics are produced by weaving loom. Figure 1 represents a Schematic diagram of a weaving loom (Long 2005).

![Schematic diagram of a weaving loom](image)

Figure 1: Schematic diagram of a weaving loom

2.1. Weave patterns in 2-D fabrics

There are some kinds of weave pattern. The common patterns are plain weave, twill weave, satin weave (has a number of harnesses in its nomination) and panama or basket weave. Every pattern has...
some advantages and some disadvantages over others that force us to use them in different conditions, for example drapeability, surface smoothness and roughness, wet out capability, amount of crimped fibers etc. Figure 2 and 3 illustrate schematic diagram of some common weave patterns.

![Figure 2: Schematic diagram of some common weave patterns](image)

Figure 2: Schematic diagram of some common weave patterns

![Figure 3: Schematic diagram of 2*2 panama or basket weave patterns](image)

Figure 3: Schematic diagram of 2*2 panama or basket weave patterns

### 2.2. 3-D fabrics

There are also 3-D woven fabrics. There is a simple difference between 2-D and 3-D fabrics. In 3-D preforms some binder yarns are entered through the thickness of preform, after weft insertion. One of the benefits of 3D weaving is that fabrics with a wide variety of fibre architectures can be produced with controlled amounts of binder yarns for the through-thickness reinforcement. Two of the most common architectures are the orthogonal and layer interlock weaves, which are illustrated in Figure 4 (Mouritz et al. 1999). The difference between these architectures is binder yarn weave pattern. Of course the amount of binder yarns is less than %5. Figure 5 shows a computer-controlled Jacquard loom capable of weaving 3D preforms for composites.
3. WOVEN FABRIC COMPOSITE APPLICATIONS

Importantly, three-dimensional woven preforms can also be designed to fold out into more complex shapes, for example, integrally woven blade-stiffened panels or I-beams, an ability that can help reduce costs in preform assembly.

![Figure 4: (a) Orthogonal and (b) layer-interlock interlock woven fibre architectures commonly used in 3D woven composites](image)

![Figure 5: A computer-controlled Jacquard loom capable of weaving 3D preforms](image)
Three-dimensional woven composites were used in the Beech Starship (The Beech craft Starship is a twin-turboprop six- to eight-passenger pressurized business aircraft produced by Beech Aircraft Corporation). Woven H-joint connectors were used for joining honeycomb-sandwich wing panels together. The use of this woven connector was reported to be critical to the cost-effective manufacture of the wing and improved stress transfer at the joint, thus reducing peel stresses. Three-dimensional woven composites are used by Lockheed Martin for the air inlet duct in the F35 military fighter jet. In this example, the stiffeners are integrally woven with the duct shell, reducing the need for secondary fastening. Ninety-five percent of the fasteners through the duct are eliminated, thereby improving aerodynamic and signature performance, minimizing the risk of fasteners being ingested by the engine, and simplifying manufacturing assembly. Other, three-dimensional woven composites have been investigated in a number of demonstration structures for aircraft including thrust reversers, rotor blades, engine mounts, T-section fuselage frames, stiffener gap fillers, and multi-blade stiffened panels. In more advanced applications, three-dimensional woven sandwich composites are also being used in prototype Scramjet engines capable of speeds up to Mach 8. The material is a ceramic-based composite consisting of three-dimensional woven carbon fibers in a silicon carbide matrix and is used in the combustion chamber. A key benefit of using a three-dimensional woven composite in this application is the ability to manufacture the chamber as a single piece and the consequent reduction in connection issues and leakage problems associated with conventional fabrication methods (Baker et al. 2004).

4. ANALYTICAL MODEL

In this section, the analysis of a bi-axial woven fabric preform under a concentrated load has been surveyed. Limited assumptions for modeling are listed as the Euler-Bernoulli beam theory is used, no slipping may occur between the yarns, every curved warp and weft yarns are equivalent to straight beams, the resin which bonds yarns at intersections are completely supposed rigid. This assumption is not far from reality because the volume of the resin is less enough to exhibit any deformations. In what followed, a straight beam model of yarns (warp or weft) is introduced as a simply supported beam, subject to multi vertical loads $F_i$ and $P$, shown in Figure 6. The deflection of beam at any point for intervals $0 < x < a_1, a_1 < x < a_2, ..., a_n < x < L$ can simply be derived by using superposition theorem for linearity and using singularity functions (the angular brackets $<...>$) which leads to

$$
y = \frac{1}{6EI} \left( \sum_{i=1}^{n} F_i \left( (L-a_i) < x >^3 - L < x-a_i >^3 + \left( (L-a_i)^3 - L^2(L-a_i)x \right) \right) + \right. \\
\frac{P}{6EI} \left( (L-a) < x >^3 - L < x-a >^3 + \left( (L-a)^3 - L^2(L-a)x \right) \right) \right)
$$

(1)

where $E$, $I$, and $L$ are Yong’s modulus, moment of area and beam length, respectively. $F_i$ represents contacting load at intersection of bi-axial yarns which may be negative or positive. $P$ indicates external force per each yarn. The definition of the Singularity Functions is $x = <x>$ if $x > 0$ else $x = 0$.

At a glance at equation (1) it may be understood that for every yarn, warp or weft, the same relation can be used. On the other hand, the only compatible relation that must be satisfied is the continuity of displacement at intersection (or contacting) points. Consequently, for each contacting point there is a compatibility equation associates with an unknown $F_i$. Thus, a definite system of linear equations is available for solving the $F_i$ and next for post-processing (calculating of displacements). One can rewrite equation (1) in the matrix form as follows
\[
\begin{align*}
\{\delta\}_1 &= [C]_1 \{F\} + \{\Delta(p)\}_1 & \text{for warp} \\
\{\delta\}_2 &= [C]_2 \{F\} + \{\Delta(p)\}_2 & \text{for weft}
\end{align*}
\]  \tag{2}

where \(\{\delta\}\) represents displacement column vector at contacting nodes, the squared matrix \([C]\) refers to constant compliance matrix (derived by equation (1)), \(\{F\}\) comprises the unknowns \(F_i\) and the known \(\{\Delta(p)\}\) denotes displacement vector as a function of \(P\). It is worth mentioning that each row of the vectors and matrices is written for a contacting node. Also, subscripts 1 and 2 represent warp and weft equations, respectively. Satisfying of compatibility condition leads to \(\{\delta\}_1 = \{\delta\}_2\) or the another form is

\[
([C]_1 - [C]_2)\{F\} = (\{\Delta(p)\}_2 - \{\Delta(p)\}_1) \quad \Rightarrow \quad \{F\} = [D]^{-1}\{\Pi(P)\}
\]  \tag{3}
5. **NUMERICAL EXAMPLE**

As a clarified example, suppose the following squared preform with 3 warps and 3 wefts (illustrated in left image of figure 7). Assume all sides of the preform are simply supported and a concentrated load \( P \) is entered in the middle of the preform. Free body diagrams for three yarns are illustrated in figure 8. For simplicity, let warp yarns be designated by \( i \) and wefts by \( j \). To evaluate the contacting forces, one can help equation (1) to write the matrix \([D]\) and the vector \([\Pi(P)]\),

It requires only 9 compatibility equations for 9 unknowns. After some calculations the matrix forms are

\[
[C]_1 = \frac{1}{EI} \begin{bmatrix}
-0.0064 & -0.0100 & -0.0044 & 0 & 0 & 0 & 0 & 0 & 0 \\
-0.0100 & -0.0208 & -0.0100 & 0 & 0 & 0 & 0 & 0 & 0 \\
-0.0044 & -0.0100 & -0.0064 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -0.0064 & -0.0100 & -0.0044 & 0 & 0 & 0 \\
0 & 0 & 0 & -0.0100 & -0.0208 & -0.0100 & 0 & 0 & 0 \\
0 & 0 & 0 & -0.0044 & -0.0100 & -0.0064 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -0.0064 & -0.0100 & -0.0044 \\
0 & 0 & 0 & 0 & 0 & 0 & -0.0100 & -0.0208 & -0.0100 \\
0 & 0 & 0 & 0 & 0 & 0 & -0.0044 & -0.0100 & -0.0064 \\
\end{bmatrix}
\]

\[\{\Delta(P)\}_1 = \frac{1}{EI} \begin{bmatrix}
0 & 0 & 0 & -0.0100 & -0.0208 & -0.0100 & 0 & 0 & 0 \\
0 & 0 & 0 & -0.0064 & -0.0100 & -0.0044 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.0100 & 0 & 0.0044 & 0 & 0 & 0 \\
0.0064 & 0 & 0 & 0.0100 & 0 & 0.0044 & 0 & 0 & 0 \\
0 & 0.0064 & 0 & 0 & 0.0100 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.0064 & 0 & 0 & 0.0100 & 0 & 0 & 0 \\
0 & 0.0064 & 0 & 0 & 0.0100 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.0064 & 0 & 0 & 0.0100 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.0064 & 0 & 0.0044 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.0064 & 0 & 0.0044 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.0064 & 0 & 0 & 0.0044 & 0 \\
\end{bmatrix}
\]

\[\{\Delta(P)\}_2 = \{0...0\}^T
\]

Finally, after using equation (3) the unknown force matrix becomes

\[\{F\} = P\{0.1585 \ 0 \ -0.1585 \ -0.5 \ -0.1585 \ 0 \ 0.1585 \ 0\}^T
\]

And displacements at contacting nodes are (right image of figure 7)

\[\{\delta\} = \frac{P}{EI} \begin{bmatrix}
-0.0016 & -0.0033 & -0.0016 & -0.0033 & -0.0072 \\
-0.0033 & -0.0016 & -0.0033 & -0.0016 \\
\end{bmatrix}^T
\]
Figure 8: Free body diagrams for three yarns of numerical example

Figure 9: Deformed and undeformed woven preform under a concentrated load in the node (i,j)=(1,1)

For clarity, the deflection of a woven preform with 3 warps and 3 wefts under a concentrated load in the node (i,j)=(2,2) is calculated above and illustrated in figure 7 and the same preform geometry under a concentrated load in the node (i,j)=(1,1) is illustrated in figure 9 and the others which are similar, are omitted.

6. CONCLUSIONS

Woven composites are superior with respect to conventional materials due to their stiffness, strength, stability, weight, cost, manufacturing, corrosion resistance, insulation purposes, taking shape and so on. Bi-axial, even tri-axial woven composites can be analyzed by the same approach which was mentioned before. After the investigation of intersection loads and comparison with mechanical properties of resin, resin failure at the intersections and separation of warp and weft yarns could be analyzed. Euler-Bernoulli beam theory can be replaced by Winkler curved beam theory.

References


