NANO-FIBER REINFORCED ENHANCEMENTS IN COMPOSITE POLYMER MATRICES

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ABSTRACT

Nano-fibers are used to reinforce polymer matrices to enhance the matrix dependent properties that are subsequently used in conventional structural composites. A quasi isotropic configuration is used in arranging like nano-fibers through the thickness to ascertain equiaxial enhanced matrix behavior. The nano-fiber volume ratios are used to obtain the enhanced matrix strength properties for 0.01, 0.03, and 0.05 nano-fiber volume rates. These enhanced nano-fiber matrices are used with conventional fiber volume ratios of 0.3 and 0.5 to obtain the composite properties. Results show that nano-fiber enhanced matrices of higher than 0.3 nano-fiber volume ratio are degrading the composite properties.

1. INTRODUCTION

Nano-fiber reinforced matrices are recently of research interest in the composite's community. One nano-fiber properties which underlies this research is their high tensile modules and tensile strength, respectively about one billion psi and one million psia, respectively. SAMPE Annual Spring conferences of the last 5 years are examples of these research activities [1]. The majority of these proceedings paper are devoted to processing techniques because of the conglomerating difficulties associated with the production of the nano-fibers [2]. Research papers in these conferences indicate the difficulty for disbursing the conglomeration, to obtain enhanced matrices with aligned nano-fibers [3]. In the 2003 SAMPE Spring Conference one paper was specifically describing some success with nano-fiber conglomeration nano-fiber dispersion. This paper sites modules and tensile strength properties which are about the values that were reported at the beginning of the Introduction [4]. Other papers covered fatigue and creep [5,6] for nano-fiber adoptive structures [7]. One recent paper [8] describes a multiscale simulation of nano-fiber reinforced with no results. Herein results are obtained by using the simulation method [9] updated for this application.

Simulation results presented in this paper are for aligned nano-fiber through the thickness nano-fiber composites. Results obtained indicate the properties are equal through the thickness and the strengths are also equal in longitudinal and transverse direction.

2. FUNDAMENTAL CONCEPT

The fundamental concept in the simulator is that all elastic properties and strength properties of the enhanced matrix be equal. To simulate the properties the logic diagram was employed as shown in Figure 1.

The input data used in the simulation are shown in Tables 1 and 2. The output data from the simulation is shown in Table 3. The results in Table 3 illustrate that the enhanced matrix is properly simulated. Another condition that must be satisfied by the enhanced matrix simulation

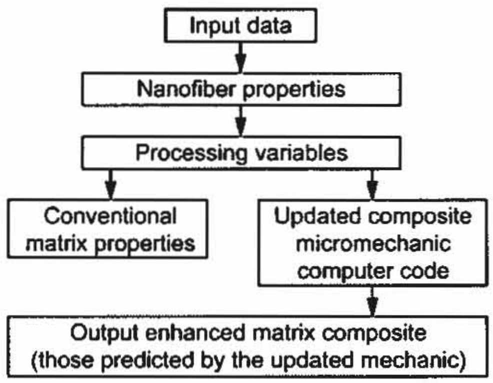

Figure 1. Logic diagram of enhanced matrix.

Table 1. Nano-fiber data[a]

1	Number of fibers per end	Nf	=	1.0000000E+06	Number
2	Filament equivalent diameter	df	=	3.0000000E-07	inches
3	Weight density	Rhof	=	6.0000000E-01	lb/in**3
4	Normal moduli (11)	Ef11	=	1.0000000E+09	psi
5	Normal moduli (22)	Ef22	=	4.0000000E+07	psi
6	Poisson's ratio (12)	Nuf12	=	2.0000000E-01	non-dim
7	Poisson's ratio (23)	Nuf23	=	3.5000000E-01	non-dim
8	Shear moduli (12)	Gf12	=	2.0000000E+07	psi
9	Shear moduli (23)	Gf23	=	1.5000000E+07	psi
10	Thermal expansion coef. (11)	Alfaf11	=	-6.0000000E-08	in/in/F
11	Thermal expansion coef. (22)	Alfaf22	=	6.0000000E-06	in/in/F
12	Heat conductivity (11)	Kf11	=	4.0000000E+02	BTU/hr/in/F
13	Heat conductivity (22)	Kf22	=	4.0000000E+01	BTU/hr/in/F
14	Heat capacity	Cf	=	1.7000000E-01	BTU/lb/F
15	Dielectric strength (11)	Kef11	=	0.0	Volts/in
16	Dielectric strength (22)	Kef22	=	0.0	Volts/in
17	Dielectric constant (11)	Gammaf11	=	0.0	in/Volts
18	Dielectric constant (22)	Gammaf22	=	0.0	in/Volts
19	Capacitance	Cef	=	0.0	Volts
20	Resistivity	Ref	=	0.0	Ohm-in
21	Tensile strength	SfT	=	1.0000000E+06	psi
22	Compressive strength	SfC	=	9.0000000E+05	psi
23	Shear strength	SfS	=	5.0000000E+05	psi
24	Normal damping capacity (11)	psi11f	=	3.0000000E-02	%Energy
25	Normal damping capacity (22)	psi22f	=	4.0000000E-01	%Energy
26	Shear damping capacity (12)	psi12f	=	4.0000000E-01	%Energy
27	Shear damping capacity (23)	psi23f	=	8.0000000E-01	%Energy
28	Melting temperature	TMf	=	6.0000000E+03	F

[a]Modulus and strength are up to date. All others are from a conventional AS graphite fiber.

Table 2. Conventional intermediate modulus high-strength (IMHS) epoxy

1	Weight density	Rhom	=	4.4000000E-02	lb/in**3
2	Normal modulus	Em	=	5.0000000E+05	psi
3	Poisson's ratio	Num	=	3.5000000E-01	non-dim
4	Thermal expansion coef.	Alfa m	=	3.6000000E-05	in/in/F
5	Heat conductivity	Km	=	8.6810000E-03	BTU/hr/in/F
6	Heat capacity	Cm	=	2.5000000E-01	BTU/lb/F
7	Dielectric strength	Kem	=	0.0	Volts/in
8	Dielectric constant	Gammam	=	0.0	in/Volts
9	Capacitance	Cem	=	0.0	Volts
10	Resistivity	Rem	=	0.0	Ohm-in
11	Moisture expansion coef.	Betam	=	3.3000000E-03	in/in/%Moisture
12	Diffusivity	Dm	=	2.1600000E-07	in**2/hr
13	Saturation	Mm	=	0.0	%Moisture
14	Tensile strength	SmT	=	1.5000000E+04	psi
15	Compressive strength	SmC	=	3.5000000E+04	psi
16	Shear strength	SmS	=	1.3000000E+04	psi
17	Allowable tensile strain	eps mT	=	2.0000000E-02	in/in
18	Allowable compr. strain	eps mC	=	5.0000000E-02	in/in
19	Allowable shear strain	eps mS	=	3.5000000E-02	in/in
20	Allowable torsional strain	eps mTOR	=	3.5000000E-02	in/in
21	Normal damping capacity	psiNm	=	6.6000000	%Energy
22	Shear damping capacity	psiSm	=	6.9000000	%Energy
23	Void heat conductivity	Kv	=	2.2500000E-01	BTU/hr/in/F
24	Glass transition temperature	Tgdr	=	4.2000000E+02	F
25	Melting temperature.	TMm	=	0.0	F

is that its failure (fracture) properties are predicated by a combined stress failure (fracture) criterion must be equal longitudinal/transverse tension/compression and that their failure (fracture) modes must be all fiber-induced. This is illustrated in Table 4. It is interesting to note in Table 4 that (1) that all fracture modes are fiber induced, (2) that for relative low nano-fiber volume ratio the tensile strengths are slightly larger than the compressive strengths, and (3) however as the volume ratio increases these two strengths increase and become equal. It is also interesting to note that a maximum nano-fiber ratio exists between 0.3 and 0.6 volume ratio of the enhanced matrix since the strengths of the enhanced matrix decreases to about 70% of their values at the 0.3 volume ratio.

Apparently then, the simulation is accurate since the elastic properties are equal as will be illustrated later; the tension/compression strength are of equal mag0nitude and they are all fiber induced. These findings are consistent with the conditions stated previously except for the maximum nano-fiber volume ratio which most probably occurs prior to nano-fiber interference with the conventional fibers.

Table 3. Composite properties

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Laminate Configuration [0/45/-45/90]S
------------------------------------------------------------------------
Composite properties - Valid only for constant temperature through thickness
Lines   1 to 31  3-D composite properties about material axes
Lines  50 to 79  2-D composite properties about structural axes
------------------------------------------------------------------------
  1   RHOC       6.0680E-02
  2   TC         4.0000E-02       50   CC11       1.1850E+07
  3   CC11       1.0542E+07       51   CC12       3.9401E+06
  4   CC12       3.9563E+06       52   CC13       0.0
  5   CC13       0.0              53   CC22       1.1850E+07
  6   CC22       1.0542E+07       54   CC23       5.4570E-10
  7   CC23       0.0              55   CC33       3.9548E+06
  8   CC33       1.0814E+06       56   EC11       1.0540E+07
  9   CC44       2.2347E+05       57   EC22       1.0540E+07
 10   CC55       2.2347E+05       58   EC12       3.9548E+06
 11   CC66       3.9563E+06       59   NUC12      3.3251E-01
 12   CTE11      0.0              60   NUC21      3.3251E-01
 13   CTE22      0.0              61   CSN13     -4.5881E-17
 14   CTE33      0.0              62   CSN31     -1.7216E-17
 15   HK11       2.4035E-01       63   CSN23      1.3798E-16
 16   HK22       2.4035E-01       64   CSN32      5.1776E-17
 17   HK33       3.5984E-04       65   CTE11      1.3136E+09
 18   HHC        9.0508E-03       66   CTE22      1.3136E+09
 19   EC11       1.0542E+07       67   CTE12      4.0204E-08
 20   EC22       1.0542E+07       68   HK11       6.0087
 21   EC33       1.0814E+06       69   HK22       6.0087
 22   EC23       0.0              70   HK12      -3.4694E-16
 23   EC31       2.2347E+05       71   HHC        2.2627E-01
 24   EC12       3.9563E+06       72   DPC11      1.9405E-07
 25   NUC12      3.3233E-01       73   DPC22      1.9405E-07
 26   NUC21      3.3233E-01       74   DPC33      1.7859E-07
 27   NUC13      4.2385E-01       75   DPC12     -3.2312E-25
 28   NUC31      4.3477E-02       76   BETAC11    1.1911E+11
 29   NUC23      4.2385E-01       77   BETAC22    1.1911E+11
 30   NUC32      4.3477E-02       78   BETAC33    1.8054E+10
 31   ZCGC       2.0000E-02       79   BETAC12    3.6884E-06
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Table 4. Enhanced matrix failure modes (SI Units)

Nano-fiber volume ratio	Longitudinal strength		Transverse strength		
	Tension	Compression	Tension	Compression	Shear
0.01	26.2 (FT)	24.2 (FC)	26.2 (FT)	24.2 (FC)	2.6 (FC)
0.03	73.1 (FT)	65.6 (FC)	73.1 (FT)	65.6 (FC)	49.7 (FC)
0.05	94.5 (FT)	94.5 (FC)	94.5 (FT)	94.5 (FC)	77.3 (FC)
0.10	143.5 (FT)	125.6 (FC)	143.5 (FT)	125.6 (FC)	93.4 (FC)
0.30	516.8 (FT)	516.8 (FC)	516.8 (FT)	516.8 (FC)	258.1 (FC)
0.60	371.2 (FT)	371.2 (FC)	371.2 (FT)	371.2 (FC)	185.6 (FC)

FT = Tension   FC = Compression

3. SPECIAL FEATURE OF ENHANCED MATRICES

The special features described below are those of nano-fibers enhanced matrix properties and those internal to it of the kind that is shown in Figure 2. The internal nano stress are shown in Figure 3. Note that some of the matrix stress is the longitudinal direction reaches about 517.5 GPA (75 ksi). This indicates that this matrix has already cracked. The corresponding nano-fiber stress 275 GPA (40 ksi) which is substantially lower than the corresponding nano-fiber stress. The transverse internal nano stress in the matrix between the fibers reaches about a nano stress in compression of about 586.5 GPA (85 ksi). This large value indicates that the inter nano-fiber matrix is already being crushed. The other three nano stresses are relatively very low and may be neglected. Figure 5 shows the nano interfaced stresses along a 45^{o} angle from the horizontal. The point to be noted in this Figure 5 is that both of these stresses reach magnitudes of 310 MPA (45 ksi) tension and 310 MPa (45 ksi) compression in the matrix region. These values definitely illustrate that the matrix is in trouble.

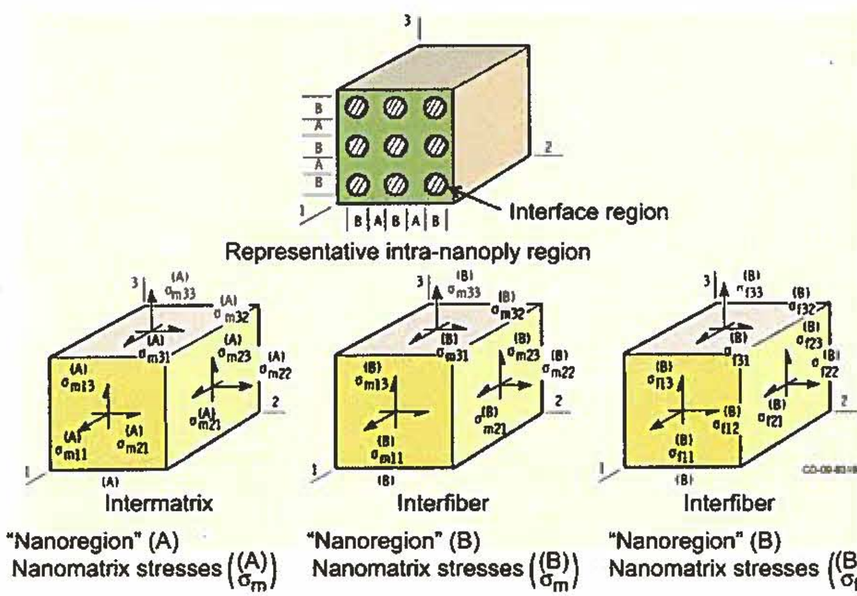

Figure 2. Enhanced matrix internal sub-element and definition/notation of nano-stresses.

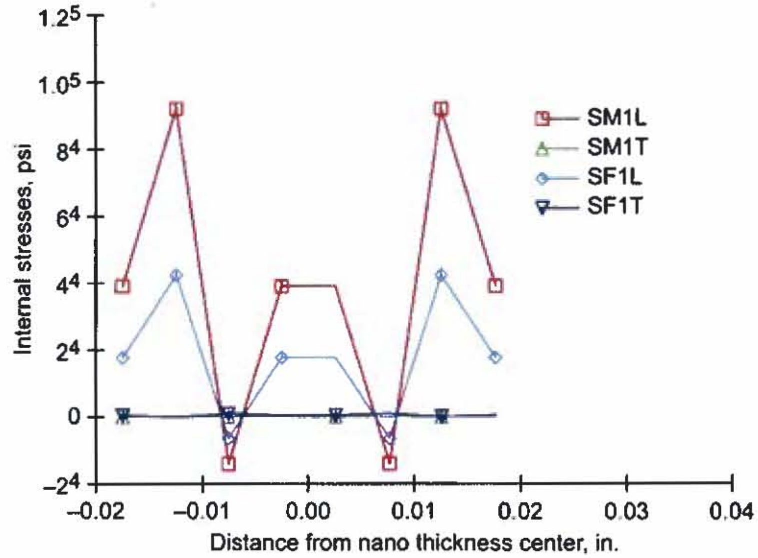

Figure 3. Internal enhanced matrix stresses (see Fig. 2) 1 lb/m^2 = 6.9 Pa; 1 in. = 2.54 cm.

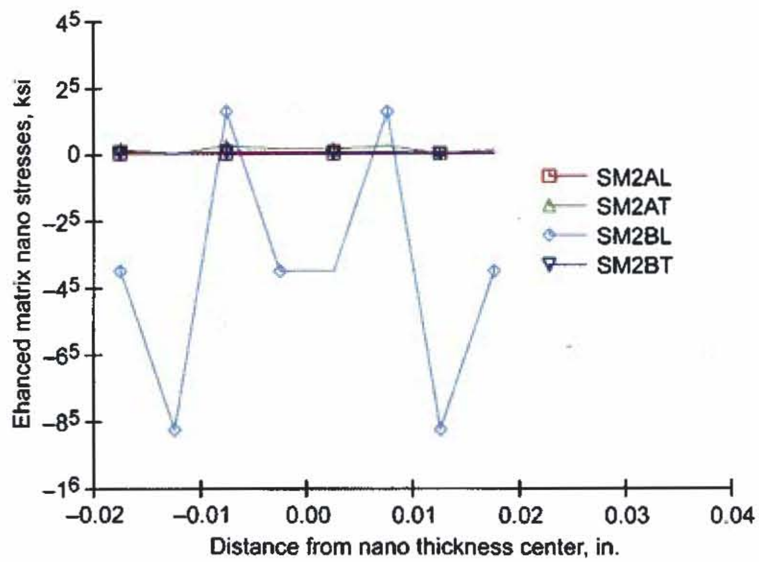

Figure 4. Enhanced matrix internal stresses (1 ksi = 6.9 MPa; 1 in. = 2.54 cm).

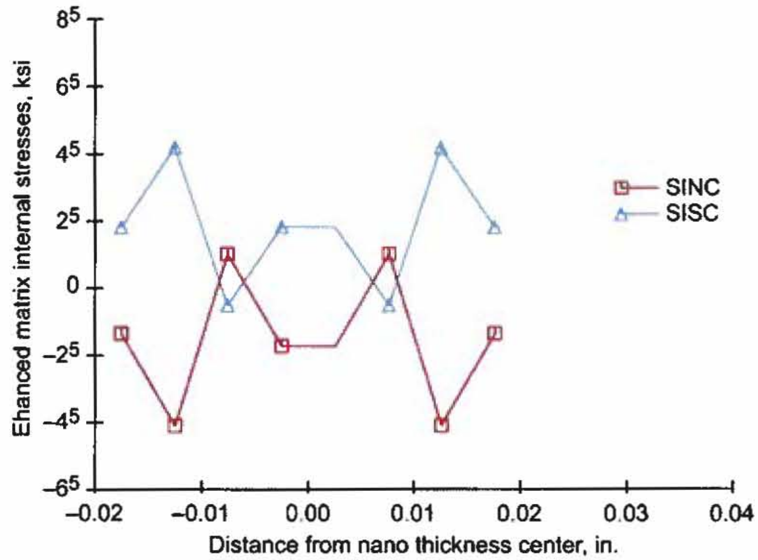

Figure 5. Enhanced matrix internal stresses (1 ksi = 6.9 MPa; 1 in. = 2.54 cm).

4. INTEGRATION WITH COMPOSITE

In this part of the paper, we will describe the integration of enhanced matrixes with composite mechanics codes. The integration is illustrated in Figure 6 below:

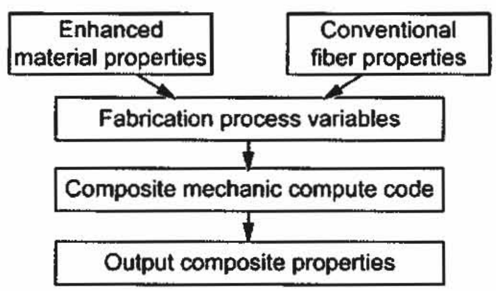

Figure 6. Logic diagram for integration of enhanced matrix properties to composite mechanics codes.

The enhanced matrix properties that were obtained from the nano-fiber simulation (Figure 1 in Table 4) are used as inputs to the composite mechanics code shown in Figure 6. Then the input data is confined with conventional fiber of larger diameter to the fiber/enhanced matrix composite properties. It is understood that this integration requires human intervention for implementation. That is the enhanced matrix with specific nano-fiber volume ratio in a specific matrix needs to be obtained first. Subsequently, this enhanced matrix is entered as input to the composite mechanics code just like any other matrix is entered. The specific composite fabrication variables loading conditions, environmental conditions are inputted required in the computer code. The composites code used for this second simulation is an in-house coded called IAN/JAVA [2]. Next the computer composite is run and the output is the required fiber/enhanced matrix composite properties. Some of these properties are illustrated in the following figures.

The composite modules are shown in Figure 7. Note that all three models are straight lines as was mentioned in one condition that the enhanced matrix should satisfy. The composite correspondence poison's ratios are illustrated in Figure 8. Note that all 3-poisons ratios are straight lines.

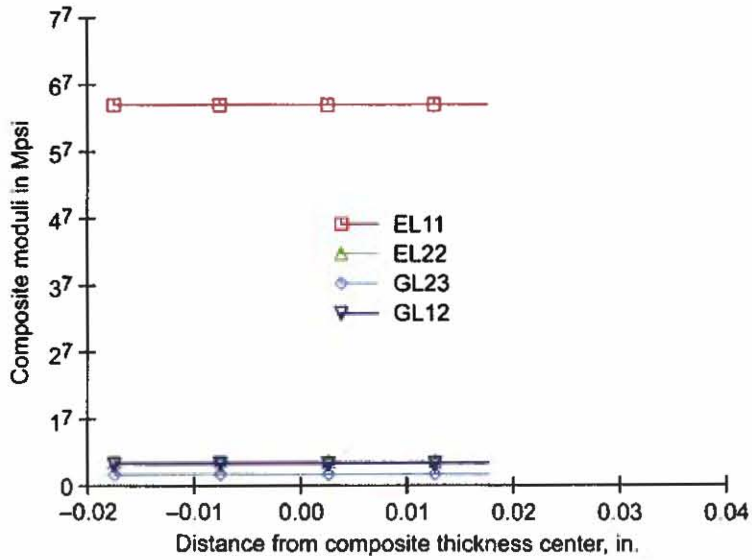

Figure 7. Moduli of AS graphite fiber/enhanced matrix composite (Fur 0.3; 1 Mpsi = 6.9 GPa; 1 in. = 2.54 cm)

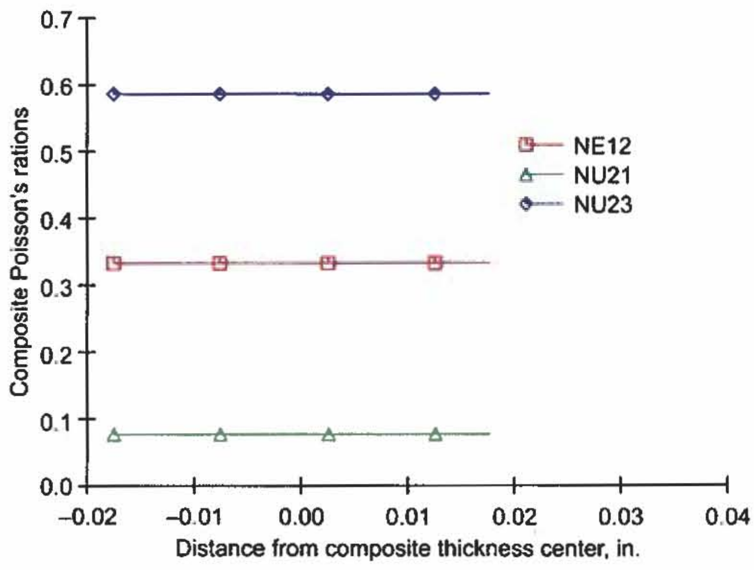

Figure 8. AS graphite fiber/enhanced matrix composite.

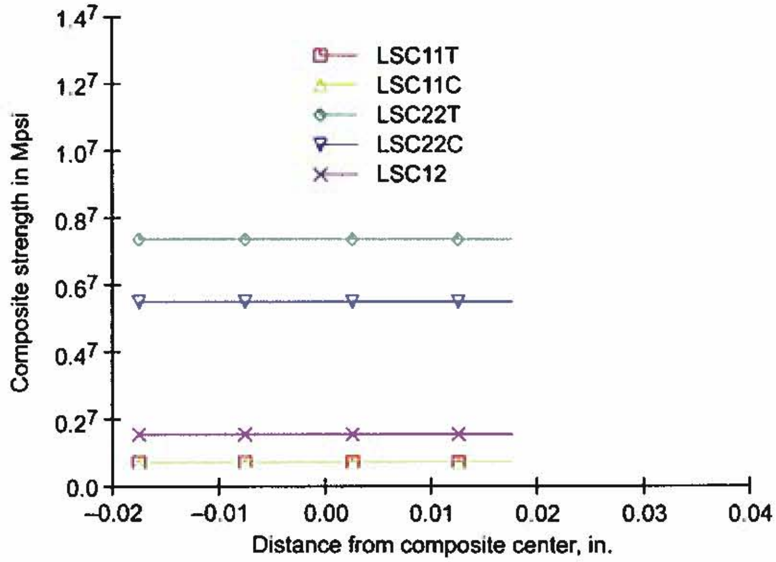

Figure 9. AS graphite fiber/enhanced matrix composite strengths (Fur = 0.3; 1 Mpsi = 6.9 GPa; 1 in. = 2.54 cm).

The composite strengths are shown in Figure 9. It is interesting to note in Figure 9 that the strength are all straight lines, the longitudinal tensile is equal the compressive, the transverse tensile is higher than the transverse compressive and the sheer strength is higher than either the longitudinal tensile or compressive strengths.

This is an illustration of the enhanced matrix properties. The composite stresses are shown in Figure 10. Note that these stresses follow the composite laminate configuration of [(0/±45/90]s. Also note that the (II) stress dominates the stresses.

The last composite feature is the combined stress failure criteria. This is shown in Figure 11. Where two criteria are shown, the modified distortion energy and the Hoffman stress criterion. Both of these failure criteria are copies of each other. This is also a result of the enhanced matrix strengths.

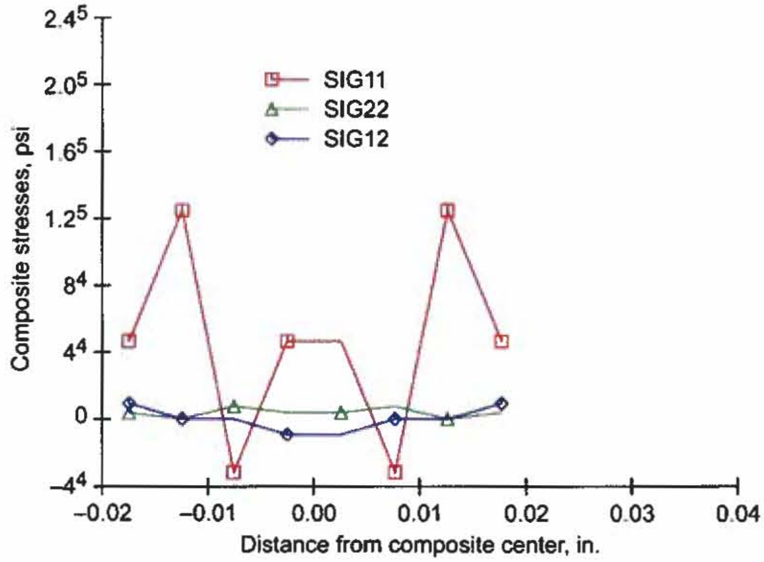

Figure 10. AS graphite fiber/enhanced matrix composite (Fur = 0.3; 1 psi = 6.9 Pa; 1 in. = 2.54 cm).

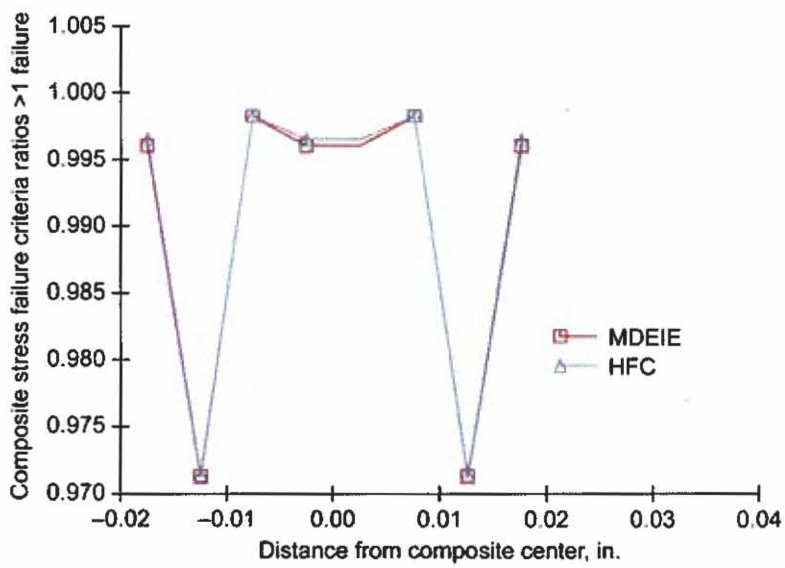

Figure 11. Combined stress failure criteria-modified distortion energy and Huffman AS graphite fiber/enhanced matrix composite.

5. CONCLUDING REMARKS

The following remarks follow from the previous discussion:

1. The enhancement of matrices with nano-fibers can be simulated by a modified composites mechanics code.

2. The simulation is performed on a matrix with (0/±45/90]s nano-fiber arrangement through the nano composite thickness.
3. Results obtained showed that enhancement of one and two orders of magnitude are obtained for the enhanced matrix.
4. The integration of the enhanced matrix with conventional fiber composite is straight forward.
5. The advantage of enhanced matrix used in conventional fiber composite simulation is illustrated in that that the transverse composite strength is greater than the longitudinal composite tensile and compressive strength.
6. Two combined stress failure criteria—modified distortion energy with Hoffman are exact copies of one another.

6. REFERENCES

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