Influences of artificial pre-stressing on ply stresses and tensile properties of Vinylon fibre-reinforced aluminium laminates (VIRALL)

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A simple micromechanical model based primarily upon the rule-of-mixtures is developed which allows prediction of the effects of fibre preload on the ply stresses (i.e., the initial residual stresses of fibre, adhesive and matrix) induced within VIRALL laminates, and the tensile stress–strain curves and mechanical properties of VIRALL laminates. The analysis of the ply stresses of VIRALL laminates indicates that pre-stressing will dramatically influence the ply stresses. The predicted tensile stress–strain curves of VIRALL laminates are in good agreement with the experimental curves and the results show that the stress–strain curves of VIRALL laminates move upwards when the prestress increases. The predicted tensile mechanical properties of VIRALL laminates at room temperature show good agreement with those obtained experimentally; both show that prestress can improve the tensile properties (i.e., elastic limit strength, 0.2% yield strength and failure strength) of VIRALL laminates.

1. Introduction

In the past decades, many classes of composite materials have been developed. Composite materials are currently widely used in the aerospace, aircraft, marine and automobile industries and also for sports and leisure equipment. For continuous fibre-reinforced composite laminates, there has been the successful development of ARALL [1–7] and CARALL [8, 9]. ARALL consists of thin layers of aramid/epoxy prepreg sandwiched between aluminium alloy sheets; whilst CARALL comprises carbon/epoxy prepreg sandwiched between aluminium alloy sheets. The two classes of composite laminates have a high modulus, high tensile strength, low density and superior fatigue crack propagation resistance in the longitudinal direction, thus they can be used in the aerospace and aircraft industries. However, neither ARALL nor CARALL can be widely applied in consumer product industries where low price is required, because of the expensive reinforcing components – Kevlar (aramid fibre) and carbon fibre. To achieve this requirement we have developed a new hybrid composite laminate "VIRALL" (Vinylon fibre-reinforced aluminium laminate) by alternately laminating Vinylon/epoxy prepreg layers and aluminium alloy sheets. This new composite may be widely used in consumer product industries because the price of VIRALL laminates is very low [10] and in addition the VIRALL laminate has good mechanical properties [10–13]. When compared with the corresponding aluminium alloy (as the matrix of VIRALL), VIRALL is superior to the aluminium alloy in mechanical properties and also has a lower density and a lower price [10]. These are very important factors for a material that is to be used for consumer products. In order to put VIRALL into industrial use as quickly as possible, some further studies are required.

In this paper a pre-load is applied to fibres prior to the cure of the composite laminate. The composite laminate is cured at a high temperature T_1 and the fibre is stressed throughout the curing process. Following the solidification of the epoxy adhesive the temperature is reduced to ambient and the stress released. During the cooling down from the high curing temperature T_1 to the ambient temperature T_0 during the cure of the composite laminates, an internal residual stress will occur within the composite laminate due to the thermal mismatch, i.e., the different thermal expansion properties of the components [14–17]. The release of the prestress will also result in residual ply stresses within the composite laminate due to the different elastic properties of the components [18]. The ply stresses should be the sum of the above mentioned two items. A simple micromechanics model based primarily upon the rule of mixtures is developed to account for the effects of the prestress on the ply stresses induced within VIRALL laminates and on the stress–strain curves and tensile properties of VIRALL laminates.

2. Experimental procedure

2.1. Materials

VIRALL specimens were prepared from the following constituents:

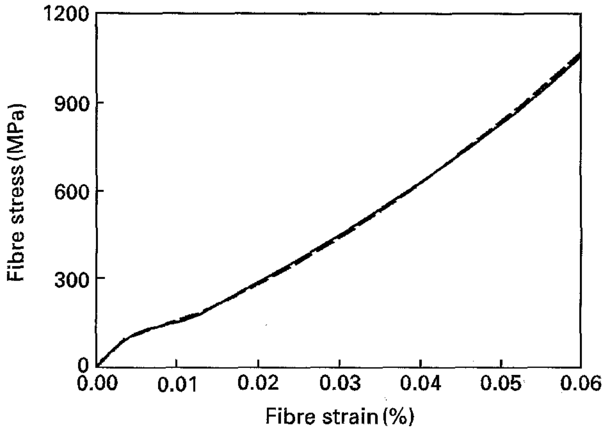

Figure 1 Tensile stress–strain curves of Vinylon fibre. The (—) line is the experimental data and (– – –) represents the fitted data.

(1) long, continuous, high strength and high modulus PVA fibre (Vinylon) with a diameter of 10 μm and a tensile strain to failure of 7–9% for a single fibre, and a coefficient of thermal expansion, -4.5×10^{-6} per °C. The experimental and fitted stress–strain curves of this material are shown in Fig. 1. The equations used in the fitting procedure were as follows:

$$\sigma_f = E_{f0}\varepsilon_f \quad \text{for} \quad \varepsilon_f < \varepsilon_{f0} \tag{1}$$

$$\sigma_f = \sigma_{f0} + E_{f1}(\varepsilon_f - \varepsilon_{f0})^n \quad \text{for} \quad \varepsilon_{f0} < \varepsilon_f < 1.2\% \tag{2}$$

$$\sigma_f = a_0 + a_1\varepsilon_f + a_2\varepsilon_f^2 \quad \text{for} \quad \varepsilon_f \geqslant 1.2\% \tag{3}$$

where σ_f and ε_f denote the stress and strain of a Vinylon fibre, respectively; σ_{f0} and ε_{f0} are the elastic limit strength and elastic limit strain of a Vinylon fibre, respectively; E_{f0} is the elastic modulus of a Vinylon fibre and the other parameters are the fitting constants. In addition, $E_{f0} = 27\,500$ MPa, $E_{f1} = 6800$ MPa, $\sigma_{f0} = 98.5$ MPa, $\varepsilon_{f0} = 0.358\%$, $n = 0.93$, $a_0 = 45.1$ MPa, $a_1 = 9201.7$ MPa and $a_2 = 132614.8$ MPa.

We can see from Fig. 1 that the stress–strain curve of a Vinylon fibre has a tensile strengthening feature. In this study we will take advantage of this strengthening feature in order to improve the mechanical properties of a VIRALL laminate by pre-loading the fibres.

(2) A 6101 epoxy resin adhesive with a coefficient of thermal expansion, 55×10^{-6} per °C. The expression for the stress–strain relationship for an epoxy resin adhesive can be written as;

$$\sigma_a = E_a\varepsilon_a \tag{4}$$

where σ_a and ε_a denote the stress and strain of the epoxy adhesive, respectively; E_a is the elastic modulus of the epoxy resin and $E_a = 4100$ MPa.

(3) LF5 aluminium alloy sheets at mild state with a thickness of 0.54 mm and a coefficient of thermal expansion, 23×10^6 per °C. The composition of this aluminium alloy is listed in Table I. The stress–strain relationship of an LF5 aluminium alloy can be expressed as:

$$\sigma_m = E_{m0}\varepsilon_f \quad \text{for} \quad \varepsilon_m < \varepsilon_{m0} \tag{5}$$

$$\sigma_m = \sigma_{m0} + E_{m1}(\varepsilon_m - \varepsilon_{m0}) \quad \text{for} \quad \varepsilon_m \geqslant \varepsilon_{m0} \tag{6}$$

TABLE I The composition of the LF5 aluminium alloy (%)

Mg	Mn	Al	Cu	Fe	Si	Zn
4.8–5.5	0.3–0.6	bal.	⩽0.10	⩽0.50	⩽0.50	⩽0.20

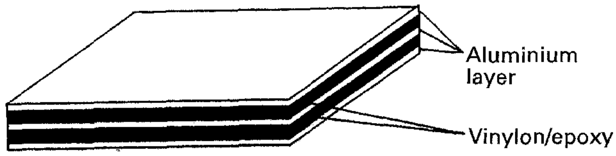

Figure 2 Schematic drawing of 3/2 VIRALL laminate.

where σ_m and ε_m denote the stress and strain of the aluminium matrix, respectively; σ_{m0} and ε_{m0} are the elastic limit strength and elastic limit strain of the aluminium matrix, respectively. And $E_{m0} = 69900$ MPa, $E_{m1} = 2080$ MPa, $\sigma_{m0} = 154.5$ MPa and $\varepsilon_{m0} = 0.221\%$.

2.2. Mechanical tests

The specimens used in the tests comprised of a 3/2 VIRALL laminate, i.e., two vinylon/epoxy prepreg layers sandwiched between three aluminium alloy sheets, as is shown in Fig. 2. Before cure of the VIRALL laminates a pre-load is applied to the fibres until the completion of the epoxy adhesive solidification at the curing temperature. Then the preloads are released, such that residual stresses will be introduced into the Vinylon fibres, epoxy resin adhesive and aluminium matrix. The mechanical tests were performed using a universal Instron machine.

3. Theoretical model

3.1. Prediction of residual stresses in composite laminates resulting from cooling down from the curing temperature to ambient and from pre-loading of fibres

We consider a composite element which consists of fibre, adhesive and matrix, as shown in Fig. 3(a and b). It is assumed that perfect bonding exists between fibre and matrix through the epoxy adhesive. The initial fibre, adhesive and matrix lengths are assumed to be l_{f0}, l_{a0} and l_{m0} respectively at the ambient temperature before the cure of a composite. During the cure of the composite the element is of a length l_0 at the high cure temperature T_1, and consists of a fibre loaded with a preload P_p. This condition is held constant throughout the curing process. Upon completion of the cure, the fibre, adhesive and matrix stresses are:

$$\sigma_f^p = \frac{P_p}{A_f} \tag{7}$$

$$\sigma_a^p = 0 \tag{8}$$

$$\sigma_m^p = 0 \tag{9}$$

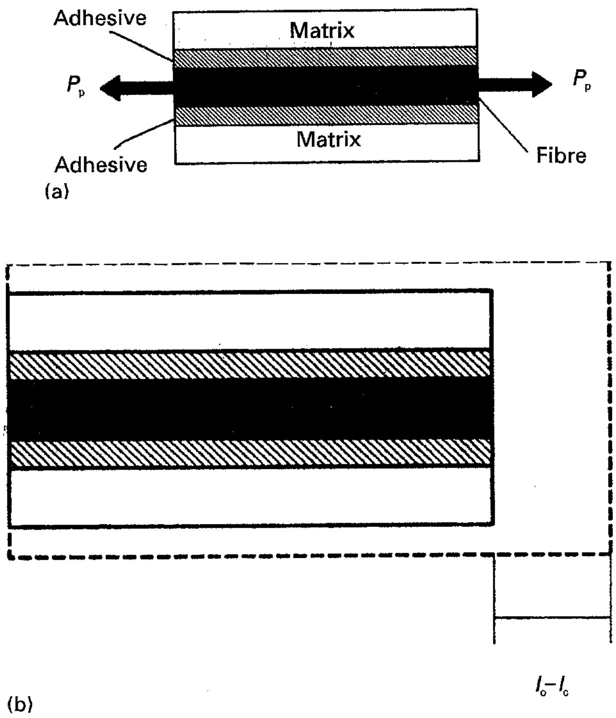

Figure 3 Representative composite element used in model derivation. (a) Prestressed element; (b) element after release of preload.

where σ_f^p, σ_a^p and σ_m^p are the initial fibre, adhesive and matrix stresses due to a preload, P_p, respectively and A_f is the fibre cross-sectional area.

A change in fibre length results from both the prestress loaded to the fibre and also the temperature change from ambient temperature T_0 to the high curing temperature T_1. The changes in the adhesive and matrix lengths result only from the change in the temperature from T_0 to T_1. Over a comparatively small temperature interval the linear thermal expansivity can often be approximated [19, 20]. In this study we will apply this approximation. Then we obtain

$$l_{f0} + \varepsilon_f^p l_{f0} + \alpha_f \delta T (l_{f0} + \varepsilon_f^p l_{f0}) = l_0 \qquad (10)$$

$$l_{a0} + \alpha_a \delta T l_{a0} = l_0 \qquad (11)$$

$$l_{m0} + \alpha_m \delta T l_{m0} = l_0 \qquad (12)$$

where α_f, α_a and α_m denote the coefficients of thermal expansion of the fibre, adhesive and matrix, respectively; δT, the change in the temperature; ε_f^p, the prestrain in the fibre resulting from the prestress. Following the cure the temperature of the composite element is reduced from the cure temperature to ambient and the pre-load P_p is released. Both the change in temperature and the relief of the pre-stress result in a change in length of the element, and the resulting length of the composite is assumed to be l_c. It is assumed that this change in length occurs uniformly across the element, such that all of the resulting lengths of fibre, adhesive and matrix are equal to l_c. Thus the residual fibre, adhesive and matrix strains within the composite laminate can be expressed as:

$$\varepsilon_{f0}^0 = \frac{l_c - l_{f0}}{l_{f0}} = \frac{l_c}{l_{f0}} - 1 \qquad (13)$$

$$\varepsilon_{a0}^0 = \frac{l_c - l_{a0}}{l_{a0}} = \frac{l_c}{l_{f0}} \frac{l_{f0}}{l_{a0}} - 1 \qquad (14)$$

$$\varepsilon_{m0}^0 = \frac{l_c - l_{m0}}{l_{m0}} = \frac{l_c}{l_{f0}} \frac{l_{f0}}{l_{m0}} - 1 \qquad (15)$$

where l_{f0}/l_{a0} and l_{f0}/l_{f0} can be derived from Equations 10–12:

$$\frac{l_{f0}}{l_{a0}} = \frac{1 + \alpha_a \delta T}{1 + \varepsilon_f^p + \alpha_f \delta T (1 + \varepsilon)_f^p} \qquad (16)$$

$$\frac{l_{f0}}{l_{m0}} = \frac{1 + \alpha_m \delta T}{1 + \varepsilon_f^p + \alpha_f \delta T (1 + \varepsilon_f^p)} \qquad (17)$$

The change in the composite element length results in a change in the fibre stress to some new value, σ_f^0, and induces the nonzero residual adhesive and matrix stresses, σ_a^0 and σ_m^0. Since the external prestress has now been released, the residual fibre stress, the residual adhesive stress and the residual matrix stress can be determined by requiring that the elements remain in equilibrium. Thus, at the equilibrium position

$$\sigma_f^0 V_f + \sigma_a^0 V_a + \sigma_m^0 V_m = 0 \qquad (18)$$

where V_f, V_a and V_m are the volume fractions of fibre, adhesive and matrix, respectively. Since the stress–strain relationships of fibre, adhesive and matrix within VIRALL laminates have been given in Equations (1–6), then by combining Equations (13–18), we can obtain the residual strains of the fibre, adhesive and matrix and hence the residual stresses of the fibre, adhesive and matrix.

3.2. Prediction of stress–strain curves and mechanical properties of VIRALL laminates

During the mechanical testing of composite laminates, if the strain of a composite laminate is assumed to be ε_c and this strain is assumed to occur uniformly along the composite laminate element, then the real strains of the fibre, adhesive and matrix can be evaluated by adding their residual strains to ε_c. Also the stresses of the fibre, adhesive and matrix can be determined from their stress–strain curves. So the stress, σ_c, of the composite laminate can be determined from:

$$\sigma_c = \sigma_f V_f + \sigma_a V_a + \sigma_m V_m \qquad (19)$$

where σ_f, σ_a and σ_m denote the stresses of the fibre, adhesive and matrix, respectively. Therefore the stress–strain relationship of the composite laminate can be determined.

When the residual stresses of both fibre and matrix are less than the elastic limit strength of the fibre and matrix respectively, then the stresses of the constituents at their elastic stages can be written as:

$$\sigma_f = \sigma_f^0 + E_{f0} \varepsilon_c \qquad (20)$$

$$\sigma_a = \sigma_a^0 + E_a \varepsilon_c \qquad (21)$$

$$\sigma_m = \sigma_m^0 + E_{m0} \varepsilon_c \qquad (22)$$

Also, the stress of the composite laminate, σ_c, can be expressed as:

$$\sigma_c = E_c \varepsilon_c \tag{23}$$

By combining Equations (18–23), we obtain the elastic modulus of the composite laminate as:

$$E_c = E_{f0} V_f + E_a V_a + E_{m0} V_m \tag{24}$$

From the above equation we can see that the elastic modulus of a composite laminate is dependent on the volume fractions and elastic moduli of the fibre, adhesive and matrix, and is unrelated to the prestress.

When the residual stress of the fibres exceeds the elastic limit strength of the fibres and the residual stress of the matrix is less than the elastic limit strength of the matrix (this will be shown in Table II), then there would not be an ideal elastic stage but instead an approximate elastic stage in the stress–strain curves of VIRALL laminates. The elastic modulus of VIRALL laminates can be evaluated from their stress–strain curves. Also the elastic limit strain of VIRALL laminates is the value of the elastic limit strain of the matrix (ε_{me}) minus its residual strain (ε_a^l). Thus the elastic limit strength of VIRALL laminates can be obtained from their stress–strain relationships.

If the failure strain of the fibre is smallest of the components and if the fibre is the main load-bearing component, then the composite will fail when the strain of the fibre reaches the failure strain of the fibre. However, for Vinylon/epoxy/aluminium system the failure strain of the adhesive is smallest amongst the components and the adhesive only bears a small part of the load, thus the composite will not fail when the strain of the adhesive reaches its failure strain. Furthermore the cracking of the adhesive will result in a stress concentration in the fibre. This stress concentration would make the fibre fracture at an early stage before the real strain of the fibres reaches the fibre failure strain. We can introduce a stress concentration factor, K, to describe the extent of the fibres influenced by the adhesive cracking. Then, at the cracking of the adhesive the stress, σ_{fc}, of fibre can be expressed as:

$$\sigma_{fc} = K \sigma_f \tag{25}$$

where σ_f expresses the average stress in the fibre. When σ_{fc} reaches or exceeds the failure strength of the fibres, the fibres will fracture and then the composite laminates will fail.

Therefore, for Vinylon fibre-reinforced aluminium laminates, the stress–strain relationships of the components, i.e., Vinylon fibre, epoxy resin adhesive and aluminium matrix have been obtained, thus the stress–strain relationship and tensile mechanical properties of VIRALL laminates can be evaluated.

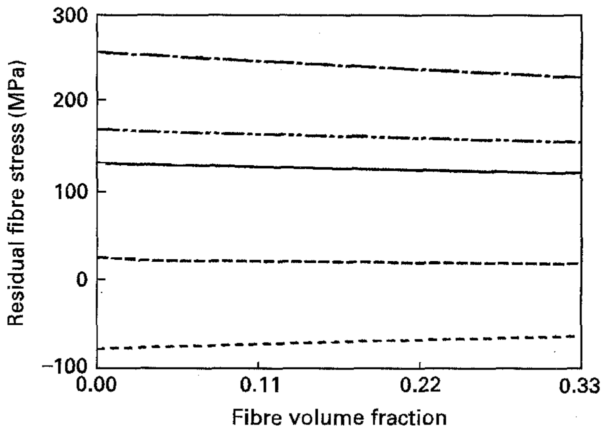

Figure 4 Residual Vinylon fibre stress existing after cooldown and release of fibre preload. Data were taken at (–––) 0 MPa, (— —) 100 MPa, (—) 160 MPa (- - - -) 200 MPa and (—·—) 300 MPa.

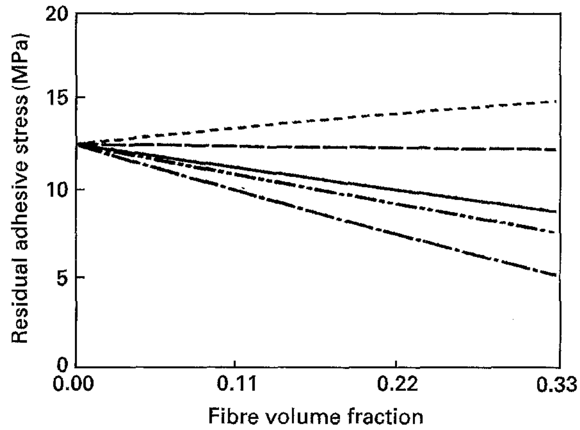

Figure 5 Residual epoxy adhesive stress existing after cooldown and release of fibre preload. Data were taken at the same values as Fig. 4 and are represented by the same line codes.

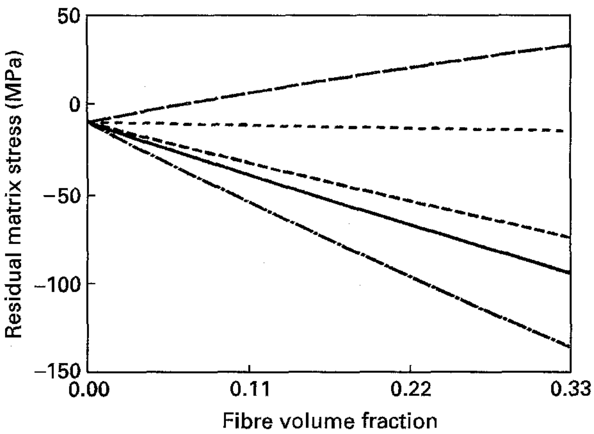

Figure 6 Residual aluminium matrix stress existing after cooldown and release of fibre preload. Data were taken at (— —) 0 MPa, (- -) 100 MPa, (— —) 160 MPa (—) 200 MPa and (—-—) 300 MPa.

4. Results and discussion

The ply stresses versus the fibre volume fraction are shown in Figs 4–6 for various prestresses. If the aluminium volume fraction is 57%, then the maximum fibre volume fraction is 0.337. It can be seen from Figs 4–6 that the prestress has a dramatic influence on the ply stresses. Fig. 4 shows that the residual fibre stress increases with the prestress and has a small change as the fibre volume fraction increases. Figs 5 and 6 show that the residual epoxy adhesive and aluminium matrix stresses decrease as the prestress

TABLE II Residual ply stresses resulting from fibre pre-stressing and thermal mismatch within VIRALL laminates

	V0	V100	V160	V200	V300
Fibre volume fraction, (%)	32	32	31	33	33
Matrix volume fraction, (%)	57	57	58	55	56
Residual fibre stress, (MPa)	− 62.8	20.5	125.2	159.1	231.8
Residual fibre strain, (%)	− 0.228	0.0746	0.617	0.983	1.641
Residual adhesive stress, (MPa)	15.0	12.3	9.1	7.4	5.0
Residual adhesive strain, (%)	0.366	0.299	0.221	0.181	0.122
Residual matrix stress, (MPa)	32.3	− 10.8	− 68.6	− 96.1	− 137.6
Residual matrix strain, (%)	0.0462	− 0.0155	− 0.098	− 0.138	− 0.196

Note: V0, V100, V160, V200 and V300 express the VIRALL laminate in which the fibres are pre-loaded with a prestress of 0, 100, 160, 200 and 300 MPa, respectively.

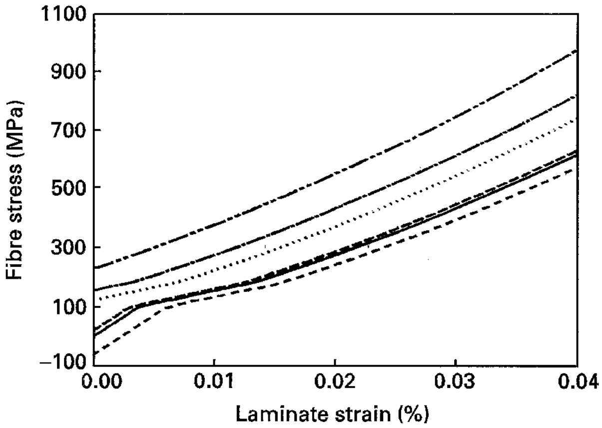

Figure 7 Predicted tensile stress of Vinylon fibres versus tensile strain of VIRALL laminate. The line codes represent: (——) uninfluenced, (–-) 0 MPa, (——) 100 MPa, (····) 160 MPa, (—-—) 200 MPa and (——---—) 300 MPa.

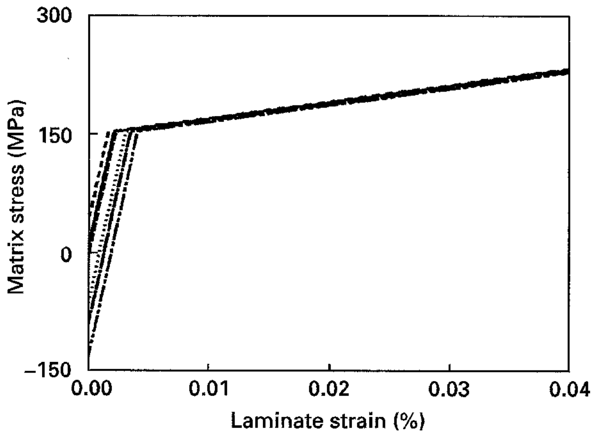

Figure 9 Predicted tensile stress of aluminium matrix versus tensile strain of VIRALL laminate. The line codes are as for Fig. 7.

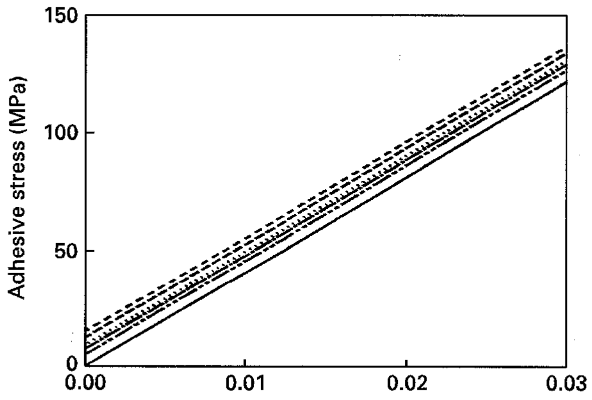

Figure 8 Predicted tensile stress of epoxy adhesive versus tensile strain of VIRALL laminate. The line codes are as for Fig. 7.

increases. Table II lists the initial residual stresses of fibre, epoxy and matrix for the Vinylon fibre-reinforced aluminium laminates of given volume fractions. The results show that the initial residual stress of the Vinylon fibre increases with the prestress but that the initial residual stresses of the epoxy adhesive and aluminium matrix decrease with the prestress.

Figs 7–9 show the stress σ_f of the Vinylon fibre, the stress σ_a of the epoxy resin adhesive and the stress σ_m of the aluminium matrix versus the strain ε_c of prestressed VIRALL laminate (that are of the volume fractions given in Table II), respectively. From Figs 7–9, we can see that when the prestress is 100 MPa, the σ_f–ε_c, and σ_a–ε_c and the σ_m–ε_c curves are close to those when the fibres, adhesive and matrix are uninfluenced. This indicates that a prestress of 100 MPa can well explain the residual stresses within VIRALL laminates. It can be seen from Fig. 7 that the prestress has a dramatic influence on the σ_f–ε_c curve and that the curve moves upwards when the prestress increases. Also, Fig. 7 shows that no elastic stage appears in the σ_f–ε_c curve when the fibre prestress is equal to or greater than 160 MPa. Figs 8 and 9 show that the prestress has a relatively small effect on both the σ_a–ε_c curve and the σ_m–ε_c curve and that both these curves move down as the prestress increases. Therefore, from Equation (19) we find that the stress–strain curves of VIRALL laminates have an elastic stage when the prestress is less than 160 MPa. Also the stress–strain curves of VIRALL laminates have an approximate elastic stage when the prestress is equal to or greater than 160 MPa, which is shown in Figs 10–14.

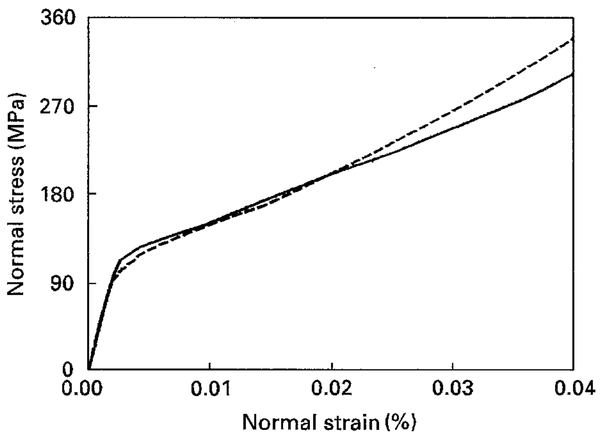

Figure 10 Comparison of the theoretical (dashed line) and experimental (solid line) tensile stress–strain curves of prestressed VIRALL laminates for $\sigma_f^p = 0$ MPa.

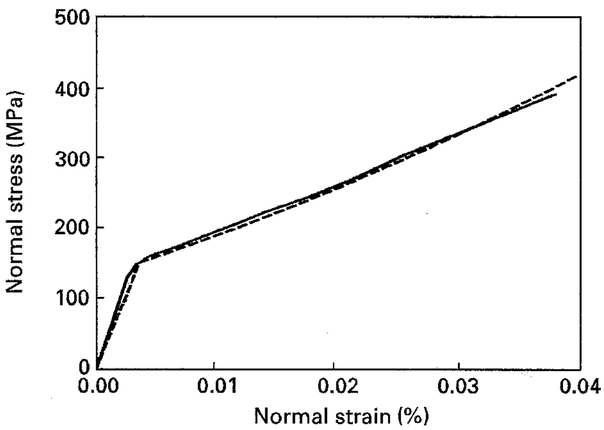

Figure 13 Comparison of the theoretical (dashed line) and experimental (solid line) tensile stress–strain curves of prestressed VIRALL laminates for $\sigma_f^p = 200$ MPa.

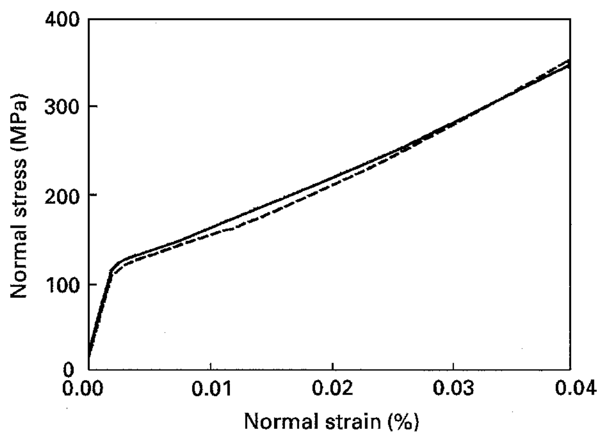

Figure 11 Comparison of the theoretical (dashed line) and experimental (solid line) tensile stress–strain curves of prestressed VIRALL laminates for $\sigma_f^p = 100$ MPa.

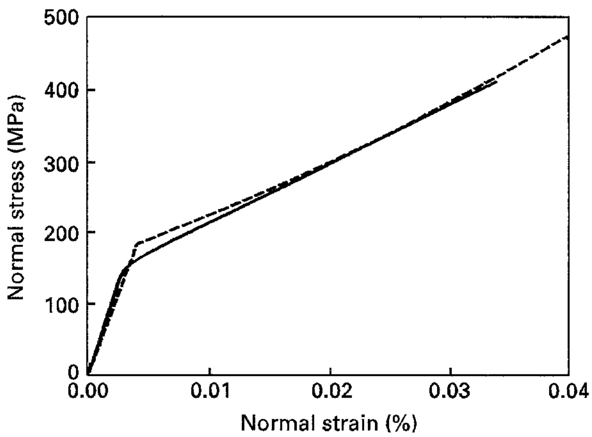

Figure 14 Comparison of the theoretical and experimental tensile stress–strain curves of prestressed VIRALL laminates for $\sigma_f^p = 300$ MPa.

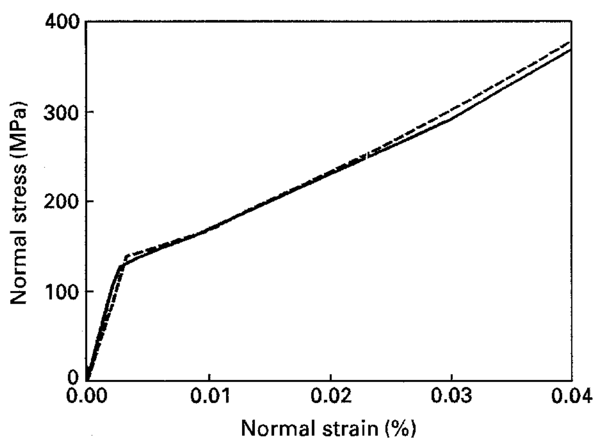

Figure 12 Comparison of the theoretical (dashed line) and experimental (solid line) tensile stress–strain curves of prestressed VIRALL laminates for $\sigma_f^p = 160$ MPa.

Figs 10–14 give a comparison between the theoretically predicted and experimentally obtained stress–strain curves of the VIRALL laminates. It can be seen that the theoretical stress–strain curves agree very well with the experimental curves. The theoretically predicted and experimentally obtained mechanical properties of VIRALL laminates are listed in Table III. By neglecting the effect resulting from the difference in the volume fractions (see Table II), Table III shows that the mechanical properties of VIRALL increase as the prestress increases. Table III also shows that the stress concentration factor, K, decreases with the prestress, which may be because the prestress delayed the adhesive cracking as is discussed in reference [21]. From Table II, we can also see that if the initial residual strain of the adhesive decreases with the prestress then the cracking of the adhesive should be delayed by the prestress. The mechanical properties of VIRALL predicted by this theory coincide closely with those obtained experimentally.

Fig. 15 shows the predicted normal stress–strain curves of prestressed VIRALL laminates for different prestresses, here $V_f = 0.32$ and $V_m = 0.57$. It can be seen from Fig. 15 that the stress of VIRALL laminate increases as the prestress increases, namely the prestress makes the stress–strain curves of VIRALL move upwards. This movement in the stress–strain curve is due to the movement in the stress–strain curve of Vinylon fibres when the prestress is applied to the fibres.

TABLE III The mechanical properties of VIRALL and the corresponding aluminium alloy

		Al	V0	V100	V160	V200	V300
Elastic modulus,	E	69.9	48.3	49.3	50.2	50.9	51.5
(GPa)	T		49.1	49.1	44.2	44.1	44.3
Elastic limit	E	147.6	116.3	121.7	129.0	142.4	155.0
strength, (MPa)	T		85.8	117.8	140.1	151.1	184.9
Elastic limit	E	0.211	0.241	0.247	0.257	0.280	0.301
strain, (%)	T		0.175	0.237	0.319	0.359	0.418
0.2% yield	E	158.3	128.4	132.9	142.2	165.4	176.0
strength (MPa)	T		122.5	133.5	148.0	162.6	194.4
Failure strength,	E	300	357	368	385	394	410
(MPa)	T		387	389	392	404	414
Failure strain, (%)	E		5.6	5.2	4.6	3.8	3.4
	T		4.6	4.4	4.1	3.8	3.4
Stress concentration factor			1.92	1.85	1.74	1.69	1.58

Note: "E" corresponds to the experimental results; "T" corresponds to the theoretical results.

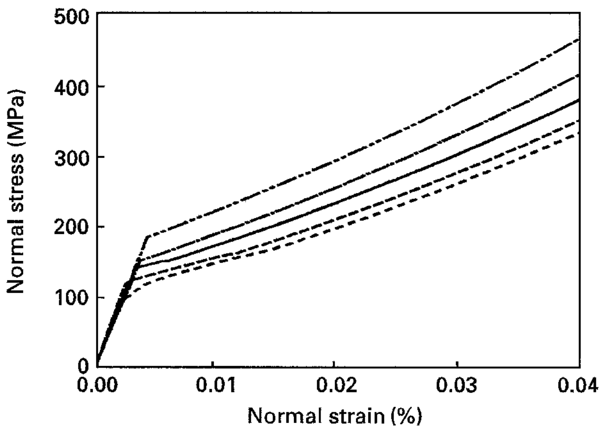

Figure 15 Predicted tensile stress–strain curves of prestressed VIRALL laminates. The line codes are (- -) 0 MPa, (– –) 100 MPa, (—) 160 MPa, (— - -) 200 MPA and (— - —) 300 MPa.

5. Conclusion

A micromechanics analysis has been presented which allows prediction of (a) the effects of fibre pre-stressing on the ply stresses within VIRALL laminates, (b) the tensile stress–strain curve and (c) the mechanical properties of VIRALL laminates. The theoretical study on the ply stresses of VIRALL laminates shows that prestressing has a dramatic influence on the ply stresses. The residual fibre stress increases as the prestress increases whilst the residual adhesive and matrix stresses decrease as the prestress increases. The theoretical and experimental studies on the stress–strain relationship and mechanical properties of VIRALL laminates show that the stress–strain curves of VIRALL laminates move upwards when the prestress increases and that the mechanical properties of VIRALL laminates increases with the pre-stress. The analysis shows that the movement upwards of stress–strain curves of VIRALL laminates is due to the contribution of the tensile strengthening of Vinylon fibres. The increase in the mechanical properties of VIRALL laminates is due to the contribution of the tensile strengthening of the Vinylon fibres and the delay of adhesive cracking by pre-loading the fibres.

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