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Near Net Shape Manufacturing of Composite Engine Components By 3-D Fiber Architecture

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ABSTRACT

Responding to the need for a higher level of through thickness strength, higher damage tolerance, and near net shape manufacturing in structural engine components, there is a worldwide revival in the interest in 3-D fabric preforms. Recent advances in computer aided design, analysis and manufacturing of fully integrated 2-D and 3-D woven, knitted, and braided fibrous structures promises to lead to major advances in composite technology. Through thickness strength imparted to composites by virtue of such integrated reinforcement will open new applications for composites that could not be considered previously, primarily due to the poor transverse strength and interlaminar shear properties of traditional laminated composites. The ability of these structures to conform to shape or assume near net structural shapes promises to simplify manufacturing processes, reduce costs, and enhance design flexibility.

INTRODUCTION

The realization of dramatic increases in engine performance relies heavily on the development of high temperature, tough materials. Monolithic ceramics, while having the desired thermal characteristics, do not have sufficient toughness for structural applications. The use of fiber reinforcement as a crack deflection mechanism, and consequently a toughening device, has been investigated for the past few decades. The explosive growth of aerospace industry in recent years has stimulated a rapid development of innovative design and fabrication techniques for advanced structural composites. The recent progress in fabric formation technology has created new options in composite structural design. Using the fabric formation technology, various fiber geometric structures can be formed easily. With the use of textile reinforcement, in particular 3-D fiber architecture, it has become feasible to construct ceramic matrix composites capable of withstanding the harsh environment of high temperature engines.

By determining the basic operating conditions and the geometric complexity of the component, it is possible to identify a fabrication technique suitable to the part. Given an understanding of the fabrication technique and its relationship to yarn conversion, a geometric model of the reinforcement can be constructed which in turn can be used as a mechanical model of the ceramic structure.

FIBER ARCHITECTURE

It is first necessary to identify the available fiber architectures for preform manufacturing. On the basis of structural integrity and fiber linearity and continuity, fiber architecture can be classified into four categories: discrete; continuous; planar interlaced (2-D) and fully integrated (3-D) structures. In Table I the nature of the various levels of fiber architecture is summarized according to Scardino [1].

Table I. Fiber Architecture for Composites

Reinforcement Level	Textile System	Fiber Construction	Fiber Length	Fiber Orientation	Fiber Entanglement
I	Discrete	Chopped Fiber	Discontinuous	Uncontrolled	None
II	Linear	Filament Yarn	Continuous	Linear	None
III	Laminar Planar	Simple Fabric	Continuous	Planar	
IV	Integrated	Advanced Fabric	Continuous	3-D	3-D

The level of architecture corresponds with the level of integrity of the fabric. A discrete (chopped fiber or whisker) system has virtually no integrity, and the 3-D integrated fabrics have the ability to form complex shapes in a single structure (fully integrated). 3-D fabrics as composite reinforcements have demonstrated significant improvements in strength and toughness

over unreinforced ceramic materials. This combined with the inherent ability of 3-D fabric systems to form near net shape preforms make them very promising candidates for engine components.

The families of three dimensional fabrics are described herein. The structural geometry of 3-D fabrics will be discussed according to the four basic methods of textile manufacturing: weaving, orthogonal nonwoven, knitting and braiding.

Woven 3-D Fabrics

3-D woven fabrics are produced principally by the multiple-warp weaving method which has long been used for the manufacturing of double cloth and triple cloths for bags, webbings and carpets. Fabrics with as many as 17 layers have been successfully woven. By the weaving method, various fiber architectures can be produced including solid orthogonal panels (Figure 1a), variable thickness solid panels (Figure 1b), and core structures simulating a box beam (Figure 1c), or truss-like structure (Figure 1d). Furthermore, by proper manipulation of the warp yarns, as exemplified by the angle interlock structure (Figure 2), the through-thickness yarns can be organized into a diagonal pattern. To address the inherent lack of in-plane reinforcement in the bias direction, progress is being made in triaxial weaving technology by Dow [2] to produce multilayer triaxial fabrics as shown in Figure 3.

Orthogonal Nonwoven Fabrics

Pioneered by aerospace companies such as General Electric [3], the nonwoven 3-D fabric technology was developed further by Fiber Materials Incorporated [4]. Recent progress in automation of the nonwoven 3-D fabric manufacturing process was made in France by Aerospatiale [5], SEP [6] and Brochier [7] and in Japan by Fukuta of the Research Institute for Polymers and Textiles [8,9].

The structural geometries resulting from the various processing techniques are shown in Figure 4 [10]. Figures 4a and 4b show the single bundle XYZ fabrics in a rectangular and cylindrical shape. Figure 4c demonstrates the multiple yarn bundle possibilities in the various directions. In Figure 4d the multidirectional reinforcement in the plane of the 3-D structure is shown. Although most of the orthogonal nonwoven 3-D structures consist of linear yarn reinforcements in all of the directions, introduction of the planar yarns in a nonlinear manner, as shown in Figures 4e, f and g can result in an open lattice or a flexible and conformable structure.

Knitted 3-D Fabrics

The knitted 3-D fabrics are produced either by the weft knitting or warp knitting process. An example of a weft knit is the near net shape structure knitted under computer control by the Presser Foot® process [11] as illustrated in Figure 5. In a collapsed form this preform has been used for carbon-carbon aircraft brakes.

The unique feature of the weft knit structures is their conformability [12]. When additional reinforcement is needed in the 0° and 90° direction, linear

laid in yarns can be placed inside the knitting loops as shown in Figure 6. The most undesirable feature of weft knit structures from the structural reinforcement point of view is their bulkiness which leads to the lowest packing density, or lowest level of maximum fiber volume fraction compared to other fabric preforms. While the weft knitted structures have applications in limited areas, the multiaxial warp knit (MWK) 3-D structures are more promising and they have undergone a great deal more development in recent years [13,14].

From the structural geometry point of view, the MWK fabric systems consist of warp (0°), weft (90°) and bias ($\pm\theta$) yarns held together by a chain or tricot stitch through the thickness of the fabric, as illustrated in Figure 7. The major distinctions of these fabrics are the linearity of the bias yarns, the number of axes, and the precision of the stitching process. Depending on the number of guidebars available and the yarn insertion mechanism, the warp knit fabric can consist of predominantly uniaxial, biaxial, triaxial or quadraxial yarns. The latest commercial non-impaled MWK fabric is produced by the Mayer Textile Corporation utilizing a multiaxial magazine weft insertion mechanism. The attractive feature of this system is the precision of yarn placement with four layers of linear or nonlinear bias yarns plus a short fiber mat arranged in a wide range of orientations. Furthermore, the formation of stitches is done without piercing through the reinforcement yarns (hence the term, "non-impaled") at a production rate of one hundred meters per hour.

The latest development in the impaled MWK is the LIBA or Hexcel system, as shown in Figure 8. Six layers of linear yarns can be assembled in various stacking sequences and stitched together by knitting needles piercing through the yarn layers. While this piercing action unavoidably damages the reinforcing fiber, the powerful knitting needles also permit the incorporation of a fiber mat as a surface layer for the composite.

3-D Braided Fabrics

The 3-D braiding technology is an extension of the well established 2-D braiding technology wherein the fabric is constructed by the intertwining or orthogonal interlacing of two or more yarn systems to form an integral structure. 3-D braiding is one of the textile processes wherein a wide variety of solid complex structural shapes can be produced in an integral manner resulting in a highly damage resistant structural preform. Figure 9 shows two basic loom set-ups in circular and rectangular configurations [15]. The 3-D braids are produced by a number of processes including the Track and Column method [16] (Figure 10), the 2-step method [17] (Figure 11) as well as a variety of displacement braiding techniques. The basic braiding motion includes the alternate X and Y displacement of yarn carriers followed by a compacting motion. The formation of shapes is accomplished by the proper positioning of the carriers and the joining of various rectangular groups through selected carrier movements. Examples of the structural shapes successfully demonstrated in the Fibrous Materials

Research Laboratory of Drexel University are shown in Figure 12.

STRUCTURE AND PROPERTIES OF 3-D CMC

The level and type of fabric integrity correspond directly to mechanical properties of the fiber reinforced composite. Although a considerable amount of work has been carried out on whisker/short fiber and unidirectional fiber reinforced ceramic matrix composites (CMC) [18 - 21], the data base for fabric reinforced CMC is virtually nonexistent in the published literature. Based on limited information, this section attempts to summarize the results of a few selected studies to develop a sense of the role of fiber architecture in the toughening of CMC. Figure 13 shows a summary of the effects of fiber volume fraction and fiber integrity on the flexural strength of SiC whisker and fiber reinforced ceramics.

As can be seen, the three dimensional nature of both the level I (randomly dispersed SiC-whisker) and the level III (3-D braided SiC yarn) composites demonstrate superior flexural strength compared with woven laminated composites. The spatial orientation of fibers provides more opportunity for crack stopping during loading. In the laminated case, the cracks are free to propagate along the planes between laminae. Currently, some consideration is being given to the use of whisker reinforced ceramics as a matrix material to reinforce three-dimensional braided or woven fiber architectures.

It is interesting to note that the whisker reinforced ceramics demonstrate an apparent optimum fiber volume fraction, above and below which the flexural strength decreases. Full studies on the laminated and 3-D systems are not available to identify the full effect of fiber volume fraction on these systems.

When fracture toughness (K_{Ic}) is examined, it is clear that increasing the amount of fiber (or whisker) in the composite is the most critical factor for improving fracture toughness. Architecture plays a small role in improving fracture toughness. Figure 14 illustrates the effects of fiber volume fraction and fabric integrity on the fracture toughness of ceramic matrix composites. Fracture toughness was measured by crack propagation due to a pyramidal indenter (hardness test) in the case of the whisker reinforced materials and by calculation (from G_{Ic} (energy release rate) values) in the case of the fabric reinforced systems.

Based on these results, three dimensional architectures appear to be a promising route for structural ceramic applications. The combination of high strength, high toughness and near net shape manufacturing identify 3-D reinforcement as the most suitable architecture for ceramic engine components.

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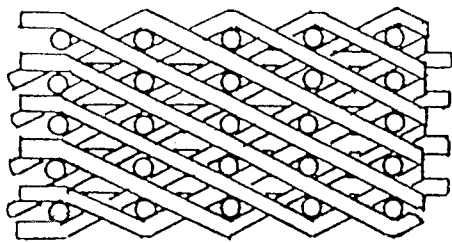


Figure 2. Structural Geometry of "Angle Interlock" 3-D Woven Fabric

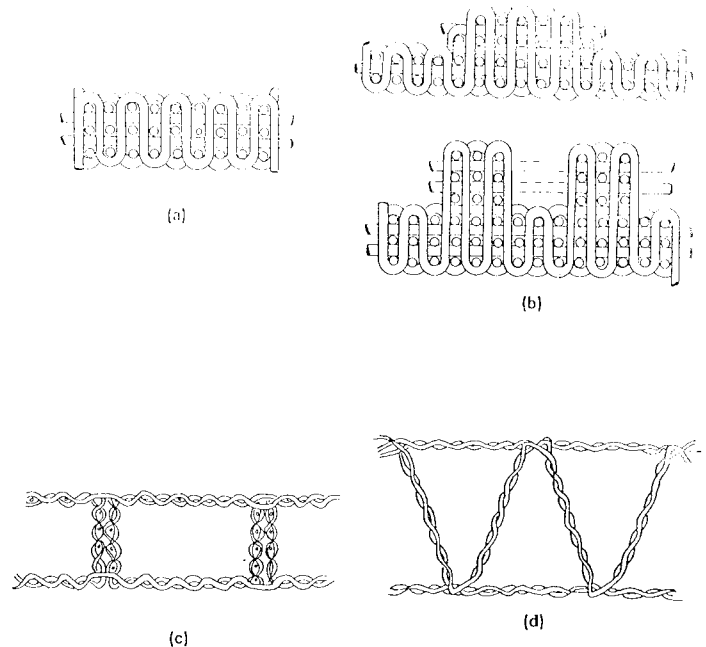


Figure 1. Various Complex Shapes Formed With 3-D Weaving Processes

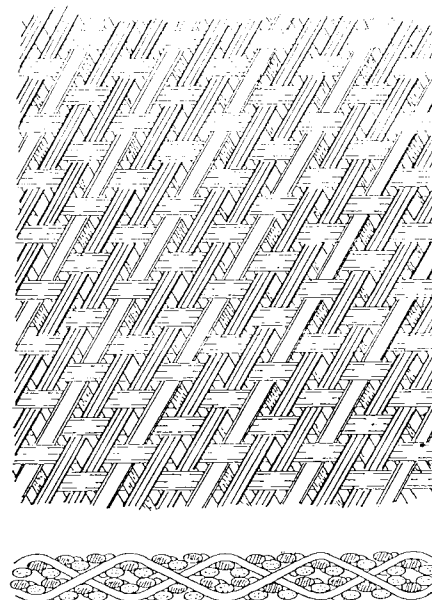


Figure 3. Structural Geometry of Multilayer Triaxial Woven Fabric

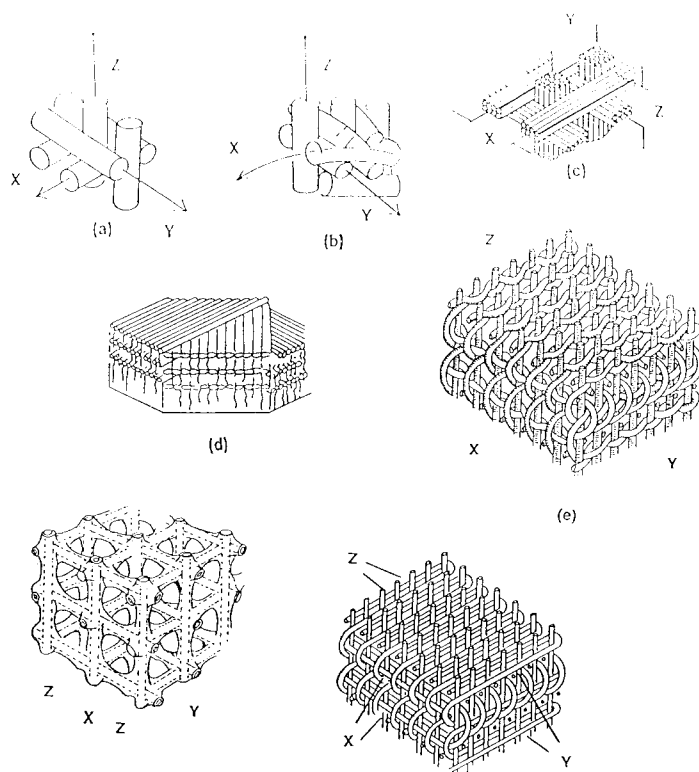


Figure 4. XYZ Orthogonal Nonwoven Fabric Structural Geometries

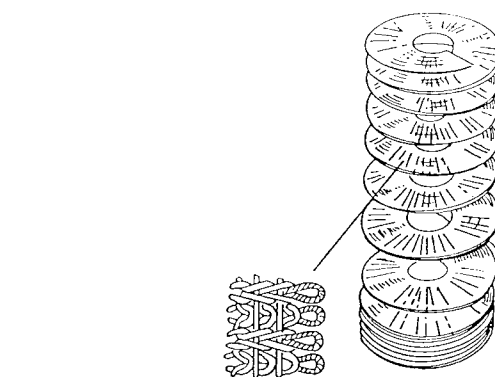


Figure 5. An Example of Complex Shapes Formed by Three Dimensional Knitting with the Presser Foot Process

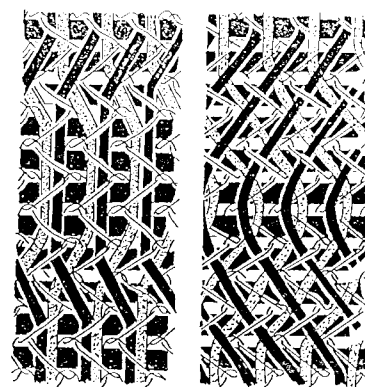


Figure 6. Typical Structural Geometry of the Warp Knit Fabric

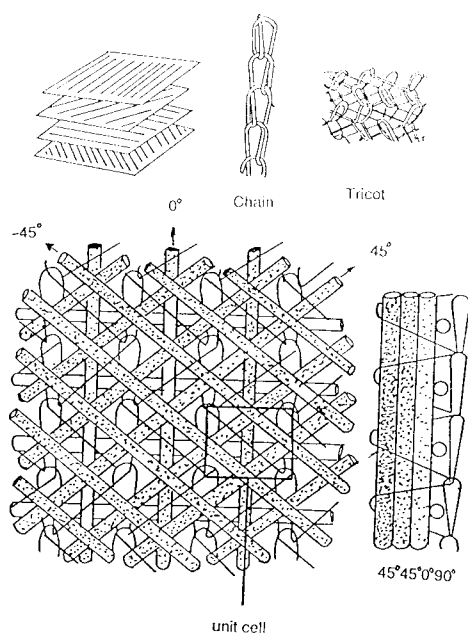


Figure 7. Typical Structural Geometry of the Multiaxial Warp Knit Fabric

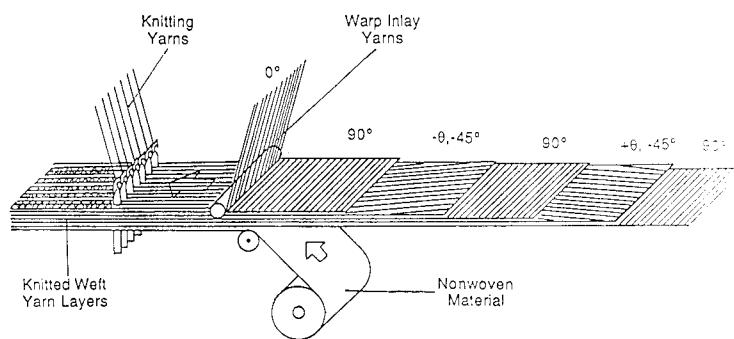


Figure 8. Process Schematic of Impaled MWK Fabric Production, Typical of LIBA or Hexcel Systems

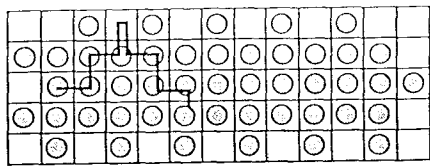


Figure 9. Schematic Representation of Three Dimensional Braiding Machines in both Rectangular and Polar Configurations

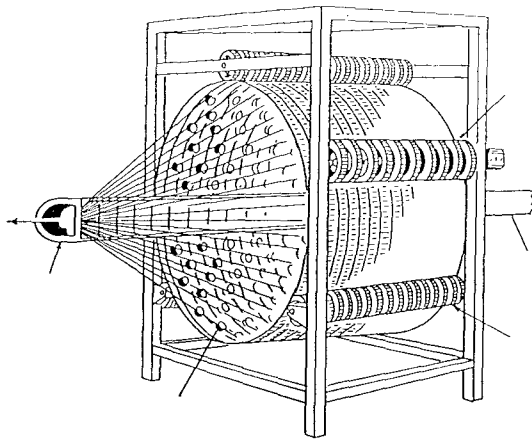


Figure 10. Typical Machine Design for the Track and Column, or Euclidean, Three Dimensional Braiding Process in a Polar Configuration

U.S. PATENT FOR THE TRACK AND COLUMN 3,719,437

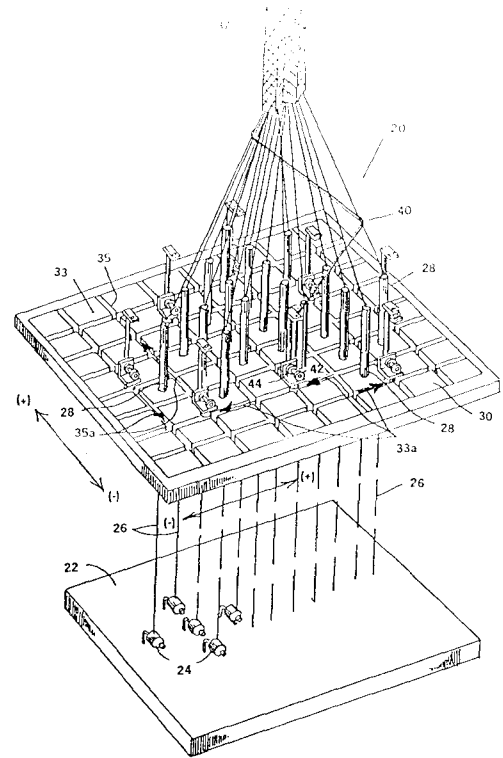


Figure 11. Typical Machine Configuration for the 2-Step® Three Dimensional Braiding Process

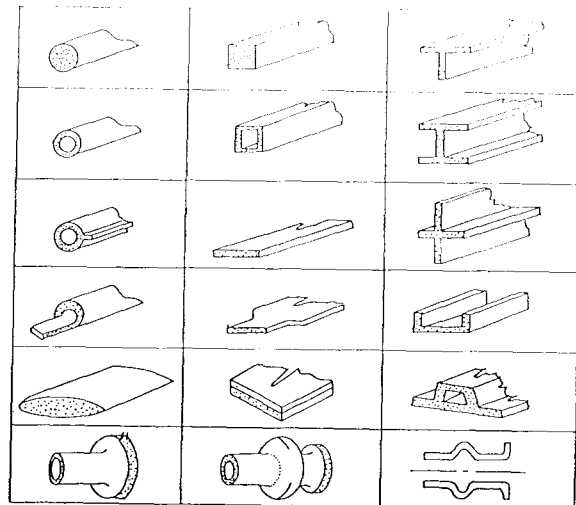


Figure 12. Schematic Illustration of Some of the Complex Shape Composite Preforms Fabricated with Three Dimensional Braiding

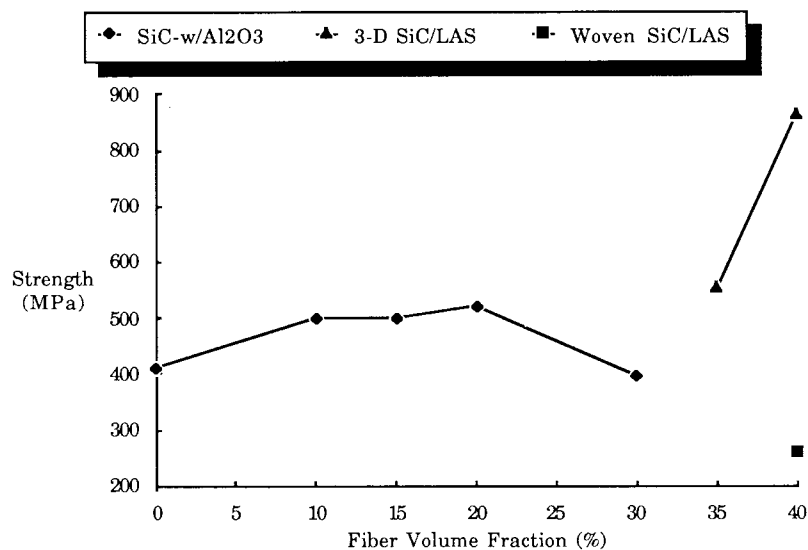


Figure 13. Effect of Fiber Volume Fraction and Fabric Integrity on Flexural Strength of CMC.

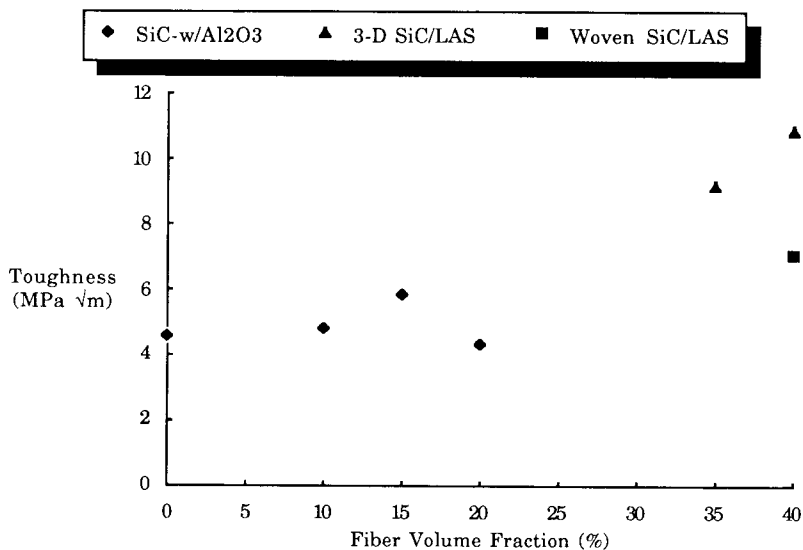


Figure 14. Effect of Fiber Volume Fraction and Fabric Integrity on Fracture Toughness of CMC.