

06M-29

M28 Fatigue

## **A Math-Based Methodology for Fatigue Longevity Prediction of 3D Woven Fiberglass Reinforced Vinyl-ester Composites**

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### **ABSTRACT**

In the DOE-Delphi Composite Chassis Cross-Member program, 3TEX 3Weave™ (3D woven fiberglass mat)/vinyl-ester (Dion 9800™) composites have been investigated as a candidate material. One of the most important mechanical properties for qualifying these composites for such applications is the mechanical fatigue longevity. In this work, a predictive math-based technology has been developed as a virtual engineering tool for the design of 3TEX 3Weave™/vinyl-ester composite parts by using a state-of-the-art simulator, GENOA™ (Generalized Optimization and Analysis) PFA (Progressive Failure Analysis), developed jointly by Alpha Star Corp and NASA. This math-based GENOA™ methodology effectively tracks the details of damage initiation, growth, and subsequent propagation to fracture, for composite structures subjected to cyclic fatigue, thereby predicting the fatigue life. The material database inputs are: the experimental data for the stress-strain curve and the S-N curve for the vinyl-ester resin, the experimentally measured volume fraction of voids in the matrix, and the Young's modulus and the S-N curve for the fiber. The last response was "reverse engineered" using GENOA™ to match values measured experimentally for a composite with a measured volume fraction of voids. The utility of the GENOA™ technology was demonstrated by predicting premature and extended fatigue lives in tensile mode of various 3TEX 3Weave (7-ply E-glass fiber)/ Dion 9800™ vinyl-ester composites. The fatigue longevity of the 3D woven ISO coupons simulated using GENOA™ agrees well with those measured in actual tensile-tensile fatigue tests using the R (minimum-to-maximum stress ratio) value of 0.1. Furthermore, GENOA™ PFA simulations quantitatively predict the effect of the void content on premature fatigue failures. Indeed, a 10% volume fraction of void defects reduces the fatigue life of the 3-D woven composite by a factor of 40 at the tensile load of 30% composite ultimate strength. On the basis of these

results, this math-based predictive methodology is currently being used by the DOE (Department of Energy)-NCC (National Composite Council) Composite Chassis Cross-Member program.

### **INTRODUCTION**

Polymer matrix composites (PMC) are finding increased applications in automotive industry due to their lightweight, relative low cost, and the evolution of automated fabrication processes (1-7). Computational simulation methods are becoming increasingly necessary for cost-saving design evaluation of composite structures. With the development of new constituent materials and fiber reinforcement configurations, 3TEX woven composites are becoming more economical for truck frame structures. Applications of 3TEX woven composites to automotive structures require reliable performance under fatigue loading caused by pressurization cycles, structural vibrations, and fluctuating surface pressures that develop due to the load environment.

Although they are strong materials, premature failures of 3TEX polymer composites in fatigue have been documented (7). Several factors can lead to premature failure: entrapped macro-voids, fiber compression due to unloading (Baushinger and crack closure effects), imperfect fiber-matrix interfacial adhesion, impurities and defects, such as micro-voids, in the matrix that reduce the matrix fracture properties, and defects in the fibers. Internal damage in composites is often initiated as matrix cracking due to tensile stresses transverse to fiber orientation, but damage initiation and progression characteristics for composite structures are diverse. In the presence of stress concentrations or defects, initial damage may also include fiber fracture. Further degradation is usually in the form of additional fiber fractures that lead to structural fracture and part failure. Because of the many possibilities with numerous

material combinations, composite geometry, fiber orientations, and loading conditions, it is essential to have an effective computational capability to predict the behavior of composite structures for any combination of these factors and boundary conditions.

The predictions of damage initiation, crack growth, proliferation, and propagation to fracture have been addressed. The PFA method is able to simulate damage initiation, damage growth, and fracture in composites under various loading, considering also the effects of residual stresses and environmental conditions (8-17). This method will be applied to determine the controlling factors for premature fatigue failure of 3TEX 3Weave™ (3-D woven fiberglass mat)/Dion 9800™ vinyl-ester composites.

The math-based methodology developed herein requires several material database as inputs to the GENOA software. The needed database are the experimental data for the stress-strain curve and the S-N curve for the vinyl-ester resin, the experimentally measured volume fraction of voids in the composites, and the Young's modulus and the S-N curve for the fiber that have been "reverse engineered" using GENOA™ to match those measured experimentally for the composite with a measured volume fraction of the voids.

In this report, we first describe the math-based methodology using the GENOA™ software. We then describe the experimental work performed to generate the required material database inputs. Finally, we discuss in detail the comparison of simulation results generated from the GENOA™ math-based methodology with those measured experimentally.

## GENOA™ MATH-BASED PREDICTIVE METHODOLOGY

### Progressive Failure Analysis (PFA)

PFA in GENOA™ takes a full-scale finite element model and accounts for the average material failure at the microscopic level. Material properties are updated for each iteration, reflecting any changes resulting from damage or crack propagation. The hierarchical approach (shown in Figure 1) implemented in the GENOA™ software allows integration of a wide range of specialized programs from micro to macro into an existing verified progressive failure and probabilistic analysis tool via a plug and play enhancement. This makes it possible to accomplish synthesis of PMC materials and structures based on progressive failure analysis and virtual testing to predict structure/component safety based on the physics and micro/macro mechanics of materials, manufacturing processes, available data, and service environments. This approach takes progressive damage and fracture

processes into account and accurately assesses reliability and durability by predicting failure initiation and progression based on constituent material properties.

The life prediction codes utilize and integrate: (a) finite element structural analysis, (b) micro-mechanics, and fracture mechanics options, (c) damage progression tracking, (d) probabilistic risk assessment, (e) minimum damage design optimization, and (f) material characterization codes to scale up the effects of local damage mechanisms to the structure level to evaluate overall performance and integrity. A significant advantage of using a life prediction tool in the design process is that the number of experimental tests at the component and substructure levels can be substantially reduced and experimental testing that is done made more efficient and effective. The damage progression module relies on a composite mechanics code (8) for composite micromechanics, macromechanics, laminate analysis, as well as cyclic loading durability analysis, and calls for a finite element analysis module that uses anisotropic thick shell elements to model laminated composites (16,17).

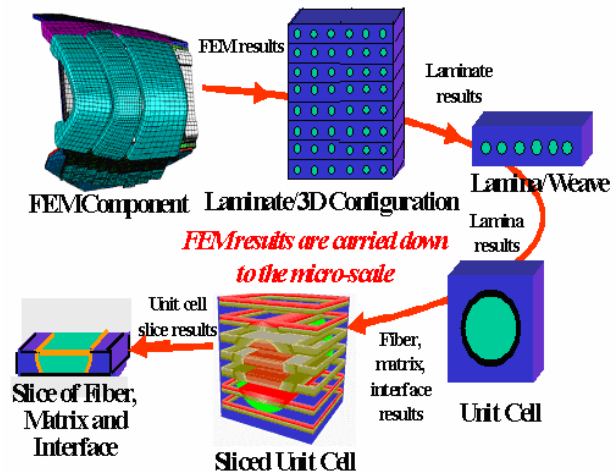


Figure 1 Hierarchical distribution of damage, stress, and strain from the macro-mechanical to the micro-mechanical levels.

### Progressive Failure Fatigue Methodology

GENOA™ permits accurate prediction of ductile fracture initiation and propagation when large-scale yielding in the material takes place. Each cycle in the simulation process begins with the definition of constituent properties from a materials databank. The composite mechanics module is called before and after each finite element analysis. Prior to each finite element analysis, the composite mechanics module computes the composite properties from the fiber and matrix constituent characteristics and the composite lay-up. The finite element analysis module accepts the composite properties that are computed at each node and performs the global structural analysis at each load increment. After a finite element analysis, the computed

generalized nodal force and moment time histories are supplied to the composite analysis module that evaluates the nature and amount of local damage, if any, in the plies of the composite laminate. The evaluation of local damage due to cyclic loading is based on simplified mathematical models embedded in the composite mechanics module (9). The fundamental assumptions in the GENOA PFA are (a) Fatigue degrades all ply strengths at approximately the same rate (10); (b) Fatigue degradation may be due to mechanical (tension, compression, shear, and bending), thermal (elevated temperature to cryogenic temperature), hygral (moisture), and combinations (mechanical, thermal, hygral, and reverse-tension compression); (c) Laminated composites generally exhibit linear behavior to initial damage under uniaxial and combined loading; (d) All ply stresses (mechanical, thermal, and hygral) are predictable by using linear laminate theory(16,17).

Ply failure modes are assessed by using margins of safety computed by the composite mechanics module via superposition of the six cyclic load ratios. The cyclic loads considered are the  $N_x$ ,  $N_y$ ,  $N_{xy}$  in-plane loads and  $M_x$ ,  $M_y$ ,  $M_{xy}$  bending moments per unit width of laminate. The lower and upper limits of the cyclic loads, the number of cycles, and the cyclic degradation parameters are supplied to the composite mechanics module at each node for the computation of a complete failure analysis based on the maximum stress criteria. Computed nodal stress resultant time-histories are used to assess the maximum and minimum values of the local load cycles and frequencies at each node. The composite mechanics module with cyclic load analysis capability evaluates the local composite response at each node subjected to fluctuating stress resultants. The number of cycles required to induce local structural damage are evaluated at each node. After damage initiation, composite properties are reevaluated based on degraded ply properties and the overall structural response parameters are recomputed. Iterative application of this computational procedure results in the tracking of progressive damage in the composite structure subjected to cyclic load increments. The number of cycles for damage initiation and the number of cycles for structural fracture are identified in each simulation iteration. After damage initiation, when the number of load cycles reaches a critical level, damage begins to propagate rapidly in the composite structure. After the critical damage propagation stage is reached, the composite structure experiences excessive damage or fracture that causes its collapse.

The degradation model is based on the assumption that all material properties may be assumed to diminish linearly on a logarithmic scale based on the number of cycles endured (9-15, 22) as shown below.

$$\frac{P}{P_o} = 1 - \beta \log N \quad (1)$$

In Equation (1),  $P$  is the current value of a property,  $P_o$  is the original value of the same property,  $\beta$  is the logarithmic degradation coefficient, and  $N$  is the number of load cycles. The log-linear degradation model is fairly effective in describing the cyclic fatigue response of a composite material that is loaded under a constant type of loading and uniform hygrothermal environment. A more general degradation model can be constructed to take into account temperature, state of stress, and other environmental effects.

## EXPERIMENTAL

### Preparation 3TEX 3Weave™ Reinforced Composite and Matrix Samples

The preparation and cure of standard 3TEX orthogonal glass fabric reinforced Dion 9800™ vinyl-ester composites has been previously documented in detail (5). N,N-dimethyl p- toluidine accelerated peroxide initiated Dion 9800™ vinyl-ester resin (Reichhold Corporation) was allowed to stand for 5 minutes after mixing to remove bubbles. It was then drawn by vacuum into a piece of 96-oz/sq. yd (3.255 kg/m<sup>2</sup>) 3Weave™ E-glass fabric mat that was sandwiched between a pair of glass plates and covered by a vacuum bag. To generate data for the GENOA™ analysis, panels without reinforcement were also made by casting between shimmed steel plates lined with aluminum foil sprayed with mold release. Because properties have been found to depend critically on the degree of cure, all samples were post-cured for 2-hours at 65°C, followed by 2-hours at 120°C, which ensured the cure reached more than 99% of completion. Although the original vinyl-resin used in the bumper formulations had been compounded with 4-wt% untreated kaolin clay for surface control and de-molding, experimental work demonstrated that the high strength requirements were clearly compromised by the presence of even small amounts of kaolin (5). Therefore, the clay was not used. In addition, wet- compression molded plaques of the 3Tex composite were also provided by Reichhold Corporation, for use as a reference low void sample. Unfortunately, as described later, analysis of the sample indicated they actually had void contents of around 10 vol%.

### Composite Geometry

The 3TEX composite with E-glass as fiber and Reichhold Dion 9800™ as matrix was used to demonstrate the cyclic fatigue simulation capability of GENOA™ for a complex, anisotropic composite structure. Reichhold Corporation's Dion 9800™ is a premium vinyl-ester resin, and its urethane-modification creates an impact resistant polymer that combines outstanding corrosion-resistance, adhesion, and excellent laminating characteristics. Figure 2 shows low magnification micrographs (negative images) of the in-

roll and cross-roll fiber configurations (18). The central in-roll bundle is almost sinusoidal with significant out-of-plane orientation. The sinusoidal nature and frequency of the z fiber is clearly visible in the lower mosaic. The upper and lower cross-roll bundles are almost semicircular, while the middle two cross-roll bundles are trapezoidal or triangular, but are still symmetric (18).

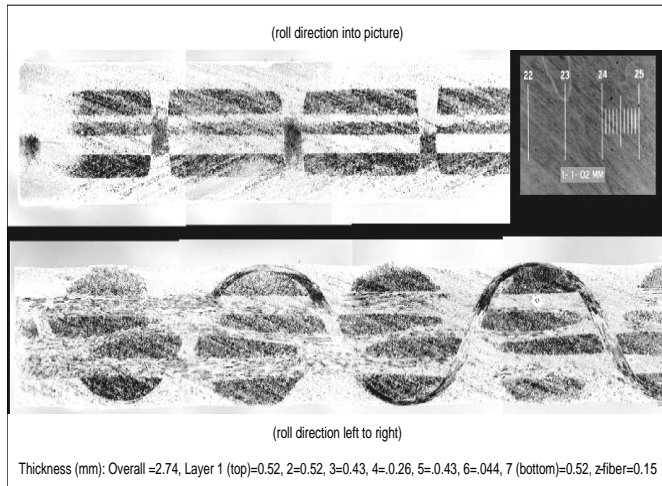


Figure 2. Microscopic sections of a 96-oz 3Tex 3 Weave/Dion 9800™ vinyl-ester composite plaque, looking into the roll direction (top) and cross roll direction (bottom).

## Fatigue Measurement

Static measurements of tensile properties of both the matrix and composite have been described previously (18). Polymer matrix fatigue tests, needed as material input for the GENOA™ software, were run at room temperature, at 5Hz, R=0.1 (R is defined as the minimum to maximum stress ratio in a cyclic fatigue test) on a hydraulic MTS Fatigue Tester. For these tests, straight-sided diamond-sawn bars 80x12.5x2-mm, were run at various tensile loadings until failure occurred (Figure 3).

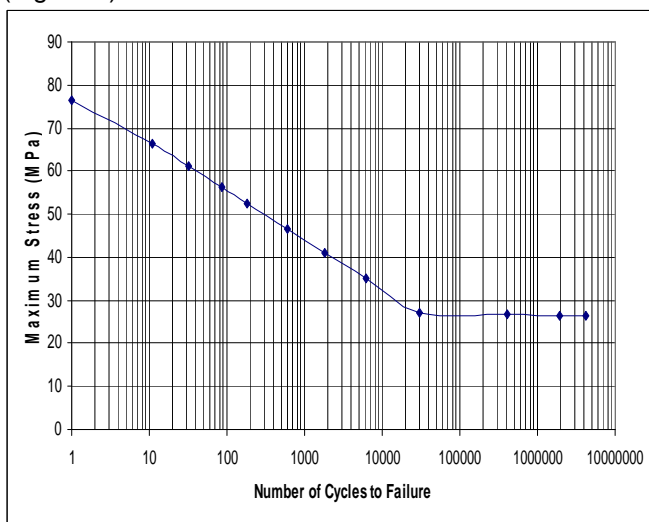


Figure 3. The experimental S-N fatigue longevity curve of Dion 9800™ resin.

The final test at 20% maximum stress was terminated after 4.5 million cycles without failure. The composite samples were tested at Oak Ridge National Laboratories, also at 5Hz and R=0.1, using 250x25x2-mm samples. Fatigue results for composites with various void contents will be presented in the section of results and discussion (Figure 7).

## Determining Matrix and Composite Void Content

Void contents were determined from careful measurements of the weight and dimensions of diamond-sawn plaques. For a binary composite system consisting of a matrix polymer and a reinforcing fiber, the void content can be accurately calculated if the relative amounts and densities of its constituents are known (6). The density of e-glass fiber is well established by Mallick (6) as 2.54 g/cc, and of the fully polymerized and post-cured Dion 9800™ polyvinyl-ester matrix the density is 1.130 g/cc (19). This latter value agrees very well with the average value of 1.127 g/cc, determined experimentally, on a series of 14 diamond sawn fatigue bars cut from selected areas of a polymer sheet cast between parallel glass plates (Table 1).

The void content of a system can be estimated by comparing its actual and theoretical densities using the following equation:

$$\text{Vol\% voids} = 100 * V_{f,v} = (\rho_c - \rho_{th}) / \rho_c \quad (2)$$

In Equation (2),  $V_{f,v}$  is the volume fraction of the voids, and  $\rho_c$  and  $\rho_{th}$  are the actual and theoretical composite densities. In a filled polymer system the theoretical density is usually known, but in a fabric-reinforced composite, it is more difficult to determine, since the thickness of the reinforcing fabric is essentially fixed, but overall thickness of the composite can vary. Hence, the ratio of polymer to reinforcement changes as a function of the composite thickness. Furthermore, because of edge effects, the total amounts of fabric and resin used do not accurately reflect their proportions in the cured composite. However, since the theoretical composite density is simply the sum of the weight of the glass and polymer in the composite divided by the total volume of glass and polymer, it can be calculated from the areal weight of glass (the weight of glass in a given area of fabric) in the composite, the area of the composite and its total volume

$$V_{\text{glass}} = (W_{\text{glass}} / \rho_{\text{glass}}) / ((W_{\text{glass}} / \rho_{\text{glass}}) + (1 - W_{\text{glass}}) / \rho_{\text{polymer}}), \quad (3)$$

The areal weight of the glass for the 96-oz 3Tex™ fabric was provided by the supplier as 3.255 kg/m<sup>2</sup> (20). Using these values, it was possible to calculate the theoretical density, the volume fraction of glass in the composite, and the volume content of the voids for any thickness of the composite (see Table 1 in the back of the paper).

## RESULTS AND DISCUSSION

### FEA Modeling 3TEX 3Weave Composite ISO Tensile Coupon

The FEA model for the ISO coupon specimen is a 5.0mm x 25.4mm panel with thickness 2.6mm. The ply schedule of this 7-ply laminate is (0/90/0/90/0/90/0), and there are two braid cards for the z-fiber, stitched in the z-direction (see Figure 2). The fiber volume fraction is set to be 55%, and the volume fraction of the voids is 10% for the original model. Finite element model of the test coupon contains 224 elements and 261 nodes

### Material Database for the Math-based Methodology

Previously, the quasi-static mechanical properties, namely, the Young's modulus, and the Poisson's ratio, for the 3TEX 3Weave/Dion 9800 composite with a void volume fraction of 10% were predicted successfully using the GENOA™ software (19). These are shown in Figures 4a and 4b, respectively. The uniaxial tensile stress-strain curves in the 11, 12 and 22 directions for the 3TEX 3Weave/Dion 9800™ vinyl-ester composite with a void volume fraction of 10% were also accurately predicted (19). This was done using the GENOA™ software with the material database inputs of the stress-strain curve of the Dion 9800™ resin (with the ultimate tensile strength of 76.53 MPa) as shown in Figure 5. The mechanical properties of the E-glass fiber are provided in the GENOA™ material databank of composite constituent material properties.

Before performing the dynamic fatigue analysis, we must again perform a similar calibration analysis (19) for the mechanical properties of the E-glass that are provided in GENOA™ material databank of composite constituent material properties using the same stress-strain data of the resin (Figure 5) (19) and the S-N fatigue longevity curve of the resin. The purpose of this calibration is to ensure the use of the same material database for predicting both the uniaxial stress-strain curves and the fatigue longevity curve of the 3TEX 3Weave™/Dion 9800™ composites with the void volume fraction of 10%. The calibrated mechanical properties of the E-glass fiber are shown in Table II. The tensile modulus of the E-glass fiber and the tensile strength shown in Table II are 12% higher and 5% lower, respectively, than those provided in GENOA™ material databank of composite constituent material properties.

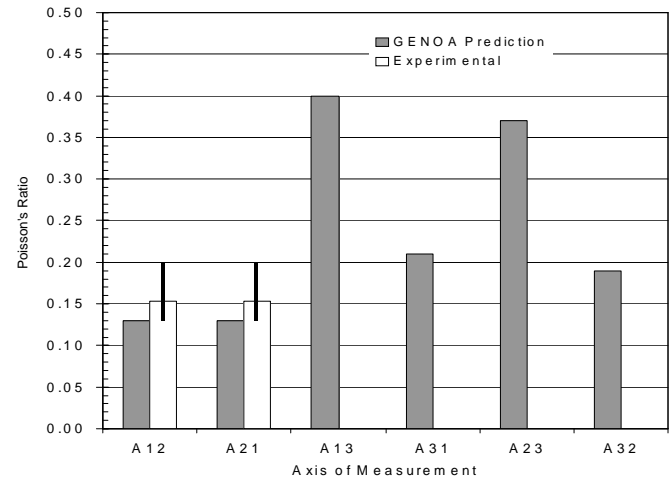
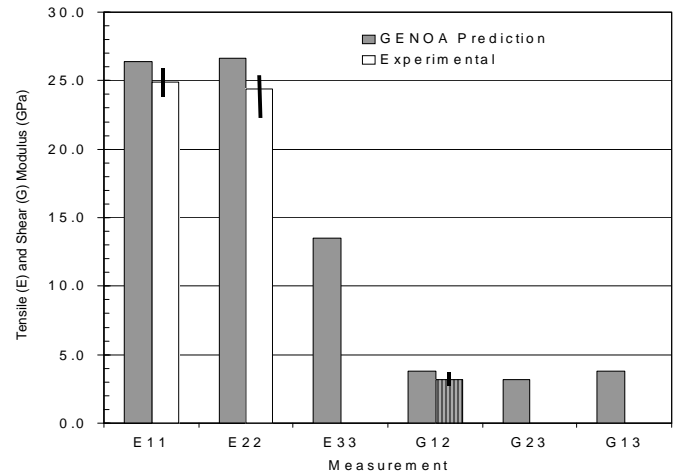


Figure 4. GENOA™ simulated results and experimental data for (a.-top) tensile and shear moduli and (b.-bottom) Poisson's ratios of 96-oz 3Tex 3Weave/Dion 9800 composites.

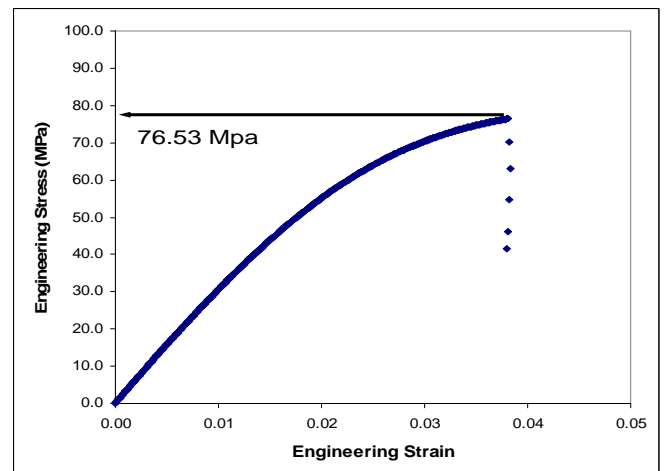


Figure 5. Experimental quasi-static uniaxial stress-strain data of Dion 9800™ resin

# Progressive Failure Fatigue Analysis

## (1) Fatigue Life of 3D Woven Composite

To perform the fatigue analysis, we need to input the following material database: (1) the stress-strain data of the resin (Figure 5) (19), (2) the calibrated mechanical properties of the E-glass (Table II), (3) the S-N fatigue longevity curve for the resin (Figure 3), and (4) the S-N fatigue longevity curve for the E-glass (Figure 6). The first and third items were measured. The fourth item, namely, the S-N fatigue longevity curve for the E-glass (Figure 6) was reverse-engineered using the GENOA™ software by matching one of the experimental S-N fatigue curves of the composites (10 vol% voids). Based on the above input material data to GENOA™, we accordingly obtained the S-N fatigue curve for the E-glass using the reverse-engineering method. The results are shown in Figure 6. It is noteworthy from Figures 3 and 6 that the maximum stress values of the E-glass fiber and the Dion 9800™ resin at 1 cycle are the same as those reported in Figure 5 and Table II, respectively. These two S-N curves are, then, employed to predict the fatigue life of the 3TEX 3Weave™/Dion 9800™ composites with other void contents (2% and 13%).

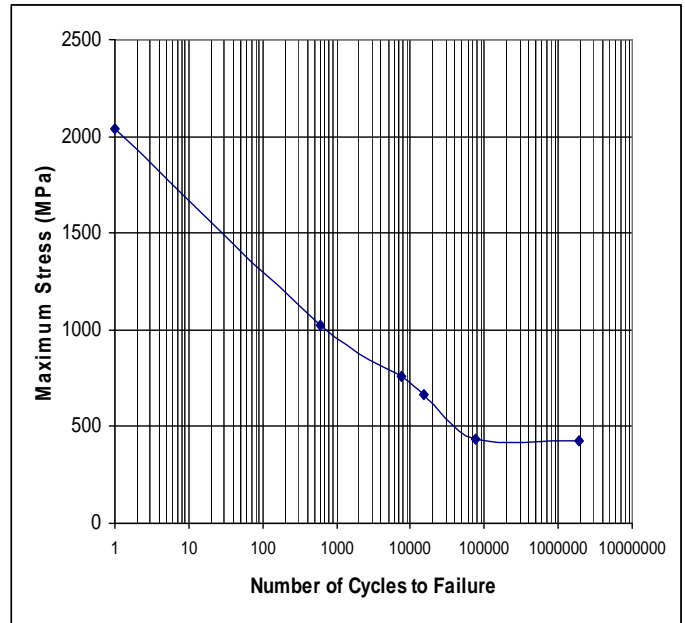


Figure 6. The GENOA™ reverse-engineered data for the S-N fatigue longevity curve for E-glass.

Table II  
Calibrated E-Glass Fiber Properties

Property	Units	Symbol	Value
Fibers / Tow	na.	$N_f$	3000
Fiber Diameter	m	$D_f$	$7.6 \cdot 10^{-6}$
Tow Density	g/cc	$\rho_f$	1.77
Axial Tensile Modulus	GPa	$E_{f11}$	89.60
Transverse Tensile Modulus	GPa	$E_{f22}$	89.60
Poisson's Ratio (12)	na	$\nu_{f12}$	0.20
Poisson's Ratio (23)	na	$\nu_{f23}$	0.20
Shear Modulus (12)	GPa	$G_{f12}$	33.31
Shear Modulus (23)	GPa	$G_{f23}$	33.31
Coefficient of Thermal Expansion			
Expansion (11)	mm/mm/C°	$\alpha_{f11}$	$5.44 \cdot 10^{-6}$
Coefficient of Thermal Expansion			
Expansion (22)	mm/mm/C°	$\alpha_{f22}$	$5.44 \cdot 10^{-6}$
Tensile Strength	GPa	$\sigma_{f11}$	2.04
Compressive Strength	GPa	$\sigma_{f11,c}$	1.45

The comparison between the experimental data and the simulation results for the S-N fatigue longevity of the 3TEX 3Weave™/Dion 9800™ composites is shown in Figure 7. These curves show (a) the 3D woven composite S-N curve, labeled Experimental I, obtained from Reichhold and was subjected to the maximum tensile loads of 30%, 50%, and 70% of the tensile strength of the composites. This data was used for “reverse engineering” S-N curves of resin and fiber. As discussed in the experimental section, the volume

fraction of the voids is 10%. (b) Fatigue data, labeled Experimental II, is from carefully manufactured test coupons subjected to the same tensile fatigue loading as in the case of Experimental I. The average volume fraction of the voids of 2% was determined experimentally. (c) Fatigue data, labeled Experimental III, is from the worst performing test coupons, and contained 13% volume fraction of the voids. The simulated fatigue life for the 3D woven composite coupon showed excellent correlation with the experimental data obtained with low void (2%) and high void (10% and 13%) coupons.

Both the simulation and experimental data show that fatigue life is dominated by the void content and applied stress level. As seen in Table III, there is very little difference between composites with 2%, 10%, or 13% voids at high stress levels (70% ultimate strength). This is attributed to the mechanism that at a high stress level, the load is mainly carried by the fibers. The damage is mainly generated at the matrix-fiber interface, which is difficult to grow and propagate through the matrix. Therefore, the fatigue longevity does not depend on the void concentration in the matrix [23-36]. However, at a lower stress level, the void content becomes increasingly important. At tensile loading of 30% ultimate strength, samples with 2% voids survive over 40 times longer than the samples with 10% voids (Figure 7). Further more, recent test data from ORNL has shown that the composites with 2% voids remain unfailed after 2.5 million cycles at tensile loading of 20% ultimate strength [21]. This is because at a low stress level, the load carried by the fibers decreases, and the damage is mainly generated in the matrix with growth of micro-cracks throughout the composite specimen [23-36].

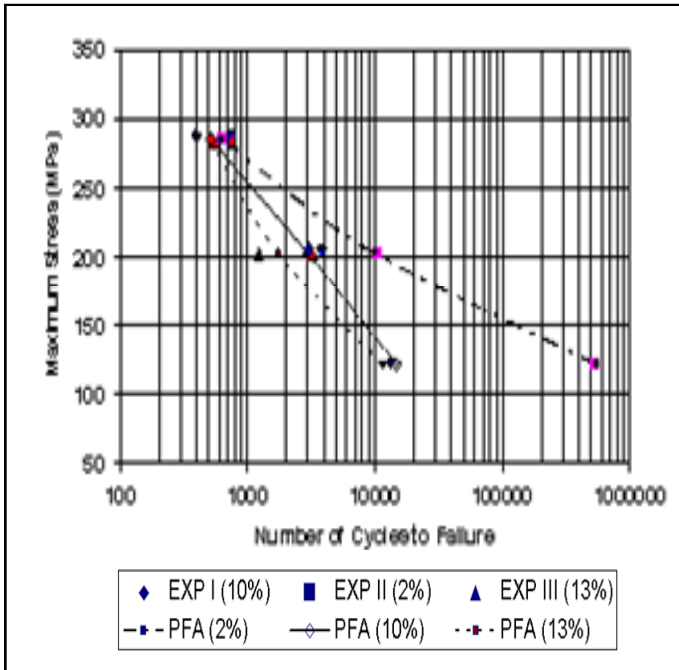


Figure 7. The comparison between the experimental data and the simulated results for the S-N fatigue longevity of the 3TEX 3Weave/Dion 9800 composites

It is also noteworthy that in the GENOA PFA simulation, the void size and its distribution are assumed to be uniform throughout the composites. Based on the good agreement between the simulation and the experimental data, we may conclude that the effect of the void size difference and void distribution on fatigue life of composites is seemingly insignificant for this composite system investigated. Certainly, the significance of the above effect of the void size difference and void distribution on fatigue life of composites will require further investigation.

**Table III**  
Comparison of Fatigue Life Cycles for Composites with High and Low Void Volume Concentrations

Load	Number of cycles to failure				Life increase (times)
	10% void		2% void		
	Test Ave.	GENOA	Test	GENOA	
30%	13,200	14,770	540,000	550,000	40.9
50%	3,421	2,969	10,500	10,080	3.1
70%	572	513	630	620	1.1

## (2) Failure Mechanisms of 3D Woven Composite

The integrated composite analyzer (ICAN) developed by NASA Glenn (15) computes the longitudinal compressive strength,  $S_{11C}$ , based on three different criteria, namely, rule of mixtures, fiber micro-

buckling, and de-lamination. The minimum value determined using these three criteria is, then, returned as  $S_{11C}$ . The equations for the three criteria are shown below (9-11).

$$S_{11C}(\text{rule\_of\_mixtures}) = S_{fc} (\phi_f + \phi_m E_m / E_{f11}) \quad (4)$$

$$S_{11C}(\text{fiber\_microbuckling}) = \frac{F_2 G_m}{1 - \phi_f \left(1 - \frac{G_m}{G_{f12}}\right)} \quad (5)$$

$$S_{11C}(\text{delamination}) = (13 S_{112} + S_{mc}) \quad (6)$$

where  $S_{fc}$  or  $S_{mc}$  is the compressive strength of the fiber or matrix, respectively,  $\phi_f$  or  $\phi_m$  is the volume fraction of the fiber or matrix, respectively,  $E_m$  Young's modulus of the matrix,  $E_{f11}$  is the fiber longitudinal Young's modulus,  $G_m$  or  $G_{f12}$  is the shear modulus of the matrix or fiber, respectively,  $S_{112}$  is the transverse strength, and  $F_2$  is a coefficient defined by  $\phi_f$  and  $\phi_m$  as shown below.

$$F_2 = 1 - ((4/\pi) \cdot (\phi_f / \phi_m))^{0.5} \quad (7)$$

Figure 8 shows the predicted damage and failure mechanisms of a 3D woven composite coupon loaded to 30% of quasi-static ultimate strength. Firstly, as the fatigue cycle reaches 12500, the resin matrix starts damaging due to the transverse tensile failure. After resin damage occurs, the resin shear modulus drops to zero, and this leads to fiber micro-buckling induced longitudinal compressive damage in the composites. As fatigue cycles continue to increase, the fibers break due to longitudinal tensile failure as shown in Figure 8. Finally, the composite coupon fails catastrophically.

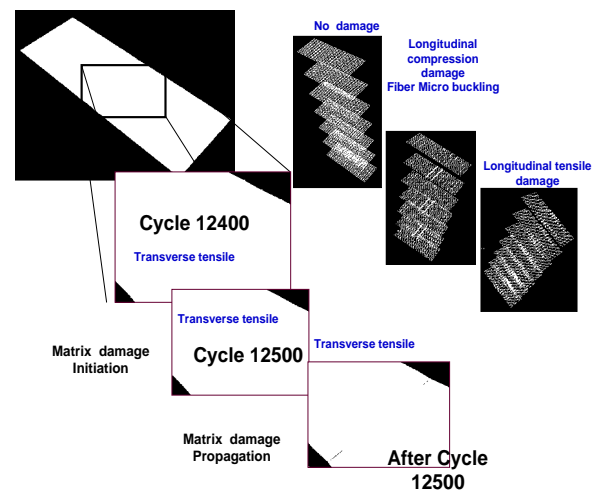


Figure 8. The failure mechanisms for the tensile-tensile fatigue of the 3TEX 3Weave™/Dion 9800™ vinyl-ester composite tensile test coupon.

### (3) Probabilistic Analysis of 3D Woven Composite

GENOA™ Probabilistic analysis was used to determine the effects of manufacturing anomalies on the fatigue life. Five material design factors were considered, namely, braid angle, fiber volume, fiber shear modulus, matrix shear strength, and void fraction. As an example, Figure 9 shows the probability sensitivity of these factors under tensile loading of 30% of the composite ultimate strength. The probabilistic results

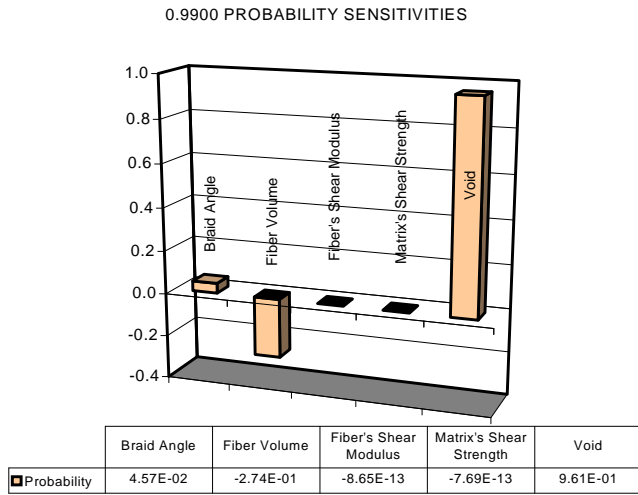


Figure 9. GENOA™ probabilistic analysis of the 3TEX 3Weave™/Dion 9800™ vinyl-ester composites ISO tensile specimen under tensile fatigue at maximum stress of 122 MPa. also show that voids are the controlling factor that dominantly affects the fatigue longevity of the 3TEX /vinyl-ester composite.

### CONCLUSIONS

Based on the results from the new math-based predictive methodology on the mechanical fatigue longevity of the 3TEX 3Weave (3D woven fiber glass mat) Dion 9800™ vinyl-ester composites and the general perspective of the available computational simulation method, we summarize the following key findings:

- (a) A GENOA™ math-based methodology has been developed for predicting the mechanical fatigue longevity of polymer matrix composites (PMC). The fatigue longevity of the 3TEX/vinyl-ester composite tensile coupon simulated using this methodology agrees well (error being less than 5%) with that measured experimentally.
- (b) This methodology has also been applied to track the details of damage initiation, growth, and subsequent propagation to fracture for the tensile coupon composite subjected to cyclic fatigue.
- (c) Premature failure of composites is mainly attributed to the distributed voids. Increasing the void concentration drastically reduces the fatigue life of the 3TEX composites, e.g., a 10% void volume fraction reduces the fatigue longevity of the composites by 40 times relative to samples with 2% voids.
- (d) Probabilistic analysis for the fatigue test of the 3TEX/vinyl-ester composite coupon using five material design factors (fiber braid angle, fiber volume fraction, fiber shear modulus, matrix shear modulus, and void content) also demonstrates that voids are the controlling factor for the premature failure of the 3TEX composite coupons subjected to cyclic fatigue.
- (e) The new math-based methodology is effective and efficient, e.g., it takes about 80 man-hours in this investigation to finish the GENOA PFA simulation on the tensile coupon model (containing 200 shell elements) subject to three levels of fatigue loading.
- (f) The method is also flexible, because it is applicable to all types of constituent materials, structural geometry, and loading. The mechanical fatigue longevity and the static mechanical properties of hybrid composites, homogeneous materials, as well as laminated, stitched, woven, and braided composites, can now be predicted accurately and cost-effectively.

**Table I**  
**Void Content of Dion 9800™ Vinyl-Ester Matrix and**  
**96-oz 3Tex 3Weave™ E-Glass Reinforced Composite Fatigue Samples**

Experimental glass glass	Sample	Theoretical W <sub>f</sub> (g/cc)	V <sub>f</sub> glass	Density glass	W <sub>f</sub> (g/cc)	V <sub>f</sub> (vol% )	Density
<u>Reichhold Low Void Matrix Fatigue Samples - Dion 9800-00, no glass cloth, cast plaque</u>							
M1	0.00	0.00	1.110	0.00	0.00	1.130	1.80
M2	0.00	0.00	1.119	0.00	0.00	1.130	1.01
Ave			1.114			1.130	1.41
<u>Reichhold Fatigue Samples - good areas: Average of 14 individual cut bars, cast plaque</u>							
Ave 14 RM1 bars	0.00	0.00	1.127	0.00	0.00	0.00	1.130
<u>Reichhold High Void Fatigue Samples --96oz 3Tex-Dion 9800, wet mold compression</u>							
R3-78wt%		0.79	0.54	1.71	0.72	0.53	1.88
R4-82wt%		0.85	0.58	1.72	0.76	0.58	1.95
Ave							10.3
<u>DRL Low Void Fatigue Samples - 96oz 3Tex-Dion 9800 no clay VARTM samples</u>							
04042801 full sheet	0.66		0.45	1.75	0.65	0.45	1.77
04042801A (UL)	0.67		0.46	1.76	0.66	0.46	1.79
04042801B (UR)	0.67		0.47	1.77	0.66	0.47	1.79
04042801C (LL)	0.66		0.45	1.74	0.65	0.45	1.76
04042801D (LR)	0.66		0.46	1.75	0.65	0.46	1.77
Ave	0.66	0.46	1.76	0.66	0.46	1.78	1.1

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