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Designing of textile preforms for ceramic matrix composites

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Abstract—Two and three dimensional fiber preforms produced by textile forming techniques have been used successfully for reinforcing ceramic-based composites. The focus of this paper is on the design of textile preforms for reinforcing ceramic matrix composites. The research work consisted of the following tasks: (1) identification of typical loading conditions on composite structural elements; (2) determination of the requirements on the orientation and volume content of fiber reinforcement; (3) identifying the fiber preforms suitable for each loading condition; (4) identifying the preforming technologies available for producing the preforms; (5) analysis and modeling of the thermo-mechanical behavior of the textile composites, using the concepts of micro- and macro-cells; and (6) characterization of textile composite performance.

Keywords: Textile preforms; ceramic matrix composites; design; analysis.

1. INTRODUCTION

Textile structural composites have gained increasing technological importance during the past two decades. Two and three dimensional fiber preforms produced by textile forming techniques have been used successfully for reinforcing polymer-, metal- and ceramic-based composites. Textile preforms offer a tremendous opportunity of enhancing through-the-thickness stiffness and strength, delamination resistance and damage tolerance of composites. The potential of near-net-shape manufacturing of composites based upon textile preforming is also very attractive [1].

The focus of this presentation is on the design of textile preforms for reinforcing ceramic matrix composites. The research work consisted of the following tasks: (1) identification of typical loading conditions on composite structural elements; (2) determination of the requirements on the orientation and volume content of fiber reinforcement; (3) identifying the fiber preforms suitable for each loading condition, and the preforming technologies available for producing the preforms; (4) analysis and modeling of the thermo-mechanical behavior of the textile composites, using the concepts of micro- and macro-cells; and (5) characterization of textile composite performance [2].

The loading conditions considered here are simple. The reinforcement and preform requirements for multi-axial loading can be approximated through superposition of those developed for the basic loading conditions. The preforming techniques considered in this study include braiding, weaving, stitching and knitting. The analytical techniques applied include those for thermo-elastic analysis, damage mechanics, and fracture toughness.

Ceramic matrix composites based upon 2D and 3D textile preforms have been fabricated using chemical vapor infiltration, slurry infiltration and preceramic polymer infiltration. Examples of damage initiation and evolution in textile ceramic matrix composites, as affected by the fiber architecture will be discussed.

2. IDENTIFICATION OF LOADING CONDITIONS

The basic loading conditions encountered in structural elements can be categorized as follows:

(1) uni-axial tension of a rod element;
(2) torsion of a cylindrical rod;
(3) internal pressure loading of a thin-walled cylinder;
(4) in-plane bi-axial tension of a plate;
(5) in-plane shear of a plate;
(6) transverse loading of a thick plate;
(7) flexural loading of a beam.

Multi-axial and combined loading conditions can be constructed from superposition of these simple loading conditions.

3. REQUIREMENTS OF FIBER REINFORCEMENT

The requirements of fiber reinforcement of a structural element composed of fiber composite material can be readily determined from the loading condition specified in Section 2. The resulting fiber reinforcement directions are illustrated in Fig. 1. It should be noted that the fiber placement strategy here is only based upon a consideration of the strength of the load-bearing element. Factors such as buckling and local stress concentration are not taken into account. Some comments in regard to the fiber orientation and volume content are given below in reference to the respective loading conditions of Section 2:

(1) The uni-axial fiber orientation is suggested for reason of simplicity. Fibers in the transverse directions can be added if the reduction of axial Poisson's ratio is needed.

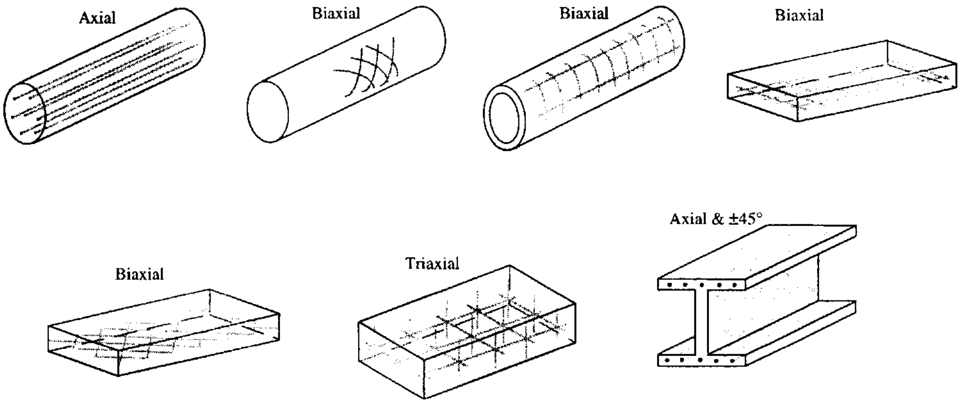

Figure 1. Reinforcement directions.

(2) A pure shear state is assumed.
(3) The difference in fiber contents in the axial and hoop directions of the thin-walled cylinder is intended to reflect the axial-to-hoop stress ratio.
(4) The volume contents of fibers in the two mutually orthogonal directions are determined by the relative magnitudes of the loading.
(5) The placement of fibers for the simple shear condition neglects the effects of buckling.
(6) The fibers in the transverse direction are intended for resisting delamination induced by the transverse shear in a thick plate.
(7) Assuming a simply supported end condition of the I-beam, the fibers in the web-section are intended for carrying the shear stress.

4. IDENTIFICATION OF FIBER PREFORMS AND PREFORMING TECHNOLOGIES

The fiber preforms, which provide the necessary fiber reinforcement as required by the loading conditions, and the related preforming techniques need to be identified. Table 1 summarizes the results of our assessment of the preforming techniques for a plate element. These include weaving, non-woven, braiding, knitting, and stitching. For each category of preforming technique, more than one method may be available, and each method produces preforms with a distinct geometric characteristic.

Here, as examples, three loading conditions in a plate element are considered: bi-axial loading, in-plane shear, and transverse loading. The following fiber preforms are suitable for the bi-axial loading condition; angle-interlock, multi-axial weave, non-woven, multi-axial warp knit, cloth lamination stitch, and dry roving stitch. Preforms suitable for in-plane shear loading include; multi-axial weave, non-woven, 4-step braid, multi-step braid, and 3D solid braid, multi-axial warp knit, cloth lamination stitch, and dry roving stitch. All the preform types indicated above

Table 1.
Preforming techniques for a plate element

Loading condition	Bi-axial loading	In-plane shear	Transverse loading
Weaving			
Angle-interlock	*		*
Multi-axial weave			
• Tube rapier	*	*	*
• Lappet weaving	*	*	
• Screw shaft	*	*	*
• Split-reeds	*	*	*
• Guide block	*	*	*
Non-woven			
3D orthogonal	*	*	*
Braiding			
2-step	*		*
4-step		*	*
Multi-step	*	*	*
3D solid braid	*	*	*
Knitting			
Multi-axial warp knit	*	*	*
Stitching			
Cloth lamination	*	*	*
Dry roving lamination	*	*	*

for both bi-axial and in-plane shear loading are available for transverse loading. Some of the multi-axial weaving techniques can be found only in patents and further development seems to be needed for practical use. Because of the general applicability of braided preforms to the loading conditions the basic concept of multi-step braiding is introduced below.

It has been found that the individual control of the rows and columns of yarn carriers on a Cartesian braiding bed allows for the fabrication of advanced 'multi-step' braids; the micro-structural possibilities of three-dimensional braids are thus greatly extended. It also has been concluded that the traditional four-step and two-step braidings are special cases of multi-step braiding. The process of braiding is termed 'multi-step' because any number of steps may be specified in a given machine cycle. As an example, consider the machine cycle depicted in Fig. 2. The cycle consists of eight steps with one unit displacement for each. Figure 3 depicts the front view of 2-step and 4-step braided preforms. The majority of fibers in the 2-step preforms are aligned in the axial direction while the 4-step preform contains off-axis fibers, although fibers can be inserted in the axial and transverse directions.

The process simulation of multi-step braiding allows for the identification of individual yarn paths, number and location of yarn groups, and braid geometry.

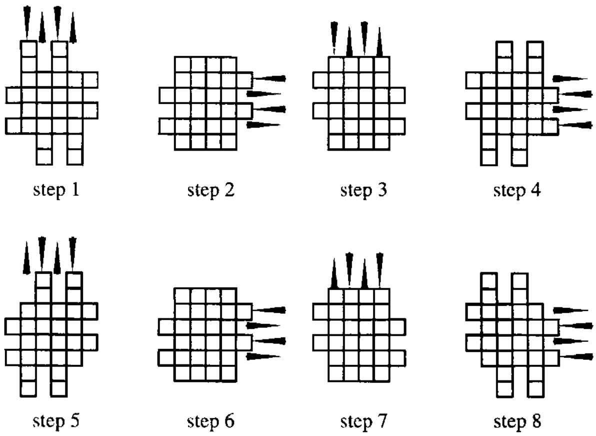

Figure 2. Multi-step braiding.

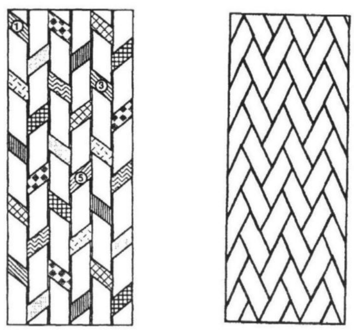

Figure 3. 2-step and 4-step braid preform geometry.

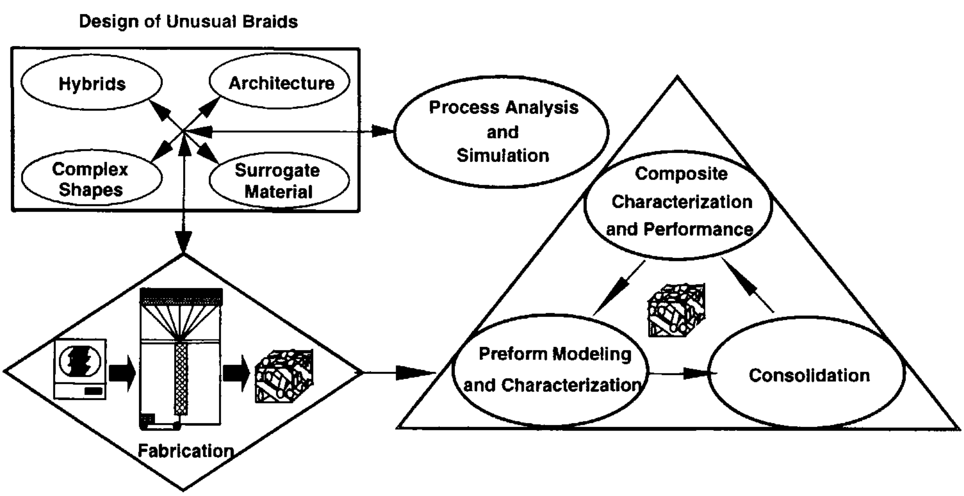

Figure 4. Overall plan for multi-step braiding.

The feasibility of fabricating a wide range of preform architectures has been demonstrated. Figure 4 illustrates the integrated research plan for multi-step prefom reinforced composites, from preform design and fabrication to composites processing and characterization [3].

5. ANALYSIS AND MODELING OF COMPOSITE THERMO-ELASTIC BEHAVIOR

A methodology has been developed to analyze the composite thermo-elastic behavior through the use of preform modeling to represent the fiber microstructure and micro-mechanical analysis to determine the effective properties. A representative volume element (macro-cell) is first identified for a given three-dimensional preform. Geometric models representing the fiber morphology of macro-cell are then constructed. Further decomposition of the macro-cell into simpler elements termed 'unit-cells' is then carried out. The macroscopic behavior of the textile composite is obtained from the properties of the unit-cells and a set of load sharing relationships among the unit-cells, using an averaging technique [4].

6. CHARACTERIZATION OF TEXTILE CMC PERFORMANCE

As an example of the characterization of textile CMC performance, the damage behavior of 2-step and 4-step braided composites are reviewed here. The study of damage mechanisms and evolution in three dimensional SiC-SiC fabric composites, fabricated by the chemical vapor infiltration (CVI) route, have led to the following

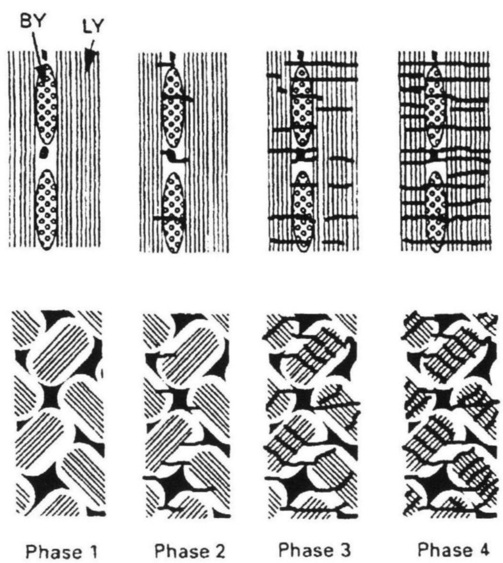

Figure 5. Damage stages in CMC.

conclusions: (1) Although the fiber, the matrix and the infiltration conditions are identical for these composites their residual pore morphology and mechanical behavior are significantly different due to their distinct fiber architectures. (2) The morphological study identifies both intrayarn pores and interyarn pores in the 2-step and 4-step braided composites. (3) Both types of composites exhibit non-linear behavior under tensile loading. The damage development can be described through the stages as shown in Fig. 5. The damage is first matrix dominated. Then, the damage becomes fiber dominated and it differs significantly between the two types of composites [5].

7. CONCLUDING REMARKS

The knowledge base for the design of textile preforms for thermo-elastic and damage resistant properties of CMCs under various simple loading conditions has been reasonably well developed. Future research should address the needs in designing of preforms for combined loading as well as the development of strength criteria for textile structural composites under multi-axial loading.

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