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Effect of curing stresses on the behaviour of fibre reinforced plastic composites under biaxial loading

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Residual stresses are induced in fibre reinforced plastic (FRP) composites during fabrication and environmental exposure. The curing residual stresses induced during fabrication are mainly due to the thermal expansion mismatch of the constituents. The residual stresses can be either microresidual or macroresidual stresses. Macroresidual stresses in 0° plies and 90° plies of $[90/0]_s$ symmetric cross-ply laminates are calculated starting with ply elastic and thermal properties for different material systems. The calculated curing stresses in Kevlar49/Epoxy unidirectional tape plies in the transverse direction are more than the transverse strength of the corresponding ply. First ply failure (FPF) envelopes are plotted using classical lamination theory and Tsai-Wu quadratic failure theory with and without considering the curing residual stresses. There is a significant effect of residual stresses on the FPF envelopes.

1. Introduction

A composite is a material system composed of a combination of two or more macro constituents differing in form and/or material composition and that are essentially insoluble in each other. Of all the composite materials, fibre reinforced plastic (FRP) composites have evoked the most interest among engineers and are finding increased use in aerospace engineering specifically and in every other discipline of engineering in general. Residual stresses are induced in FRP composites due to its heterogeneity. The understanding of the residual stress formation and its behaviour is an important subject and it has received much attention in the past [1–10]. Typical residual stresses which are attracting increased attention are the curing stresses and swelling stresses. The former is mainly induced by thermal expansion mismatch of the constituents during fabrication of the composites and the latter by the difference in swelling when moisture is absorbed during environmental exposure. The other main parameters which contribute to the residual stress formation are: processing temperature, elastic properties of the reinforcement and the matrix, polymer shrinkage, fibre-volume ratio, void content and the laminate construction. The residual stresses can be either microresidual or macroresidual stresses. The microresidual stresses are influenced by the local geometry of the constituents within the ply. The macroresidual stresses are integrated averages through the ply thickness. They are present in those composites that have plies oriented at different angles and whose use temperature differs from the cure or processing temperature.

Curing stresses are formed due to different thermal expansion coefficients (TEC) of materials in composites even at uniform temperature situation. Determination of curing stresses in a composite laminate requires some understanding of the fabrication processes involved. Unidirectional (UD) tape prepregs are mainly used for making the UD tape laminates. The resin is B-staged in the prepregs. During the fabrication of the laminates, as the temperature is increased, the epoxy softens again and flows until a change in the internal structure starts to take place in the form of entanglement of polymer molecules. That is, crosslinking occurs. As a result free motion of polymer molecules is prohibited and the epoxy begins to harden. At this point, a pressure is applied to drive out volatiles. The temperature is further increased and maintained for some hours to finish the cure. The temperature is then lowered to the room temperature and the cured laminate is ready for use. The resulting deformation of a UD tape laminate in the transverse direction is much larger than the longitudinal direction. Therefore, within the laminate the deformation of one ply is constrained by the other plies with different fibre orientations and hence curing stresses are built up in each ply. The understanding of the first ply failure (FPF) behaviour of the composite laminates under given loading conditions and the subsequent ply by ply analysis are the important steps in the FRP composites design. The FPF depends also on the residual stresses present within the laminate. The present work deals with the determination of macroresidual stresses during fabrication in symmetric crossply UD tape laminates. The failure envelopes under biaxial loading in zero shear plane are also presented for different material systems. The effect of curing stresses on the FPF envelope were also investigated.

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TABLE I Engineering constants and fibre volume fraction of typical unidirectional composites

Type	Material	E_{11} (GPa)	E_{22} (GPa)	μ_{12}	G_{12} (GPa)	V_f
T300/5208	graphite/epoxy	181	10.3	0.28	7.17	0.70
AS/3501	graphite/epoxy	138	8.96	0.30	7.10	0.66
B(4)/5505	boron/epoxy	204	18.5	0.23	5.59	0.50
Scotchply 1002	glass/epoxy	38.6	8.27	0.26	4.14	0.45
Kevlar49/epoxy	aramid/epoxy	76	5.5	0.34	2.30	0.60

2. Analytical calculations of macroresidual stresses

Macroresidual stresses induced in a ply of a laminated composite during fabrication process can be estimated from the mechanical and thermal properties of the UD plies. For the present study, UD ply elastic, strength and thermal properties for different material systems have been taken from [11] and are presented in Tables I–III.

Thermal strains do not produce a resultant force or moment when the body is completely free to expand, bend and twist. Thus when a laminate as a whole is considered, a temperature change does not effect the resultant force or moment. However, an individual ply in the laminate is not completely free to deform. Its deformation is influenced by the other plies. The ply stresses are induced by the constraints placed on the deformation by adjacent plies. The stresses in a ply are produced only by the strains that are in excess of the thermal strains for its free expansion. Since the change in temperature is constant, the formation of curing residual stresses are governed by the difference between the laminate TEC and the ply TECs.

The effective laminate TEC for a symmetric laminate is given in [12]. For a symmetric crossply laminate, the expressions are simplified and are given below:

Effective laminate TEC,

$$\alpha_x^+ = \alpha_y^+ = \alpha^+ = \frac{2(Q_{11}\alpha_1 + Q_{12}\alpha_2 + Q_{22}\alpha_2 + Q_{12}\alpha_1)}{(Q_{11} + Q_{22} + 2Q_{12})} \tag{1}$$

Here, Q_{ij} = ply stiffness components, and α_{ij} = ply TEC components.

Midplane strains due to only thermal load,

$$T_{\varepsilon_x^o} = T_{\varepsilon_y^o} = \alpha^+ \Delta T \tag{2}$$

where ΔT is the uniform change in temperature.

For 0° ply,

$$T_{\varepsilon_1} = [\alpha^+ - \alpha_1]\Delta T$$
$$T_{\varepsilon_2} = [\alpha^+ - \alpha_2]\Delta T \tag{3a}$$

and for 90° ply,

$$T_{\varepsilon_1} = [\alpha^+ - \alpha_2]\Delta T$$
$$T_{\varepsilon_2} = [\alpha^+ - \alpha_1]\Delta T \tag{3b}$$

Here, it may be noted that x and y refer to the laminate principal directions, whereas 1 and 2 refer to the ply principal directions.

TABLE II Typical strengths of unidirectional composites

Type	X_t (MPa)	X_c (MPa)	Y_t (MPa)	Y_c (MPa)	S (MPa)	V_f
T300/5208	1500	1500	40	246	68	0.70
AS/3501	1447	1447	52	206	93	0.66
B(4)/5505	1260	2500	61	202	67	0.50
Scotchply 1002	1062	610	31	118	72	0.45
Kevlar49/epoxy	1400	235	12	53	34	0.60

TABLE III Thermal expansion coefficients of typical unidirectional composites

Type	α_{11} (μm/m) K^{-1}	α_{22} (μm/m) K^{-1}	V_f	Specific gravity
T300/5208	0.02	22.5	0.70	1.60
AS/3501	−0.30	28.1	0.66	1.60
B(4)/5505	6.10	30.3	0.50	2.00
Scotchply 1002	8.60	22.1	0.45	1.80
Kevlar49/epoxy	−4.00	79.0	0.60	1.46

The residual stresses in the kth ply along the principal direction of the ply can be obtained by substituting the corresponding residual strains in the constitutive relation (4).

$$^R[\sigma_i]_k = [Q_{ij}]_k \, ^T[\varepsilon_i]_k \qquad i,j = 1,2,6 \tag{4}$$

3. Failure envelopes in normal stress resultant space

Failure envelopes for $[90/0]_s$ UD tape laminates under biaxial loading in normal stress resultant space can be plotted using classical lamination theory and Tsai-Wu quadratic failure theory [11].

Midplane strains due to only mechanical load for a symmetric crossply laminate are given by,

$$M_{\varepsilon_x^o} = a_{11} N_x + a_{12} N_y$$
$$M_{\varepsilon_y^o} = a_{12} N_x + a_{22} N_y \tag{5}$$

Here N_x and N_y are the laminate normal stress resultants and a_{ij} are the laminate compliance components. It may be noted that the laminate shear stress resultant, $N_{xy} = 0$.

The midplane laminate strains are transformed along the ply principal directions for both 0° and 90° plies.

Tsai-Wu quadratic failure theory in strain space for a specially orthotropic ply is given by [11],

$$G_{11}\varepsilon_1^2 + 2G_{12}\varepsilon_1\varepsilon_2 + G_{22}\varepsilon_2^2 + G_{66}\gamma_{12}^2 + G_1\varepsilon_1 + G_2\varepsilon_2 = 1 \quad (6)$$

Here, G_{ij}'s and G_i's are strength parameters in strain space, ε_1 and ε_2 are the ply normal strains in the principal direction, and γ_{12} is the ply shear strain. For the loading condition and laminate configuration considered, $\gamma_{12} = 0$.

Using the expressions (5) and (6), N_x and N_y at failure can be calculated. In turn σ_x and σ_y for the laminate can be calculated using the expressions,

$$\sigma_x = N_x/t \quad \text{and} \quad \sigma_y = N_y/t$$

where t is the thickness of the laminate.

For different combinations of σ_x and σ_y, failure envelopes can be plotted in normal stress resultant space for both 0° and 90° plies. The intersecting area of these two plots is the area enclosed by the FPF envelope of the $[90/0]_s$ laminate. These are the failure envelope plots without considering the residual stresses.

The failure envelope plots considering the curing stresses can be plotted by superimposing the ply mechanical strains over the ply thermal strains. The mechanical strains given in the expressions (5) are transformed in the ply principal directions and superimposed over the thermal strains given by the expressions (3) for the corresponding plies. These effective strains for 0° ply and 90° ply can be substituted in the expression (6) and the corresponding failure envelopes considering the residual stresses can be plotted in normal stress resultant space.

4. Results and discussion

The curing macroresidual stresses can be determined using the expression (4). They are presented in Table IV for $[90/0]_s$ laminates for the five material systems. Typical curing stress distribution in a $[90/0]_s$ balanced crossply laminate is presented in Fig. 1. For the calculation of the curing stresses the cure temperature of 177 °C and the use temperature of 30 °C were considered.

TABLE IV Residual stresses in $[90/0]_s$ UD tape laminates (MPa)

Type	R_{σ_x} 0°	90°	R_{σ_y} 0°	90°	V_f
T300/5208	− 32	32	32	− 32	0.70
AS/3501	− 34	34	34	− 34	0.66
B(4)/5505	− 58	58	58	− 58	0.50
Scotchply 1002	− 12	12	12	− 12	0.45
Kevlar49/epoxy	− 60	60	60	− 60	0.60

The curing stresses depend upon the elastic and thermal properties of the plies and the cure temperature. The calculated curing stresses in Kevlar49/Epoxy UD tape plies in the transverse direction are more than the transverse strength of the corresponding ply. Hence the FPF takes place during fabrication itself. Such a behaviour is observed during experimentation [1, 3, 4]. The curing stress values given in the present work are based on the difference in the curing temperature and the use temperature. The numerical value of the curing stresses calculated will be reduced if the gel temperature is considered instead of curing temperature. It has been suggested by Hahn [2] that with thermosetting resins the temperature at which stresses in a laminate begin to build up may be lower than the cure temperature. If this is not taken into account there will be an overestimate of curing residual stresses.

Failure envelopes in normal stress resultant space for $[90/0]_s$ laminates for different material systems as shown in Table I are presented in Figs 2–9. The corresponding focal points of the failure envelopes are given in Table V. Failure envelopes under biaxial loading without considering the curing stresses were plotted as explained in Section 2. In Tsai-Wu quadratic failure theory, normalized interaction term F_{12}^* was

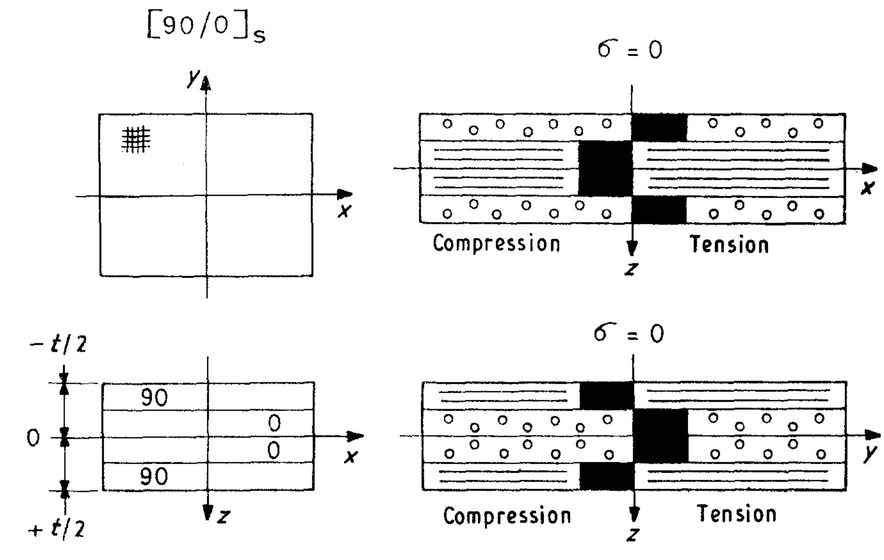

Figure 1 Typical residual stress distribution in a $[90/0]_s$ balanced crossply laminate. Note: the maximum tensile residual stress in the 90° plies and the maximum compressive residual stress in the 0° plies have the same value.

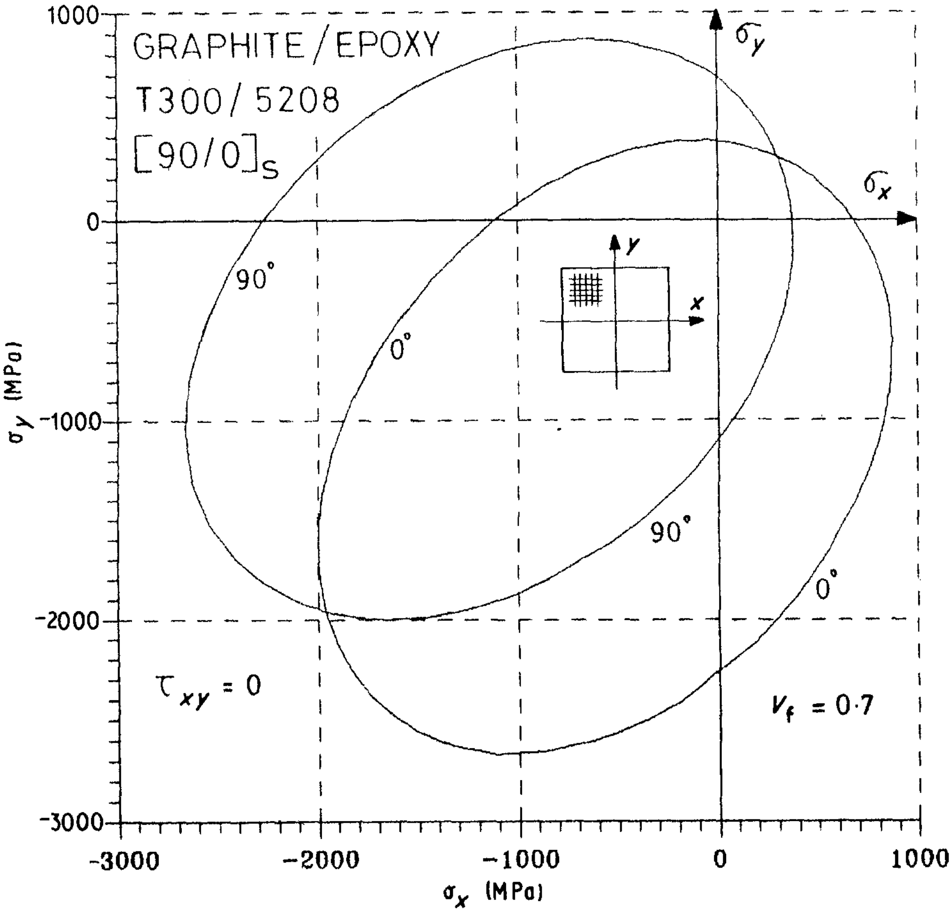

Figure 2 Failure envelopes in normal stress resultant space for $[90/0]_s$ laminate without residual stresses.

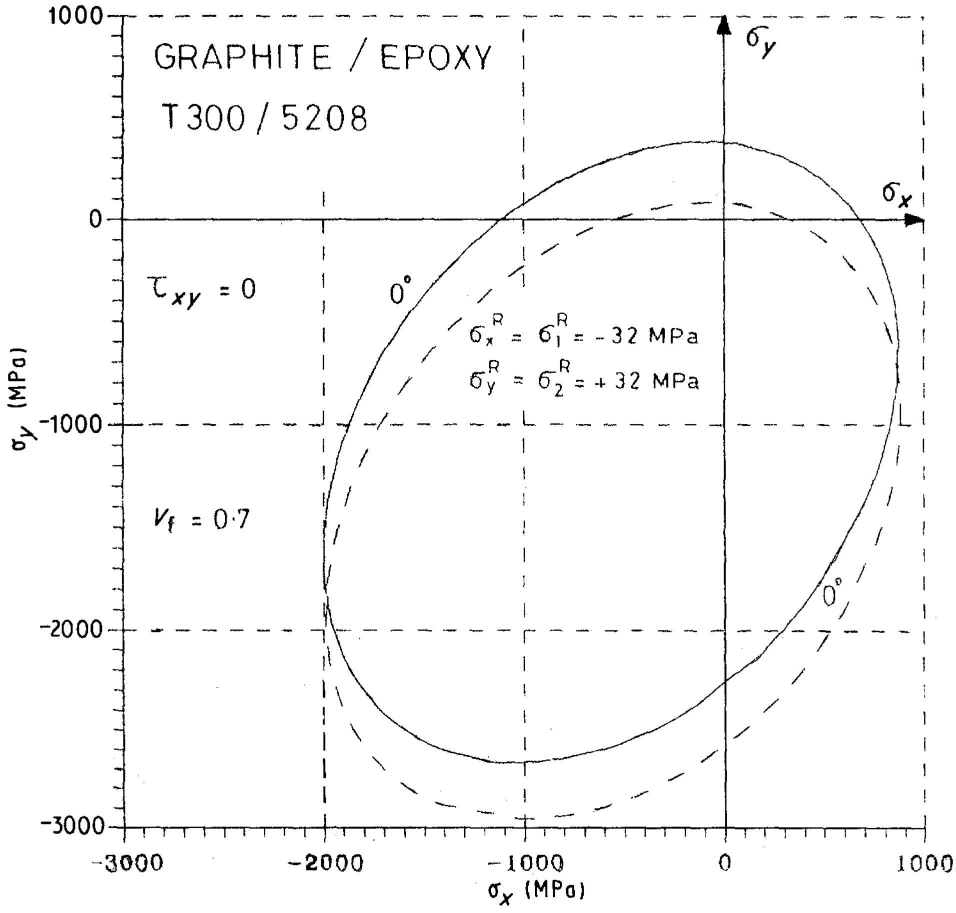

Figure 3 Failure envelopes for 0° ply of $[90/0]_s$ laminate. (——) Without and (– – –) with residual stresses.

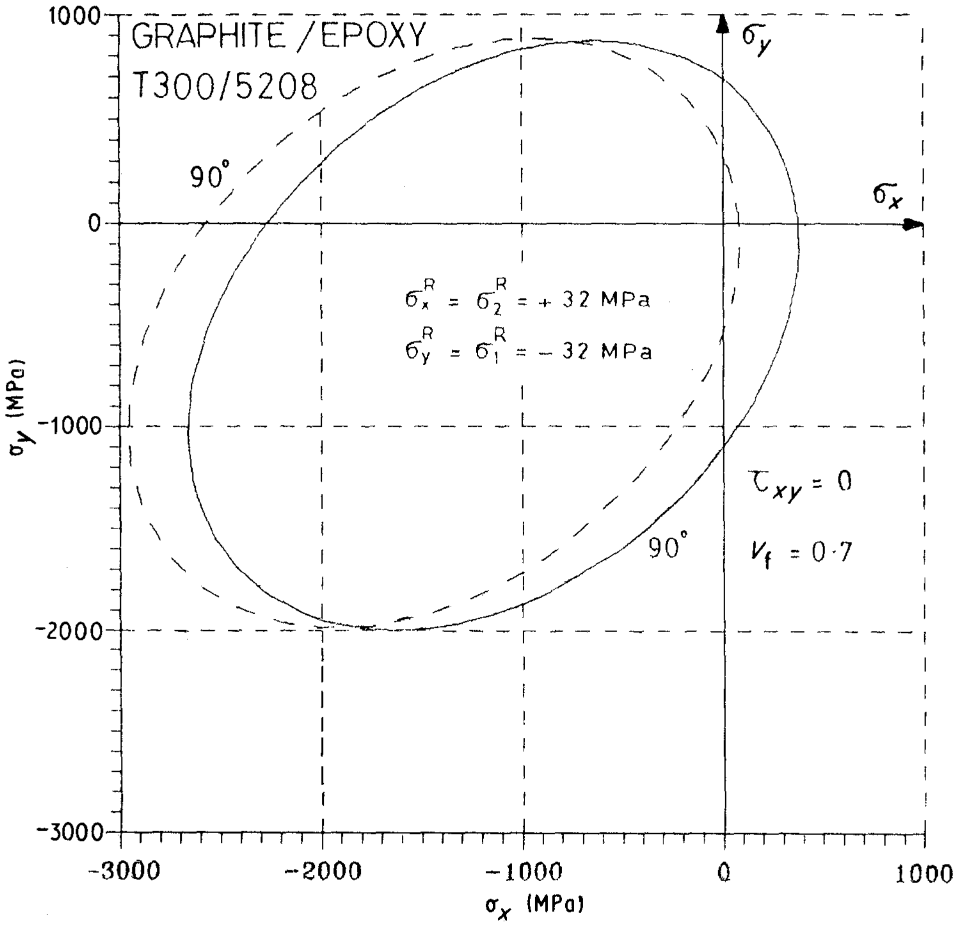

Figure 4 Failure envelopes for 90° ply of $[90/0]_s$ laminate. (——) Without and (– – –) with residual stresses.

TABLE V Failure envelope focal points for $[90/0]_s$ laminate in normal stress resultant space (MPa)

Type	0° Without residual stresses		With stresses		90° Without residual stresses		With stresses	
	σ_x	σ_y	σ_x	σ_y	σ_x	σ_y	σ_x	σ_y
Graphite/epoxy	682	0	330	0	373	0	79	0
	− 1108	0	− 549	0	− 2269	0	− 2574	0
T300/5208	0	373	0	79	0	682	0	330
	0	− 2269	0	− 2574	0	− 1108	0	− 549
Graphite/epoxy	700	0	470	0	427	0	143	0
	− 1038	0	− 608	0	− 1680	0	− 1973	0
AS/3501	0	427	0	143	0	700	0	470
	0	− 1680	0	− 1973	0	− 1038	0	− 608
Boron/epoxy	619	0	77	0	370	0	19	0
	− 1893	0	− 1001	0	− 1209	0	− 1579	0
B(4)/5505	0	370	0	19	0	619	0	77
	0	− 1209	0	− 1579	0	− 1893	0	− 1001
Scotchply 1002	505	0	403	0	89	0	53	0
	− 626	0	− 514	0	− 338	0	− 375	0
Glass/epoxy	0	89	0	53	0	505	0	403
	0	− 338	0	− 375	0	− 626	0	− 514
Kevlar49/epoxy	691	0	—	—	89	0	—	—
	− 183	0	—	—	− 398	0	—	—
Aramid/epoxy	0	89	—	—	0	691	—	—
	0	− 398	—	—	0	− 183	—	—

taken as − 0.5 [11]. Midplane strains due to only mechanical load was superimposed over midplane strains due to only thermal load and the effective strains were considered for plotting the failure envelopes with curing residual stresses.

It is seen from Figs 5 and 6 that the major axis of the failure envelopes of graphite/epoxy plies are oriented almost at 45° to the x-axis. This can be attributed to the equal strength of graphite/epoxy ply both in tension and compression in the longitudinal direction.

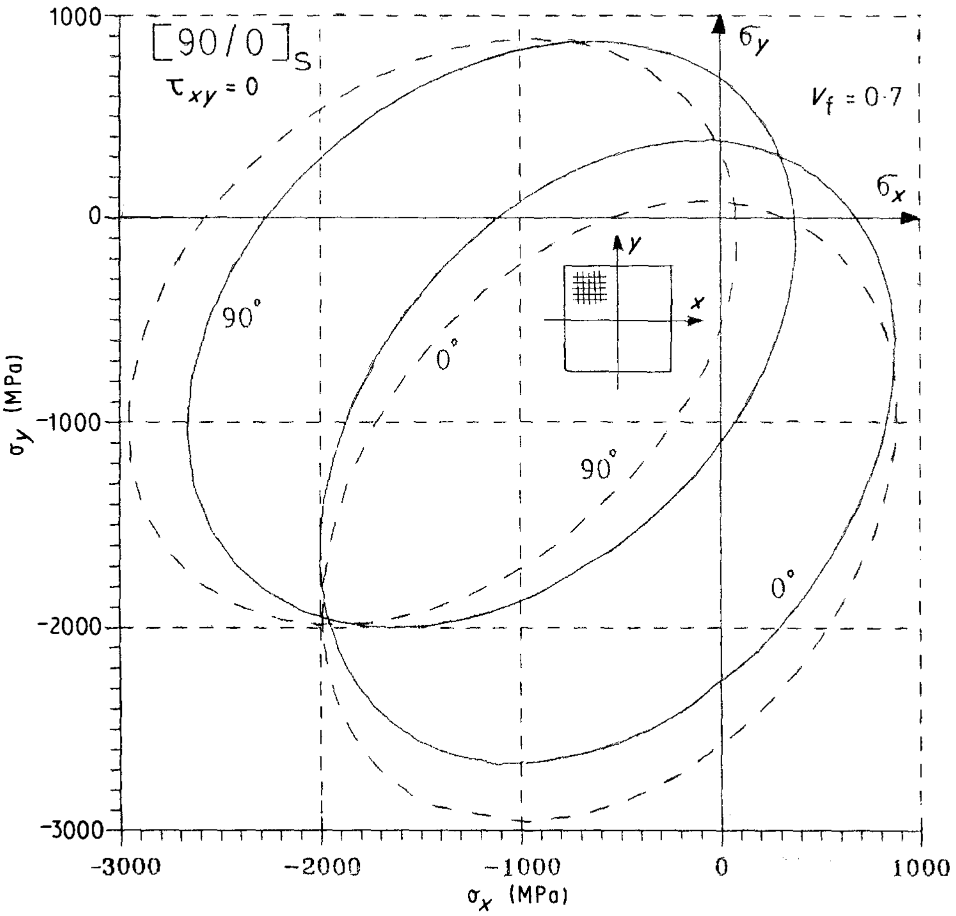

Figure 5 Failure envelopes in normal stress resultant space for T300/5208. (——) Without and (– – –) with residual stresses.

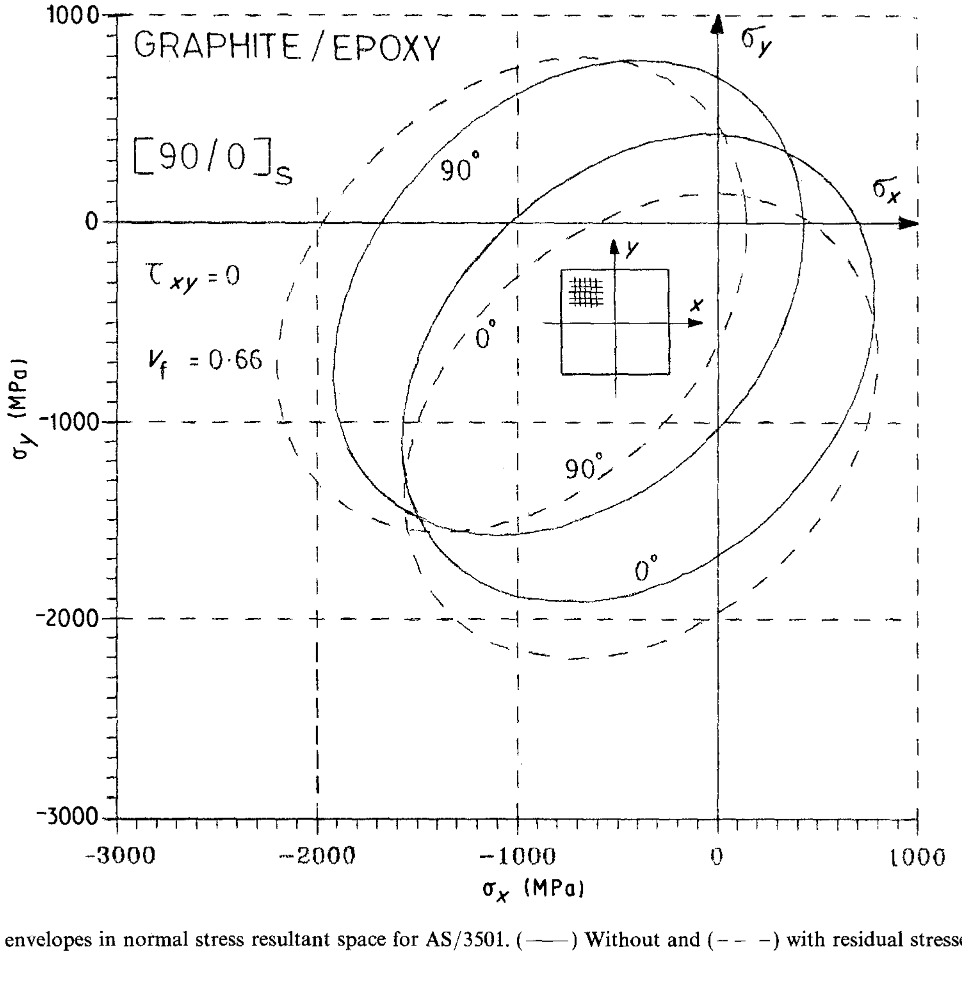

Figure 6 Failure envelopes in normal stress resultant space for AS/3501. (——) Without and (– – –) with residual stresses.

But in the case of boron/epoxy (Fig. 7) and glass/epoxy (Fig. 8), it is seen that the major axis of the failure envelopes of the plies are almost parallel to either x-axis or y-axis.

Figs 3 and 4 show that the failure envelopes of the 0° ply shift vertically downwards moving from the tension zone to the compression zone and that of 90° ply shift horizontally towards the left, again moving from tension zone to compression zone. This is due to the presence of the tensile curing stresses in the transverse direction of the ply. This trend is also seen for the other material systems considered. There is a marked reduction in the area enclosed by the FPF envelopes in the case of graphite/epoxy laminates due to the shift in the failure envelopes of the plies and their initial orientation with the global axes. But the reduction of the area enclosed by the FPF envelopes in the case of boron/epoxy and glass/epoxy is not significant.

It is seen that in the tension–tension zone there is a substantial reduction in the area enclosed by the FPF envelope, but the gain in the compression zone is very small in the case of graphite/epoxy laminates. In the case of boron/epoxy the loss in the area enclosed by the FPF envelope in the tension zone is almost gained in the compression zone and also it is seen that for the temperature difference considered the laminate has almost no strength left in the tension–tension zone as the curing stress is nearly equal to the ply transverse strength. In general, it is observed that the shifting of the FPF envelopes is towards the third quadrant (compression–compression zone) and the shift is along the major axis of the FPF envelope.

For Kevlar49/epoxy ply as seen from the Table IV, the curing stress exceeds the transverse strength of the ply. It implies that the laminate has failed during fabrication.

5. Conclusions

The curing macroresidual stresses for $[90/0]_s$ laminates for different material systems are presented. The maximum tensile curing stresses in the 90° plies and the maximum compressive curing stresses in the 0° plies have the same value. The calculated curing stresses in Kevlar49/epoxy UD tape plies in the transverse direction are more than the transverse strength of the corresponding ply. It indicates that the ply would fail during fabrication itself.

There is a significant effect of curing residual stresses on the FPF envelopes. It is observed that the FPF envelope shifts towards the third quadrant along its major axis.

In general, the effect of residual stresses is to increase the tensile strength and decrease the compressive strength of the ply along the fibre direction. On the other hand the tensile strength is decreased and the compressive strength is increased across the fibre direction.

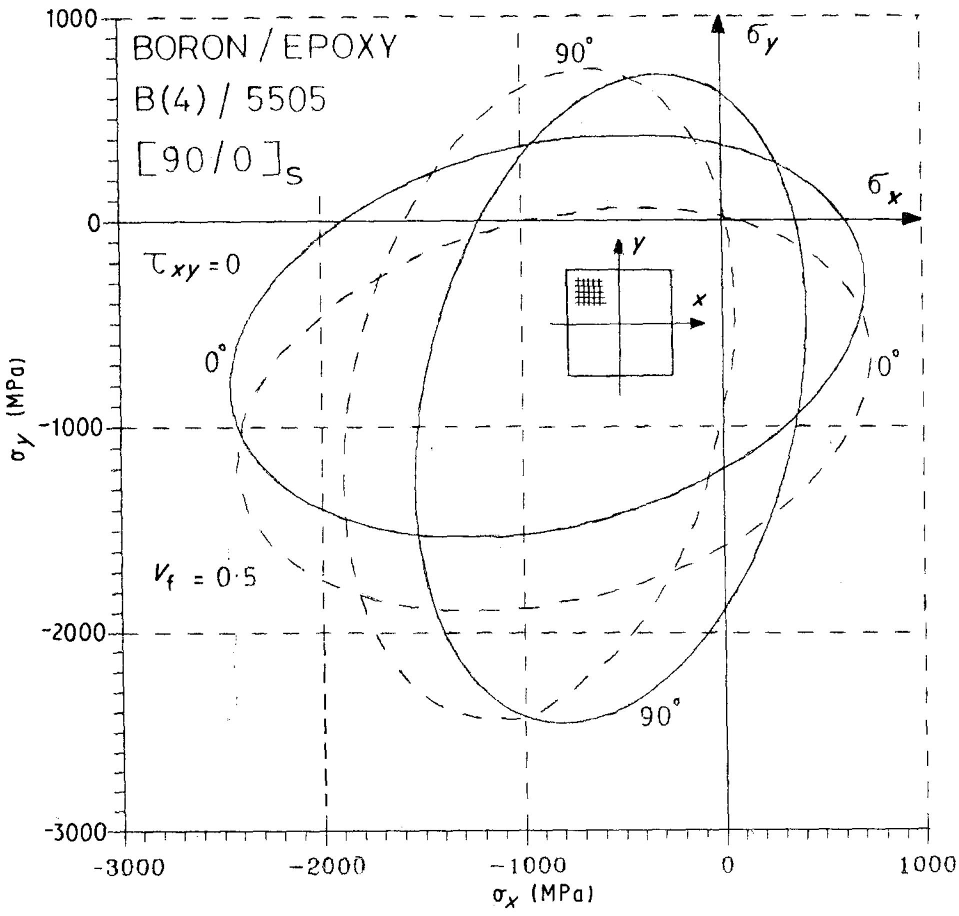

Figure 7 Failure envelopes in normal stress resultant space for B(4)/5505. (——) Without and (– – –) with residual stresses.

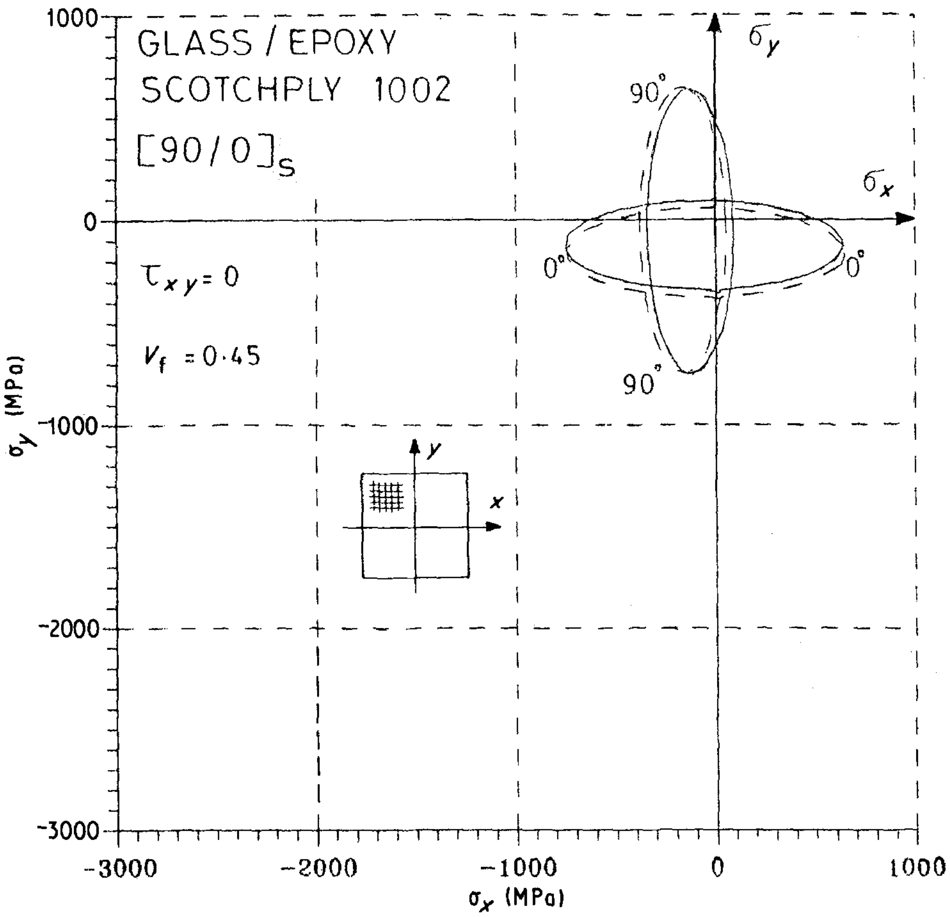

Figure 8 Failure envelopes in normal stress resultant space for Scotchply 1002. (——) Without and (– – –) with residual stresses.

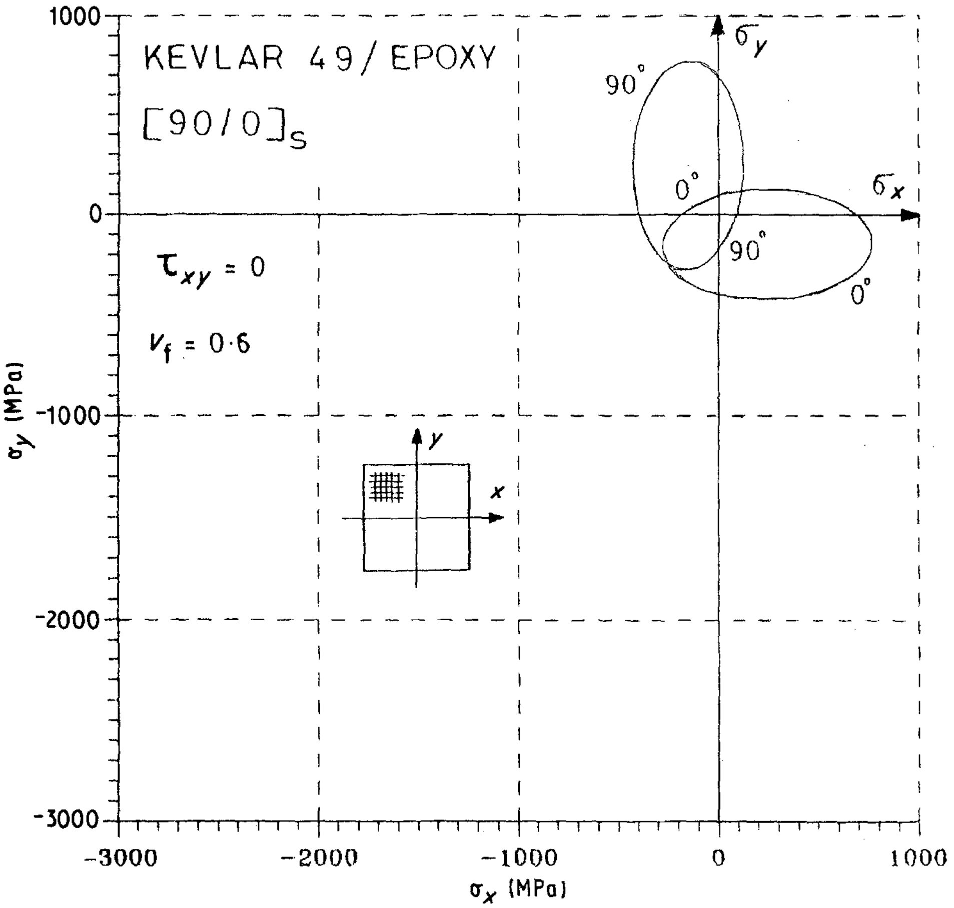

Figure 9 Failure envelopes in normal stress resultant space for Kevlar49/Epoxy without residual stresses.

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