3D WOVEN COMPOSITE APPLICATIONS FOR THE NEXT GENERATION OF AIRCRAFT ENGINES

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Abstract

The use 3D woven composites is on the rise, especially in aircraft engine components. OEMs are recognizing the many performance and economic advantages offered by the 3D weaving process, especially in aircraft engine applications that require high damage tolerance. Near net shape preforms with high fiber volume can be produced using the 3D weaving process. 3D weaving also offers the designer with the choice of virtually unlimited fiber architectures and design possibilities. However, a good, reliable and computationally efficient design tool for 3D woven composites is a basic necessity in order to enable the designer to fully exploit the advantages offered by the 3D weaving process. A simple analytical tool like TEXCAD can provide reliable and quick estimates and parametric studies of the 3D stiffnesses and strengths over the full range of fiber architectures that are possible with 3D weaving. Challenges in the use 3D woven composites relate to the lack of structural progressive damage modeling capability, the lack of standards and methods for the quality control, inspection and process control of 3D weaving processes and a lack of a good understanding of the effects of defects and fiber architecture variability on mechanical properties.

***Keywords**: 3D woven composite, strength, stiffness, modeling, processing, engine, design, perform*

Introduction

Aircraft Engines can be classified into two general categories: turbojet and turbofan engines. In a turbojet engine all of the incoming air entering through the fan blades is fed into the engine's compressor. In a turbofan engine not all but some of the incoming air is fed into the engine's compressor and some of the air is diverted outside the compressor (Fig.1). This "bypass" airflow provides a second source of thrust - similar to that provided by a propeller in a turboprop engine. The ratio of the air that goes through the core to the air that bypasses the engine core is a critical design parameter and is referred to as the bypass ratio. The trend in engine design in the past 2-3 decades has been towards higher and higher bypass ratios in order to increase engine efficiency, reduce noise and reduce greenhouse gases. Higher bypass ratios require larger fan diameters resulting in fan sections that account for over 30% of the engine weight. The trend to larger and heavier fan sections is a key driver for the adoption of composites in future engines.

The addition of 1 lb/0.45 kg to the fan blade assembly requires a compensatory 1 lb/0.45 kg increase in the weight of the fan containment case (which must prevent broken blades from exiting the engine and damaging the aircraft) [1]. That 2 lb/0.9 kg increase, in turn, will mandate a compensatory 0.5 lb/0.23 kg increase in the weight of rotor and engine structures as well as an incremental 0.25 lb/0.11 kg uptick in the aircraft's wing/fuselage structures [1]. This cascading effect on aircraft mass has put a premium on weight reduction in fan components, providing the greatest opportunities for expanding the use of composite materials and technology in jet engines [1]. In the mid 1990s, the GE90 engine made by General Electric became the first commercial turbofan engine to successfully use composite fan blades [2]. These composite fan blades are made using laminates that can comprise up to 1000 plies of unidirectional carbon prepreg tape and fabric near the blade root, where the thickness is up to four inches. Each ply has to be cut to the correct shape and located precisely in the laminate stack-up to create the highly contoured and cambered airfoil shape [2]. This is a multistep, highly time-intensive process. Also, laminated structure is much more susceptible to delamination, especially under high velocity impact from birds. These limitations of the laminated construction can be overcome by using automated 3D woven construction.

Integrally 3D woven architecture has superior impact resistance as it does not have weak interlaminar planes along which delaminations can propagate. Thus, 3D weaving technology can provide both performance and economic advantages in the manufacture of composite fan blades for aircraft engines. Pratt and Whitney made and tested the first 3D woven composite fan blades (Fig.2) in 1998 [3]. CFM International (a joint venture between General Electric and Snecma) has recently (in 2008) announced the use of 3D woven composite fan blades on the LEAP-X engine.

3D Weaving Basics

In order to understand the 3D weaving process, it is instructive to look at the 2D weaving process. A basic 2D weave is created on a loom in which two sets of yarns - wrap and fill (or weft) are interlaced. There are three basic motions during the weaving of a fabric (Fig.3) [4]. The first motion is called "shedding". In shedding, to form a plain weave for example, alternate warp yarns are raised and lowered to make room for the insertion of the fill (or weft) yarn into the shed formed by the raised and lowered warp yarns. Shedding is automatically performed by the use of harnesses on a modern weaving loom. A harness is a rectangular frame to which a series of wires, called heddles, are attached. Each warp yarn passes through an opening in the heddle. "Weft insertion" is the next basic motion in which the weft (or fill) yarn is inserted through the shed. After passing through the heddle eyelets, the warp yarns pass through openings in another frame that looks like a comb and is known as a "reed". After each weft insertion operation, the reed pushes or "beats" each weft yarn (after insertion) against the portion of the fabric that has already been formed in the "beating-up" motion. This results in a firm and compact fabric construction.

The pattern of the weave depends on the manner in which groups of warp yarns are raised by the harnesses on the loom to allow the insertion of the fill (or weft) yarns. For example a plain weave requires two harnesses (Fig.4) and a four harness-satin weave is produced by using 4 harnesses on the loom. Each harness is used to raise / lower one set of warp yarns when the fill yarn is inserted. For example in a 4-harness satin weave, the motion of the yarns numbered "1" in Fig.4 is controlled by the same harness. When this harness is raised, it raises all the "1" yarns and at the same time the harnesses that control the motion of the "2", "3", and "4" yarns are lowered and then the fill yarn is inserted. The resulting yarn interlacing is depicted in Fig.4 by the dark colored fill yarn. When all the "2" yarns are raised and the "1", "3", and "4" yarns are lowered before the insertion of the fill yarn, we get the yarn interlacing shown in Fig.4 by the fill yarn just above the dark colored fill yarn.

A 3D weave is also created on a loom in which layers of warp "weaver" yarns are interlaced with layers of fill (or weft) yarns 4. All warp yarns do not need to be interlaced with weft yarns. The non-interlacing warp yarns (called warp stuffer yarns) traverse in between the layers of fill yarns in a unidirectional manner. Unlike a 2D weave, a 3D weave interlaces warp weaver yarns in the thickness direction either from one layer to another (as in a layer-to-layer angleinterlock weave) or from the top to the bottom layer (as in a through-thickness angle-interlock weave). As shown in Fig.5, angle-interlock weaves consist of two or three sets of yarns. Warp weaver yarns and warp stuffer yarns are oriented along the loom feed direction. Fill (or weft) yarns are oriented normal to the warp yarns and are inserted between layers of warp yarns. The warp weaver yarns traverse through the thickness of the weave and interlock with fill yarn layers. The weaver yarns criss-cross the weave thickness at off-axis angles usually between 5-75 degrees. Depending on the type of loom used, angle-interlock weaves can be made with numerous and complex architecture variations in which the yarn sizes, yarn spacings, interlock lengths and depths, stuffer yarn distributions, fill yarn patterns, etc., can be varied. The capability of today's electronically controlled looms provides the designer with an infinite choice of weave architecture parameters to achieve desired inplane and through-thickness composite properties.

3D weaving offers the capability to produce near net shape preforms with high fiber volume. It is possible to make components with integral tapers, curvatures, bifurcations, holes, stiffeners, flanges, etc. 3D weaving can be used to provide load-carrying fiber paths through intersecting planes and joints. Thus 3D weaving has the potential to reduce part count, reduce the use of fasteners, improve overall process automation and reduce manufacturing steps. Also, fully integrated 3D woven structures are tougher, more damage tolerant and more impact resistant.

However, this flexibility in the manufacture of angle-interlock weaves can be fully exploited by the designer only if he can evaluate several architecture variations using simple analytical tools. Mechanical testing to characterize the effects of all the weave architecture possibilities could be an economically unrealistic proposition. In order to facilitate the design of integrally woven composite structures, it is therefore crucial to develop experimentally verified analytical models for the prediction of both the inplane and through-thickness stiffness and strength properties of 3D woven composites. A good design tool for 3D woven composites needs to not only provide effective 3D stiffness and strength properties, but it also needs to provide a computationally efficient means to run parametric studies to assess the effects of varying the yarn spacing, yarn filament count, yarn types, yarn interlacing architecture, the Z-yarn content, and the Z-angle. Only with the help of such a tool can the designer have the means to tailor the fiber architecture of a 3D woven component to meet specific design requirements and to fully exploit the dvantages offered by the 3D weaving process.

Design Tool for 3D Woven Composites

3D Geometry Model

A simplified modeling approach to calculate the 3D effective properties and strengths of a 3D woven composite was developed by the author [5, 6, 7]. The analysis of a 3D woven composite requires, first, a proper three dimensional description of the preform architecture. The geometric modeling of the preform architecture is performed by utilizing the periodicity of the 3D woven composite to isolate a repeating unit cell (RUC) as shown in Fig.6. The geometric modeling of the 3D weave is performed by discretely modeling the yarn geometry (cross-sectional areas and yarn paths) within the textile repeating unit cell (RUC) using simplified equations [5]. Inputs to this model are yarn sizes, yarn spacings, number of warp yarns and fill yarns per column, yarn interlocking length and depth, and desired composite fiber volume. Outputs from this model are yarn slice orientations, yarn slice thicknesses, yarn slice cross-sectional areas, interstitial matrix volume, and composite thickness. Details of this geometry modeling are given in Ref. [5].

3D Stiffness Model

For each yarn within the RUC the yarn centerline path is described by connected piecewise straight yarn slices. The orientation of each yarn slice (straight part of the yarn path) in 3D space is described by using two orientation angles; θ - to describe the local inplane orientation of the yarn with respect to the longitudinal direction, and β - to describe the local through-thickness orientation of the yarn with respect to the plane of the laminate. Having described the yarn paths in three-dimensional space, the 3D woven composite is modeled as a multi-directionally reinforced composite (Fig.7). The 3D effective stiffnesses for the composite are computed by using the transversely isotropic material properties and the fiber volume fraction of all the yarn slices in a volume stress averaging scheme that assumes an iso-strain state within the RUC. The interstitial resin is modeled as an isotropic material slice with orientation angles, $\theta=0$ and $\beta=0$. The effective stiffness matrix $[C_{eff}]$ of the RUC is written in terms of the yarn slice stiffness matrices, $[C']_m$, transformation matrices, $[T]_m$, and yarn slice fiber volume fractions, V_m, as :

$$\left[C_{eff}\right] = \sum_{m=1}^{N} \left(V_m \, [T]_m^T \, [C']_m \, [T]_m\right) \tag{1}$$

where, N, is total number of yarn slices in the RUC. The transformation matrix, $[T]_m$, is defined in Ref.[6]. The superscript T indicates matrix transformation. The overall stiffness matrix $[C_{eff}]$ is inverted to obtain the overall compliance matrix $[S_{eff}]$ which is used to determine overall moduli and Poisson's ratios [6].

Failure and Damage Progression Model

Failure and damage progression analysis is performed by using an incremental scheme which accounts for the nonlinear effects of inplane shear and damage accumulation. The Full Newton-Raphson Method [7] is used for the failure analysis of the 3D woven composite. The applied stress is increased in small incremental steps and the overall stiffness matrix is recomputed (using the iso-strain assumption) at each incremental step to account for the accumulation of damage in each of the yarn slices within the RUC. For each increment of the applied stress the effect of nonlinear shear is included by the use of a three parameter equation to represent the nonlinear shear response of both the impregnated yarns and the interstitial resin [7].

Failure Criteria and Stiffness Reduction

Fiber dominated failure of the impregnated yarn slices is predicted using a maximum strain criterion for both tension and compression [6]. Matrix dominated failures within the yarn slices are predicted using maximum stress criteria for each matrix dominated failure mode, such as, transverse tension (σ_{22}, σ_{33}) transverse shear (τ_{23}), and longitudinal shear (τ_{12}, τ_{13}). Interstitial matrix failure is predicted using two different failure criteria. A maximum principal stress criterion is used in the absence of applied shear stresses, while, a maximum octahedral shear stress criterion is used in the presence of shear stresses. At each incremental step, the corresponding stiffnesses of each impregnated yarn slice in the model are reduced based on the predicted mode of failure [7]. Composite failure is predicted when either (i) fiber dominated loading leads to axial yarn slice failure anywhere in the RUC; or (ii) when matrix dominated loading (i.e. inplane shear, interlaminar shear, interlaminar tension) leads to failure of entire sets of yarn slices in the same failure mode. The TEXCAD program implements the above stiffness and damage progression modeling approach for 3D textile Composites [6, 7].

Experimental Verification

The correlation with test data (Table-1) for all the measured stiffnesses and strengths are reasonably good [5]. The bad correlation with the interlaminar tension strengths is probably due to the effect of the stress concentration at the groove in the test specimen which was not modeled in the present analysis. It is also important to note that many of the throughthickness stiffness and strength properties are not easily measured and that an experimentally verified analysis such as this could provide an alternative to obtain these properties.

Impact of 3D Woven Composite Panels

The integrally woven fiber architecture of a 3D woven composite leads to significantly better impact resistance compared to a 2D laminated construction. Panels that were shot using gelatin projectiles (to simulate soft-body bird impact) exhibited lower damage areas for the same impact energies. Fig.8 shows the comparison of the high velocity soft body impact resistance measured by the ratio of the impact energy to the damage area) of 3D layer-to-layer and through-thickness angle-interlock woven composites to comparable 2D, 5HS laminates [8].

Table-1 : Experimental Verification for a Layer-to-Layer angle-Interlock 3D Woven Composite [5]

Property	Test	Prediction
E_{11}, GPa	63 ± 4.4	66.67
E_{22}, GPa	36 ± 3.2	40.68
E_{33}, GPa	---	17.24
G_{12}, GPa	4.27 ± 0.4	4.62
G_{23}, GPa	---	4.21
G_{13}, GPa	---	5.24
ν_{12}	0.11	0.074
ν_{21}	0.04	0.046
ν_{23}	---	0.280
ν_{13}	---	0.300
S_{11}, tension, MPa	788 ± 44	786.03
S_{11}, comp., MPa	405 ± 46	413.70
S_{22}, tension, MPa	420 ± 17	399.91
S_{22}, comp., MPa	257 ± 23	241.33
S_{12}, MPa	98 ± 2	82.74
S_{13}, MPa	---	82.74
S_{33}, MPa	41.9 ± 1.7	99.29

Challenges in the Application of 3D Woven Composites

Although there are many advantages to using 3D woven composites, there also many challenges to their application in a production environment. There is a lack of understanding and analysis capability of the failure and damage mechanisms of 3D woven composites under fatigue, impact, and high strain rate loading. There is also a lack of Finite Element progressive damage modeling capability on a structural level that accounts for the 3D weave fiber architecture and the damage mechanisms on the meso-scale of the 3D weave RUC. The quality control, inspectability, and structural health monitoring of 3D woven composite components is a major challenge since there are no established methods for nondestructive inspection (NDI). There is also a lack of standards for acceptable defects in a 3D woven structure and a lack of understanding of the effects of defects and fiber architecture variability on mechanical properties. The process control and repeatability of the 3D weaving process is also not fully matured.

Summary

The 3D weaving process offers many performance and economic advantages for use in aircraft engine applications that require high damage tolerance. The use of 3D woven composites can potentially reduce part count and the use of fasteners and improve overall process automation and reduce manufacturing steps. Near net shape preforms with high fiber volume can be produced using the 3D weaving process. 3D weaving also offers the designer with the choice of virtually unlimited fiber architectures and design possibilities. However, a good, reliable and computationally efficient design tool for 3D woven composites is a basic necessity in order to enable the designer to fully exploit the advantages offered by the 3D weaving process.

A simple analytical tool like TEXCAD [6,7] can provide reliable and quick estimates and parametric studies of the 3D stiffnesses and strengths over the full range of 3D fiber architectures that are possible with 3D weaving.

The current challenges in the use 3D woven composites relate to the lack of finite element based structural progressive damage analysis capability that can model the damage and failure mechanisms in the 3D weave RUC. There is also a lack of standards and methods for the quality control, inspection and process control of the 3D weaving process and a lack of understanding of the effects of defects and fiber architecture variability on mechanical properties. The 3D weaving process also needs to be made more robust and repeatable.

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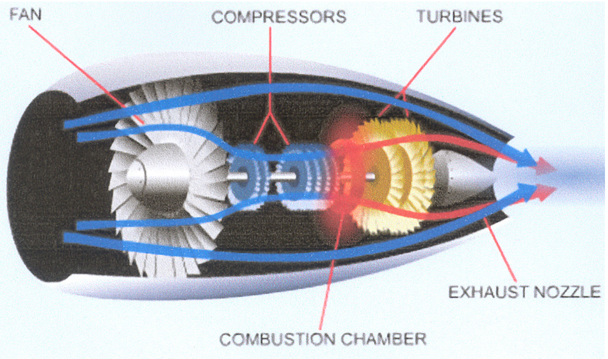

Fig.1 Illustration of Bypass Airflow in a Turbofan Engine

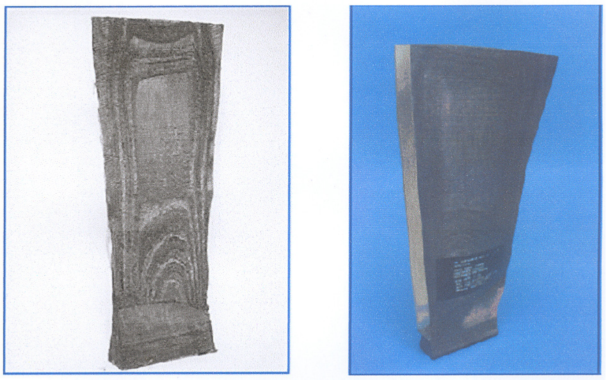

Fig.2 Pratt & Whitney 3D Woven Fan Blade Perform and Finished Resin Transfer Molded Blade-3

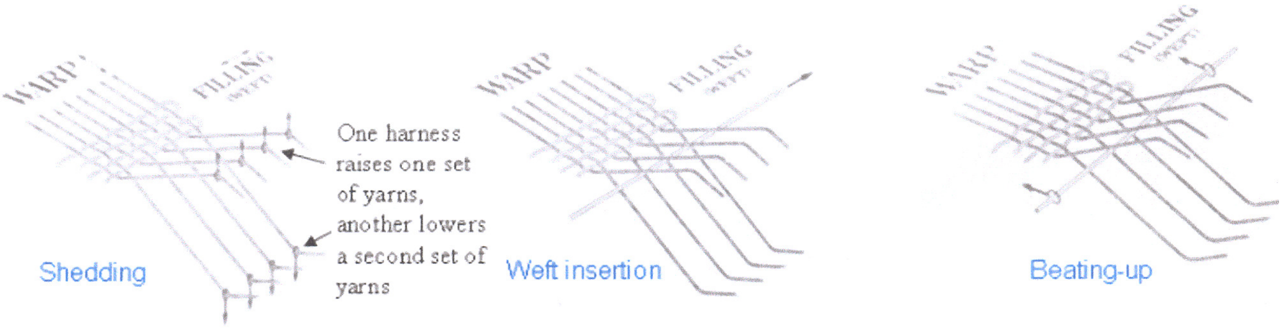

Fig.3 The Three Basic Motions During Weaving

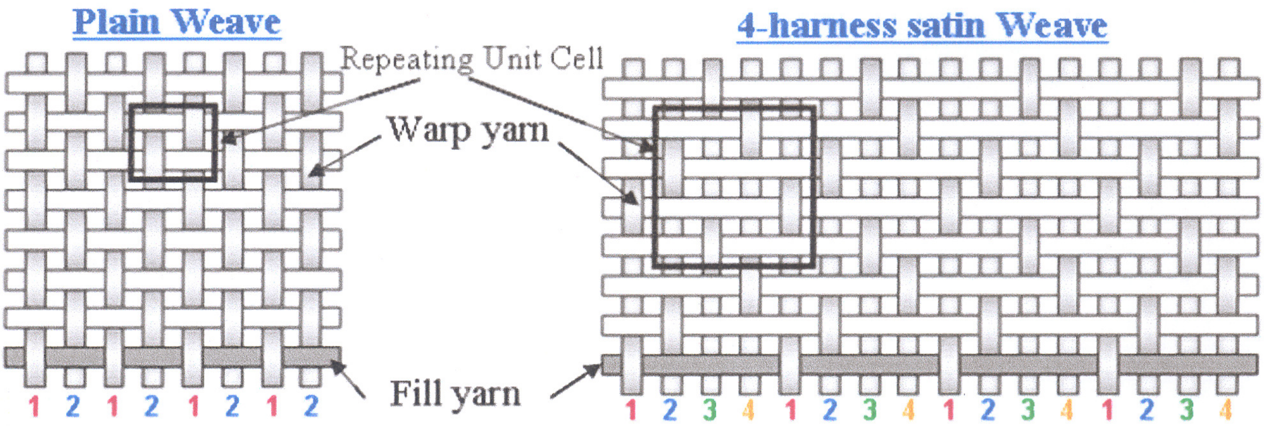

Fig.4 Illustration of the Sets of Yarns that are Raised and Lowered to Form the Weave Pattern

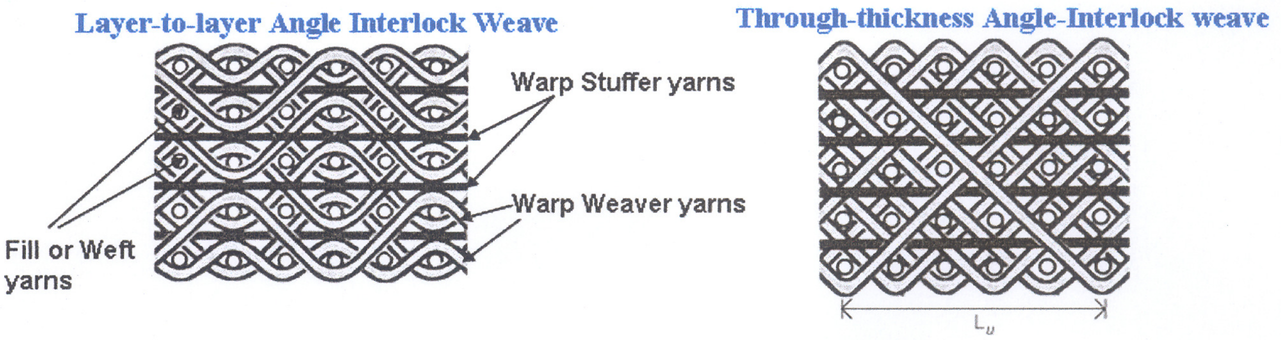

Fig.5 Fiber Architecture for a Layer-to-Layer and a Through-Thickness Angle-Interlock Weave

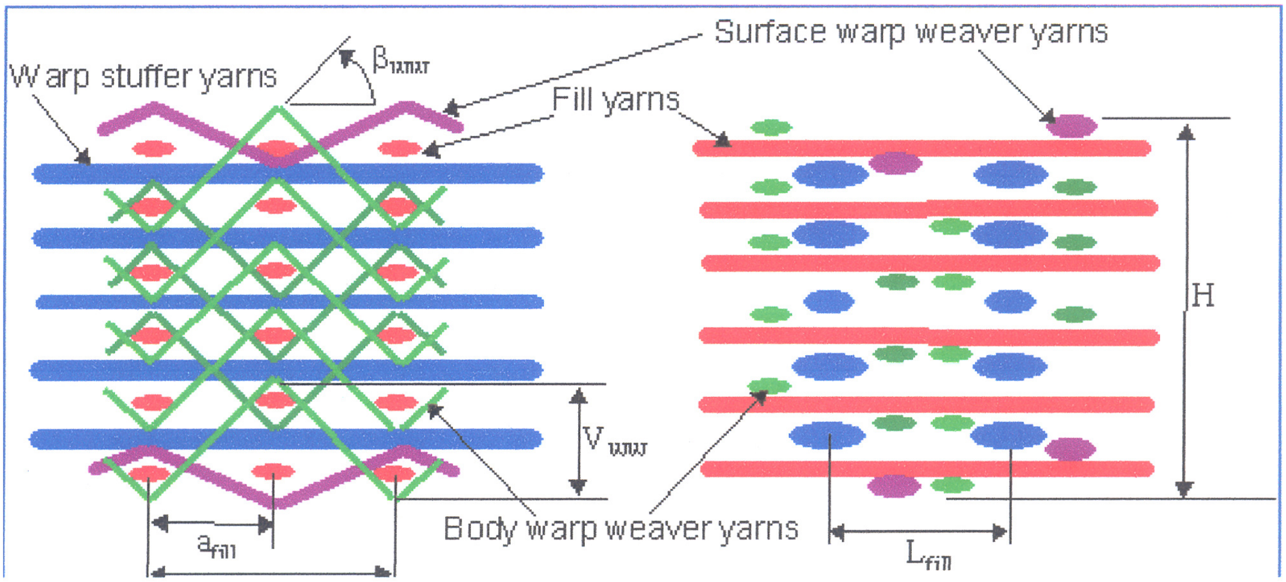

Fig.6 RUC for a Layer-to-Layer Angle-Interlock 3D Woven Composite

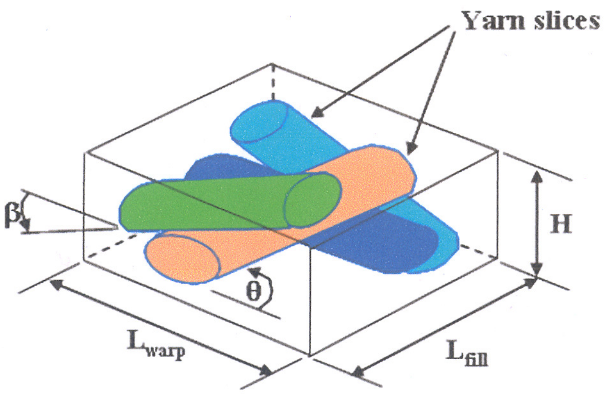

Fig.7 Multi-directionally Reinforced Composite Model for a 3D Woven Composite

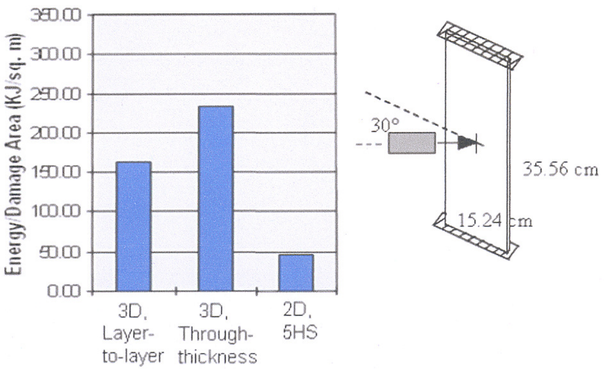

Fig.8 Comparison of High Velocity Impact Resistance of 3D Woven Composite Panels