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LAMINA PROPERTIES, LAY-UP CONFIGURATIONS AND LOADING CONDITIONS FOR A RANGE OF FIBRE-REINFORCED COMPOSITE LAMINATES

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Abstract
This paper gives details of the input data and a description of the laminates provided to all participants in an exercise to predict the strength of composite laminates. The input data include the elastic constants and the stress/strain curves for four unidirectional laminae and their constituents. Six types of laminates, chosen for the analysis, are described together with the lay-up, layer thicknesses, stacking sequences and the loading conditions. Consideration is given as to why these six laminates were selected and of the challenges imposed by the selected problems. The detailed instructions issued to the contributors are also presented. © British Crown Copyright 1998, Defence Evaluation and Research Agency, published by Elsevier Science Ltd with permission

Keywords: biaxial loading, carbon and glass fibre composites, mechanical properties, lay-up, lamina, multidirectional laminates

1 INTRODUCTION

In order to confirm the current state-of-the art of predicting failure in composite laminates, an exercise was launched by Hinton and Soden.[1] In this exercise, selected workers, including leading academics and developers of software and numerical codes, were invited to submit papers describing their current theory and its intended application, predict the deformation and strength of selected laminates under a variety of biaxial loads and compare their prediction with experimental results provided.

The process of selecting and setting a manageable, useful and balanced set of tasks to achieve the aims of the exercise was by no means simple or easy. However, six laminates were selected to represent a wide range of parameters. These parameters include the type of composite material (fibre and matrix), the type of laminate lay-up (unidirectional, angle-ply, cross-ply, quasi-isotropic, etc.) and the loading conditions. The choice of laminates and loading conditions was determined, to some extent, by the availability of experimental data for use at a later stage of the exercise. The availability of data for particular laminates had, in turn, a large influence on the selection of materials for the exercise.

The theoretical predictions and details of the theories used by the individual contributors are presented in Refs 2–13 and the predictions of various theories are compared in Ref. 14. In all of these predictions, the authors were asked to employ exactly the same input data to allow rational comparison between the predictions of various theories.

The purpose of the present paper is to provide full details of the input data given to all participants. The input data included the elastic constants, stress/strain curves and strengths for four unidirectional laminae and their constituents. The six types of laminates chosen for the analysis, the lay-ups, layer thicknesses, stacking sequences and the loading conditions for each laminate are described. The sources and experimental data on material properties and on the behaviour of the selected laminates are discussed separately in Ref. 14.

2 MATERIAL PROPERTIES

2.1 General

Many different types of composite materials are available. To make the exercise manageable, consideration was limited to continuous-fibre-reinforced thermosetting plastics. Taking into consideration the availability of suitably extensive experimental data for laminates, two important and widely used classes of fibres (carbon and E-glass) and one group of resin systems (epoxy resins) were selected for the exercise.

A unidirectional (UD) lamina made of continuous fibres in a softer matrix was considered to be the basic building block for the multidirectional laminates. The properties of the laminate depend very much on the

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properties of the laminae. The behaviour of each lamina is, in turn, governed by its constituents, i.e. the properties of the fibres, the surrounding matrix, the interface and the relative amount of fibres and matrix in the lamina. Tables 1–10 present typical data for the properties of four unidirectional laminae, four epoxy resin matrices and four types of E-glass or carbon fibres. The stress/strain behaviour of composite laminates is sometimes highly non-linear, particularly in shear. Figures 1–7 show typical stress/strain curves for the selected laminae under a variety of uniaxial loadings. These data were presented to the participants.

For performing theoretical analysis of the mechanical behaviour of multidirectional laminates under various loadings, most theories require the properties of each of the individual layers in the laminates. The properties required include: elastic constants and thermal properties, strengths, failure strains, in some cases, full stress/strain curves and occasionally fracture toughness. Some methods of analysis require information on the properties of the constituent fibres and matrix.

The three-dimensional elastic constants for an orthotropic UD lamina consist of the following independent in-plane and through-thickness properties (see for

Table 1. Mechanical and thermal properties of four unidirectional laminae

Fibre type	AS4	T300	E-glass 21xK43 Gevetex	Silenka E-Glass 1200tex
Matrix	3501-6 epoxy	BSL914C epoxy	LY556/HT907/ DY063 epoxy	MY750/HY917/ DY063 epoxy
Specification	Prepeg	Filament winding	Filament winding	Filament winding
Manufacturer	Hercules	DFVLR	DLR	DRA
Fibre volume fraction, V_f	0·60	0·60	0·62	0·60
Longitudinal modulus, E_1 (GPa)	126[a]	138	53·48	45·6
Transverse modulus, E_2 (GPa)	11	11	17·7	16·2
In-plane shear modulus, G_{12} (GPa)	6·6[a]	5·5[a]	5·83[a]	5·83[a]
Major Poisson's ratio, ν_{12}	0·28	0. 28	0·278	0·278
Through thickness Poisson's ratio, ν_{23}	0·4	0·4	0·4	0·4
Longitudinal tensile strength, X_T (MPa)	1950[b]	1500	1140	1280
Longitudinal compressive strength, X_c (MPa)	1480	900	570	800
Transverse tensile strength, Y_T (MPa)	48	27	35	40
Transverse compressive strength, Y_c (MPa)	200[b]	200	114	145[b]
In-plane shear strength, S_{12} (MPa)	79[b]	80[b]	72[b]	73[b]
Longitudinal tensile failure strain, ε_{1T} (%)	1·38	1·087	2·132	2·807
Longitudinal compressive failure strain ε_{1C} (%)	1·175	0·652	1·065	1·754
Transverse tensile failure strain ε_{2T} (%)	0·436	0·245	0·197	0·246
Transverse compressive failure strain, ε_{2C} (%)	2·0	1·818	0·644	1·2
In-plane shear failure strain, γ_{12u} (%)	2	4	3·8	4
Strain energy release rate, G_{IC} (J m^{-2})	220	220	165	165
Longitudinal thermal coefficient, α_1 (10^{-6}/°C)	−1	−1	8·6	8·6
Transverse thermal coefficient, α_2 (10^{-6}/°C)	26	26	26·4	26·4
Stress free temperature (°C)	177	120	120	120
Curing			2 h at 120°C 2 h at 150°C	2 h at 90°C 1·5 h at 130°C 2 h at 150°C

[a]Initial modulus.
[b]Nonlinear behaviour and stress/strain curves and data points are provided.

Table 2. Mechanical and thermal properties of four fibres

Fibre type	AS4	T300	E-glass 21xK43 Gevetex	Silenka E-Glass 1200tex
Longitudinal modulus, E_{f1} (GPa)	225	230	80	74
Transverse modulus, E_{f2} (GPa)	15	15	80	74
In-plane shear modulus, G_{f12} (GPa)	15	15	33·33	30·8
Major Poisson's ratio, ν_{f12}	0·2	0·2	0·2	0·2
Transverse shear modulus, G_{f23}	7	7	33·33	30·8
Longitudinal tensile strength, X_{fT} (MPa)	3350	2500	2150	2150
Longitudinal compressive strength, X_{fc} (MPa)	2500	2000	1450	1450
Longitudinal tensile failure strain, ε_{f1T} (%)	1·488	1·086	2·687	2·905
Longitudinal compressive failure strain, ε_{f1C} (%)	1·111	0·869	1·813	1·959
Longitudinal thermal coefficient, α_{f1} (10^{-6}/°C)	−0·5	−0·7	4·9	4·9
Transverse thermal coefficient, α_{f2} (10^{-6}/°C)	15	12	4·9	4·9

Table 3. Mechanical and thermal properties of four matrices

Matrix type	3501-6 epoxy	BSL914C epoxy	LY556/HT907/ DY063 epoxy	MY750/HY917/ DY063 epoxy
Manufacturer	Hercules	DFVLR	Ciba Geigy	Ciba Geigy
Modulus, E_m (Gpa)	4·2	4·0	3·35	3.35
Shear modulus, G_m (Gpa)	1·567	1·481	1·24	1·24
Poisson's ratio, ν_m	0·34	0·35	0·35	0·35
Tensile strength, Y_{mT} (MPa)	69	75	80	80
Compressive strength, Y_{mC} (MPa)	250	150	120	120
Shear strength, S_m (MPa)	50	70	—	—
Tensile failure strain, ε_{mT} (%)	1·7	4	5	5
Thermal coefficient, α_m (10^{-6}/°C)	45	55	58	58

instance Ref. 16): $\mathbf{E_1}$, $\mathbf{E_2}$, $\mathbf{E_3}$, $\mathbf{G_{12}}$, $\mathbf{G_{13}}$, $\mathbf{G_{23}}$, ν_{12}, ν_{13}, ν_{23} where the subscripts 1, 2 and 3 refer to the three mutually perpendicular principal material directions. Figure 8 shows a schematic diagram of a UD lamina with the co-ordinate system used. The rest of the Poisson's ratios can be obtained by applying the reciprocal Maxwell relations,[16] which give $\nu_{ij}/E_i = \nu_{ji}/E_j$. Four of these constants ($\mathbf{E_1}$, $\mathbf{E_2}$, ν_{12} and $\mathbf{G_{12}}$) pertain to the in-plane behaviour of thin laminae and the rest are related to the through-thickness (direction 3) behaviour.

It is usually assumed that a unidirectional fibre-reinforced lamina can be treated as transversely isotropic. For a transversely isotropic lamina, the independent elastic constants are reduced to five because $E_2 = E_3$, $G_{12} = G_{13}$, $\nu_{12} = \nu_{13}$ and $G_{23} = E_2/2(1+\nu_{23})$.[16] For two-dimensional (plane stress) analysis only four independent constants are required. Methods of measuring these properties are described in a number of references, e.g. Ref. 16.

Table 4. In-plane shear stress/strain data for AS4/3501-6 lamina

Strain (%)	Stress (MPa)
0·000	0·0
0·076	5·0
0·114	7· 5
0·152	10·0
0·190	12·5
0·228	15·0
0·266	17·5
0·305	20·0
0·344	22·5
0·383	25·0
0·424	27·5
0·465	30·0
0·507	32· 5
0·551	35·0
0·587	37·0
0·596	37·5
0·644	40·0
0·746	45·0
0·860	50·0
0·991	55·0
1·142	60·0
1·319	65·0
1·527	70·0
1·772	75·0
2·000	79·0

Orthotropic composites generally possess nine strengths and nine failure-strain values. These are longitudinal tensile and compressive properties X_{1T}, ε^u_{1T}, X_{1C} and ε^u_{1C}, transverse tensile and compressive properties X_{2T}, ε^u_{2T}, X_{2C} and ε^u_{2C}, through-thickness tensile and compressive properties X_{3T}, ε^u_{3T}, X_{3C} and ε^u_{3C} and in-plane and through-thickness shear properties S_{12}, γ^u_{12}, S_{13}, γ^u_{13}, S_{23} and γ^u_{23}.

The assumption of transverse isotropy and plane stress conditions reduces the number of uniaxial strength properties required to five for a UD lamina.

The fracture energy of a unidirectional composite is yet another property that some analyses rely upon. Normally, G_{IC} is determined from a double cantilever beam (DBC) test (see for instance Refs 17 and 18 for description of other methods used).

There are a number of methods for measuring strengths and failure strains in tension, compression and in shear[16,18–21] and the failure properties obtained from different methods can be different. Some properties (e.g. compression and shear strengths[22,23]) are particularly difficult to determine accurately. Indeed, composite material characterisation is one of the key areas of concern and hence the problem of standardising test

Table 5. Data for in-plane shear stress/strain curve of T300/ BSL914C epoxy lamina

Strain (%)	Stress (MPa)
0·000	0·0
0·182	10·0
0·273	15·0
0·364	20·0
0·455	25·0
0·548	30·0
0·644	35·0
0·747	40·0
0·864	45·0
1·004	50·0
1·185	55·0
1·431	60·0
1·777	65·0
2·002	67·5
2·272	70·0
2·743	73·5
2·984	75·0
3·447	77·5
4·0	80·0

methods for determining design allowables is currently being addressed by several agencies in the USA and Europe.

The difficulties in measuring mechanical properties sometimes lead to a wide range of values being quoted for the same property of the same material. Wherever possible the material properties given in Tables 1–10 were obtained from the same source as experimental data for the laminates considered and are consistent with properties published elsewhere (see Part B of the Exercise[14]). Inevitably, some of the materials data given in Tables 1–3 will be inaccurate.

2.2 Properties of the fibres

Four types of fibres were selected in the analysis, two types of E-glass fibres and two types of carbon fibres. They were chosen for consistency with data for particular laminates. The fibres are:

- E-Glass fibres, Silenka, 1200tex
- E-Glass fibres, Gevetex, 21xK43
- T300 carbon fibres
- AS4 carbon fibres

The properties assumed for these fibres are listed in Table 2. Both types of E-glass fibres are isotropic while the carbon fibres are anisotropic. In the latter case, the modulus along the fibre direction is much higher than that in the transverse direction.

Determining the properties of the fibres is not always straightforward as the fibres are normally of diameters in the range 5–20 μm, and hence they are difficult to handle. In order to obtain the mechanical properties, indirect methods are usually adopted. In these methods, tests are carried out on unidirectional laminae where the fibres are embedded within a matrix. Suitable micromechanics relations are then used to extract the properties of the fibres form the results of UD tests. As a result, some variations of the extracted properties are expected.[14]

2.3 Properties of the matrices

A variety of matrices are available for fibre-reinforced composite materials. Epoxy resins have been

Table 6. Data for in-plane shear stress/strain curve of E-glass/MY750/HY917/DY063 epoxy lamina

Strain(%)	Stress (MPa)
0·0	0·0
0·1	5·830
0·2	11·660
0·3	17·490
0·4	23·320
0·5	29·150
0·6	34·980
0·7	37·705
0·8	41·298
0·9	44·535
1·0	47·446
1·1	50·056
1·2	52·391
1·3	54·475
1·4	56·331
1·5	57·982
1·6	59·447
1·7	60·748
1·8	61·902
1·9	62·927
2·0	63·839
2·1	64·653
2·2	65·382
2·3	66·041
2·4	66·639
2·5	67·188
2·6	67·696
2·7	68·173
2·8	68·624
2·9	69·055
3·0	69·472
3·2	70·273
3·4	71·039
3·5	71·409
3·7	72·109
3·8	72·432
3·9	72·728
4·0	72·991

Table 7. Data for in-plane shear stress/strain curve of E-glass/LY556/HT907/DY063 epoxy lamina

Strain (%)	Stress (MPa)
0·0	0·0
0·1	5·830
0·2	11·660
0·3	17·490
0·4	23·320
0·5	29·150
0·6	34·980
0·7	37·705
0·8	41·298
0·9	44·535
1·0	47·446
1·1	50·056
1·2	52·391
1·3	54·475
1·4	56·331
1·5	57·982
1·6	59·447
1·7	60·748
1·8	61·902
1·9	62·927
2·0	63·839
2·1	64·653
2·2	65·382
2·3	66·041
2·4	66·639
2·5	67·188
2·6	67·696
2·7	68·173
2·8	68·624
2·9	69·055
3·0	69·472
3·2	70·273
3·4	71·039
3·5	71·409
3·7	72·109

Table 8. Data for the transverse compressive stress/strain curve of E-glass/MY750/HY917/DY063 epoxy lamina

Strain (%)	Stress (MPa)
0·000	−0·0
−0·062	−10·0
−0·123	−20·0
−0·185	−30·0
−0·247	−40·0
−0·309	−50·0
−0·371	−60·0
−0·434	−70·0
−0·499	−80·0
−0·566	−90·0
−0·640	−100·0
−0·723	−110·0
−0·822	−120·0
−0·944	−130·0
−1·103	−140·0
−1·200	−145·0

employed in a number of load-bearing application. Four types of epoxy matrices were used in the analysis. These are

- MY750/HY917/DY063 (Ciba-Geigy)
- LY556/HT907/DY063 (Ciba-Geigy)
- 3501-6 (Hercules)
- BSL914C (Ciba-Geigy)

Typical properties for these four matrix materials are shown in Table 3. The data listed in Table 3 were selected from a wide range of values available in the literature.[14]

2.4 Properties of the unidirectional laminae

Table 1 lists typical values of properties of four different unidirectional (UD) laminae used in the exercise. The four UD laminae are:

Table 9. Data for the transverse compressive stress/strain curve of AS4/3501-6 lamina

Strain (%)	Stress (MPa)
0·000	0·0
−0·091	−10·0
−0·182	−20·0
−0·273	−30·0
−0·364	−40·0
−0·455	−50·0
−0·545	−60·0
−0·636	−70·0
−0·728	−80·0
−0·819	−90·0
−0·911	−100·0
−1·003	−110·0
−1·096	−120·0
−1·191	−130·0
−1·288	−140·0
−1·388	−150·0
−1·493	−160·0
−1·604	−170·0
−1·723	−180·0
−1·854	−190·0
−2·000	−200·0

Table 10. Data for longitudinal tensile stress/strain curve of AS4/3501-6 lamina

Strain (%)	Stress (MPa)
0·0	0·0
0·157	200·0
0·235	300·0
0·312	400·0
0·388	500·0
0·463	600·0
0·537	700·0
0·610	800·0
0·682	900·0
0·754	1000·0
0·824	1100·0
0·893	1200·0
0·962	1300·0
1·029	1400·0
1·095	1500·0
1·160	1600·0
1·224	1700·0
1·287	1800·0
1·380	1950·0

1. E-Glass/MY750 epoxy (Silenka E-glass/MY750/HY917/DY063)
2. E-Glass/LY556 epoxy (Gevetex E-glass/LY556/HT907/DY063)
3. AS4 Carbon/epoxy (AS4/3501-6)
4. T300 Carbon/epoxy (T300/BSL-914C)

The constituent fibres and the epoxy resin matrices were as described in Sections 2.2 and 2.3 above. The material properties were derived by a variety of methods and the data and its sources are discussed in Ref. 14 Cooling after curing results in residual stresses and the assumed stress-free temperatures are included in Table 1.

3 DETAILS OF LAMINATES SELECTED

Undoubtedly, there are many interesting and unresolved problems in the area of predicting the stress strain

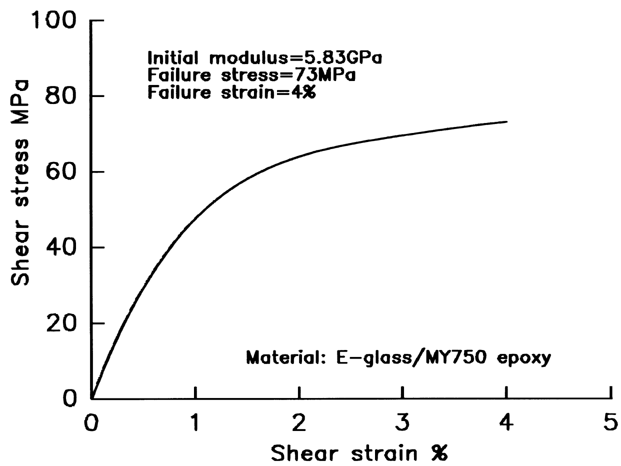

Fig. 1. In-plane shear stress/strain curve for E-glass/MY750/HY917/DY063 epoxy lamina.

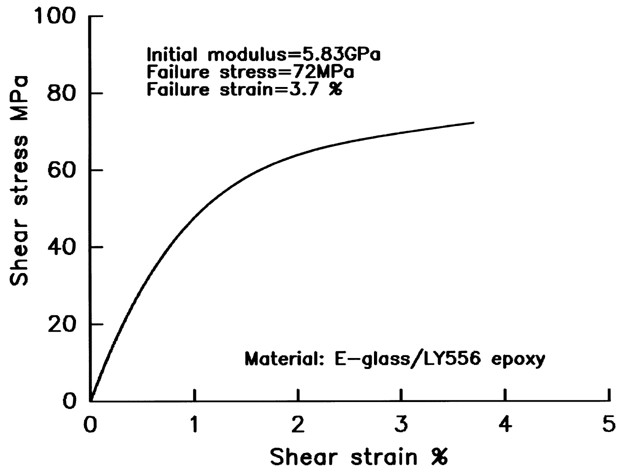

Fig. 2. In-plane shear stress/strain curve for E-glass/LY556/HT907/DY063 epoxy lamina.

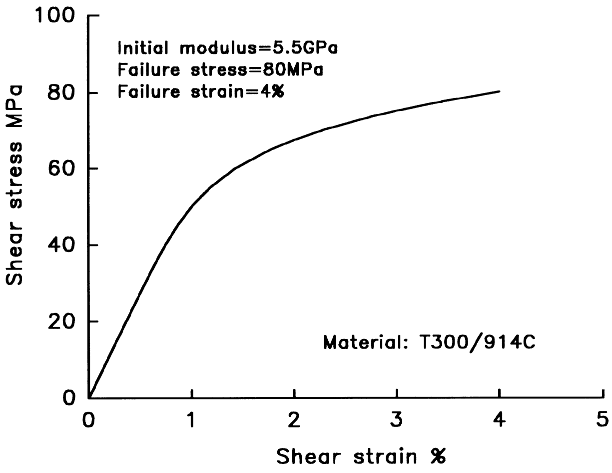

Fig. 4. In-plane shear stress/strain curve for T300/BSL914C epoxy lamina.

characteristics and fracture of composite laminates. Selecting the laminates and loading conditions to be analysed was not easy. The following factors were taken into consideration:

- The problems should cover a wide range of lay-ups. For this reason, six different lay-ups were chosen. These lay-ups are 0° unidirectional lamina, (90°/±30°/90°), (0°/±45°/90°), (±55°), (0°/90°) and (±45°).
- A wide range of loading conditions should be analysed. The problems selected include generating the complete failure envelopes under two types of combined stresses, namely combined direct stresses σ_y vs σ_x and combined direct stress and shear stress (σ_y vs τ_{xy}) or (σ_x and τ_{xy}).
- The problems should include predicting the stress/strain curves under both uniaxial and biaxial loading because changes in laminate stiffness may be critical in some applications.
- The laminates analysed should develop different types of damage as a consequence of loading in shear, tension and compression, transverse and parallel to the fibre direction.
- Both linear and non-linear properties of unidirectional laminae should be considered.
- Experimental results should be available which could be used to check the effectiveness of the theoretical predictions.

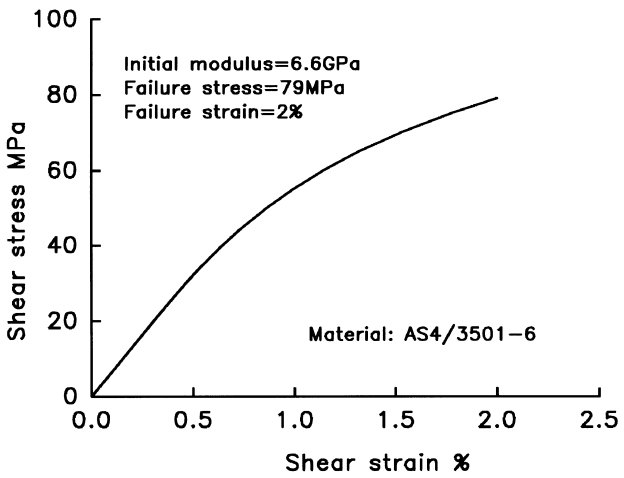

Fig. 3. In-plane shear stress/strain curve for AS4/3501-6 epoxy lamina.

The six types of laminate lay-ups selected were analysed under a variety of loading conditions. The instructions to participants (see Appendix), specified how loads were to be applied and how results were to be presented. Table 11 summarises laminate type, material type and the graphical results requested. Figure 9 shows a diagrammatic representation of a failure envelope. The laminates selected are as follows:

1. 0° unidirectional lamina of thickness 1 mm.
2. Balanced and symmetric (90°/±30°/90°) laminate. Layer orientation: 90°/+30°/−30°/−30°/+30°/90°. The total thickness is 2 mm. The thickness of the ±30° plies is 82·8% and that of the 90° plies is 17·2% of the total thickness of the laminate.

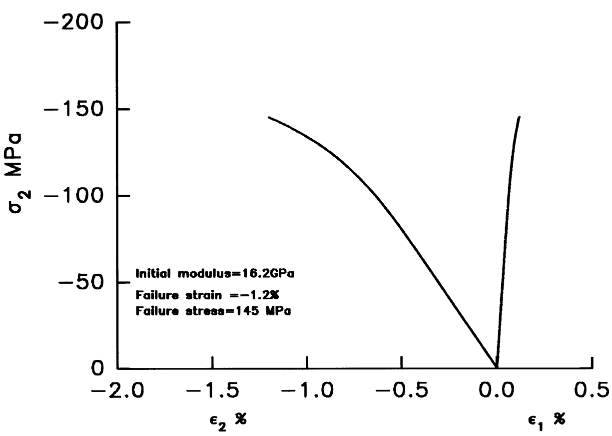

Fig. 5. Transverse compressive stress/strain curve for E-glass/MY750/HY917/DY063 epoxy lamina.

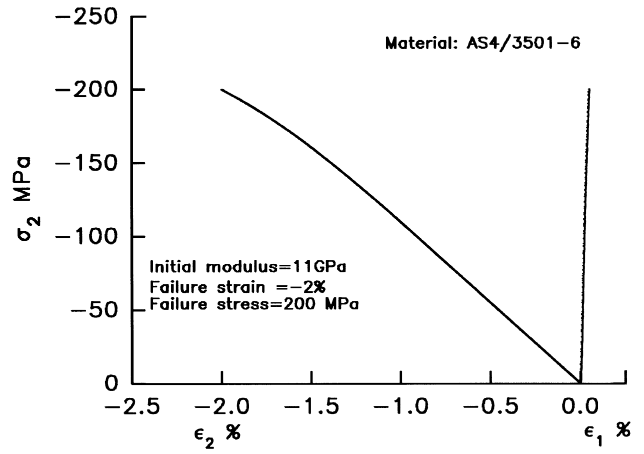

Fig. 6. Transverse compressive stress/strain curve for AS4/3501-6 epoxy lamina.

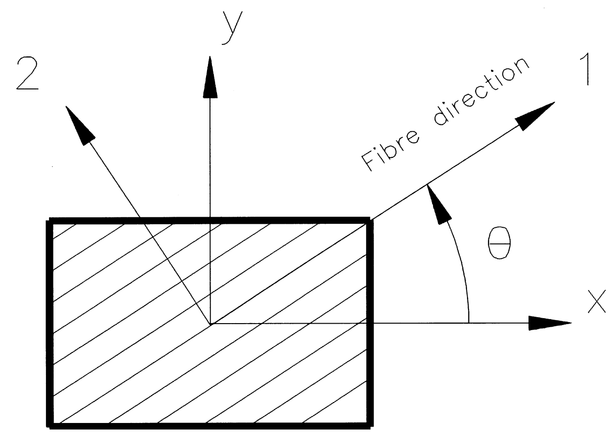

Fig. 8. Schematic showing the co-ordinate system used for a unidirectional lamina.

3. Balanced and symmetric (0°/±45°/90°) quasi-isotropic laminate. Layer orientation: 90°/+45°/−45°/0°/0°/−45°/+45°/90°. The total thickness of the laminate is 1·1 mm, and all the plies have identical thickness.
4. Balanced and symmetric (±55°) angle ply laminate. The layer orientation is +55°/−55°/−55°/+55°. The total thickness is 1 mm and the thickness of each lamina is 0·25 min.
5. Balanced and symmetric (0°/90°) cross ply laminate. The layer orientation is 0°/90°/90°/0°. The total thickness is 1·04 mm and each ply has a thickness of 0·26 mm.
6. Balanced and symmetric (±45°) angle ply laminate. The layer orientation is +45°/−45°/−45°/+45°. The total thickness is 1 mm and each ply has a thickness of 0·25 mm.

Schematic diagrams showing the loading directions, layer and laminate dimensions and stacking sequence of the laminates are shown in Figs 10–15. Note that the angles of the fibres in each layer are measured from the

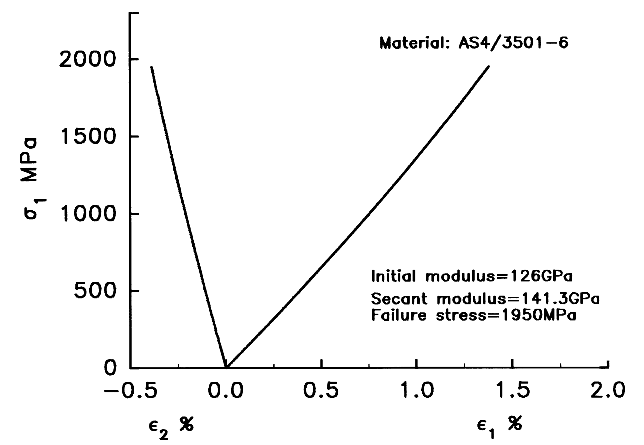

Fig. 7. Longitudinal tensile stress/strain curve for AS4/3501-6 epoxy lamina.

x direction as shown in Fig. 8. The selection of the laminates and the loading conditions was based upon the following considerations.

3.1 Selection of 0° unidirectional laminae

Many failure theories are formulated on the basis of the behaviour of a single lamina and are applied by using laminate theory which assumes that a lamina subjected to combined stresses will behave identically whether it is isolated or within a multidirectional laminate. Before proceeding to analyse the behaviour of laminates, participants were first asked to predict failure envelopes for unidirectional laminae under biaxial loads. The objective was to demonstrate and compare the assumptions and predictions at this basic level which will presumably be reflected in the accuracy of more complex laminate predictions.

Figure 10 shows diagrams of 0° unidirectional lamina under various types of combined biaxial loads (σ_y and τ_{xy}) (σ_x and τ_{xy}) and (σ_y and σ_x). The unidirectional composite materials selected for the analysis were:

E-glass/MY750 subjected to combined σ_y and σ_x.
E-glass/LY556 subjected to combined σ_y and τ_{xy}.
T300/914C subjected to combined σ_x and τ_{xy}.

3.2 Selection of (±30°/90°) laminate

This (±30°/90°) E-glass/LY556 laminate (Fig. 11) was selected partly because experimental results are available for the final failure under combined biaxial loading of σ_y with σ_x and σ_x with τ_{xy}. The construction of the laminate is such that the thickness of the ±30° plies, being 82·8% of the total thickness, is different from that of the 90° plies, which form 17·2% of the total thickness of the laminate. That laminate is not quasi-isotropic, a number of different modes of failure are expected to be encountered under biaxial loading and the final failure stresses are not expected to be simply due to fibre failure.

Table 11. Summary of laminate types, material types and plots required from contributors

Laminate type	Material type	Plots required and description of loading conditions
0° unidirectional lamina	E-glass/LY556/HT907/DY063 T300/BSL914C E-glass/MY750/HY917/DY063	1. σ_y vs τ_{xy} failure stress envelope 2. σ_x vs τ_{xy} failure stress envelope 3. σ_y vs σ_x failure stress envelope
(90°/±30°/90°) laminate	E-glass/LY556/HT907/DY063	4. σ_y vs σ_x failure stress envelope 5. σ_x vs τ_{xy} failure stress envelope
(0°/±45°/90°) laminate	AS4/3501-6	6. σ_y vs σ_x failure stress envelope 7. Stress/strain curves under uniaxial tensile loading for $\sigma_y/\sigma_x = 0/1$ 8. Stress/strain curves for $\sigma_y/\sigma_x = 2/1$
±55° angle ply laminate	E-glass/MY750/HY917/DY063	9. σ_y vs σ_x failure stress envelope 10. Stress/strain curves under uniaxial tensile loading for $\sigma_y/\sigma_x = 0/1$ 11. Stress/strain curves for $\sigma_y/\sigma_x = 2/1$
(0°/90°) cross ply laminate	E-glass/MY750/HY917/DY063	12. Stress/strain curve under uniaxial tensile loading for $\sigma_y/\sigma_x = 0/1$
±45° angle ply laminate	E-glass/MY750/HY917/DY063	13. Stress/strain curves for $\sigma_y/\sigma_x = 1/1$ 14. Stress/strain curves for $\sigma_y/\sigma_x = 1/-1$

3.3 Selection of (0°/±45°/90°) laminate

Quasi-isotopic laminates are an important class of composites and most familiar to the aerospace industries. One of the common quasi-isotropic laminates is that chosen for study in the exercise which consisted of (0°/±45°/90°) lay-up, made of AS4/3501-6 carbon/epoxy material (Fig. 12). Unlike the (±30°/90°) laminate described above, the $(0°/\pm45°/90°)_s$ quasi-isotropic laminates are expected to exhibit the same strengths when loaded in the 0° and 90° directions. Experimental results are available for failure of this type of laminates under combined tension-tension and tension-compression biaxial loading. Therefore, one of the tasks given to the contributors was to generate the biaxial failure stress envelope (σ_y vs σ_x).

In addition, two stress/strain curves were requested. The contributors were asked to predict the stress strain curves under uniaxial tensile loading ($\sigma_y/\sigma_x = 1/0$) and the stress/strain curves under biaxial tension ($\sigma_y/\sigma_x = 2/1$).

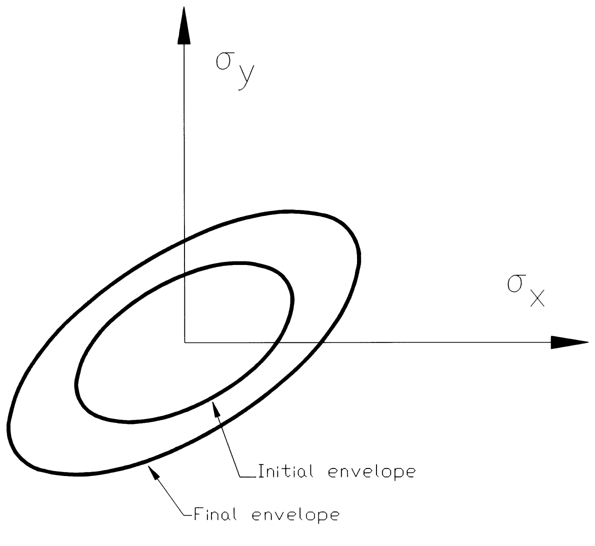

Fig. 9. Schematic of a failure envelope where initial and final failure stages are marked.

3.4 Selection of (±55°) laminate

The mechanical response of angle ply laminates should provide useful information on the ability of failure theories to predict various forms of failure induced by the presence of various stress components. Three stress components normally exist in the individual plies and

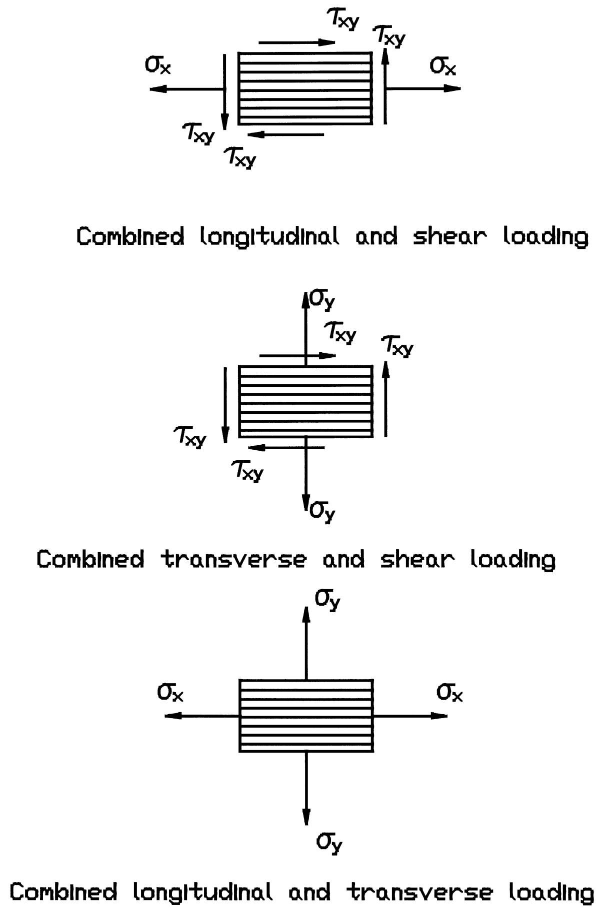

Fig. 10. Diagrams of 0° unidirectional lamina under various types of combined biaxial loads of (σ_x and τ_{xy}) (σ_y and τ_{xy}) and (σ_y and σ_x).

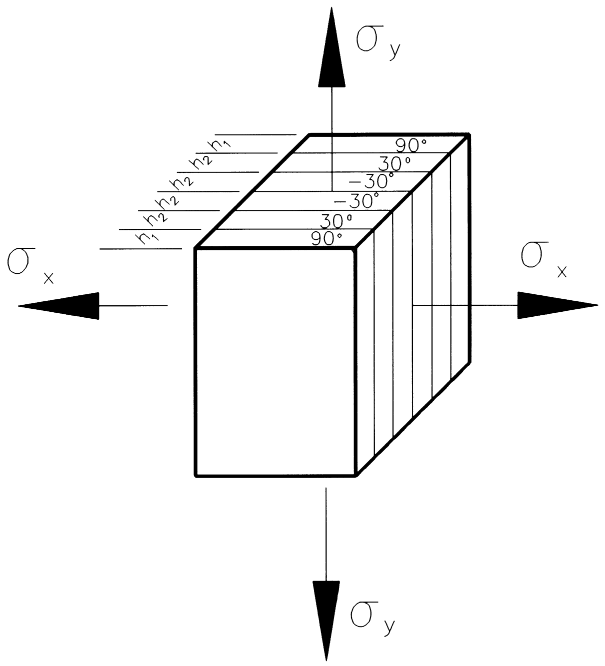

Fig. 11. Diagram showing the lay-up and loading configurations of the 90°/±30°/90° laminate. Note the total thickness of the laminate is 2 mm where $h_1 = 0{\cdot}172$ mm and $h_2 = 0{\cdot}414$ mm.

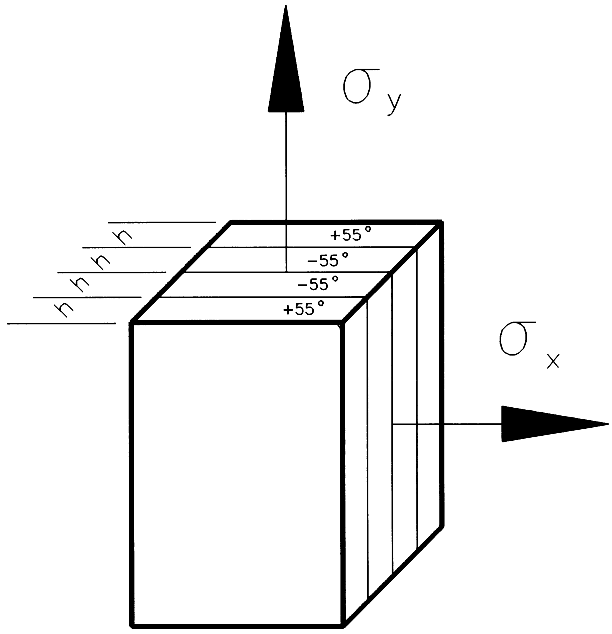

Fig. 13. Diagram showing the lay-up and loading configurations of the ±55° laminate. Note that the total thickness of the laminate is 1 mm and all the four layers have the same thickness.

those are tension (or compression) parallel and transverse to the fibre direction and shear stresses. However, the relative magnitude of these stresses depends on fibre orientation and loading conditions. The ±55° laminate (Fig. 13) was selected on the basis of the following considerations

- Its wide spread use in industrial pipework.
- The availability of experimental results on the failure under a wide range of biaxial failure stresses including those in the compression–compression quadrant.

For the ±55° laminates as for the quasi-isotropic laminate, one of the tasks given to the contributors was to generate the biaxial failure stress envelope (σ_y vs σ_x). In addition, two stress strain curves were requested. The contributors are asked to predict the stress strain

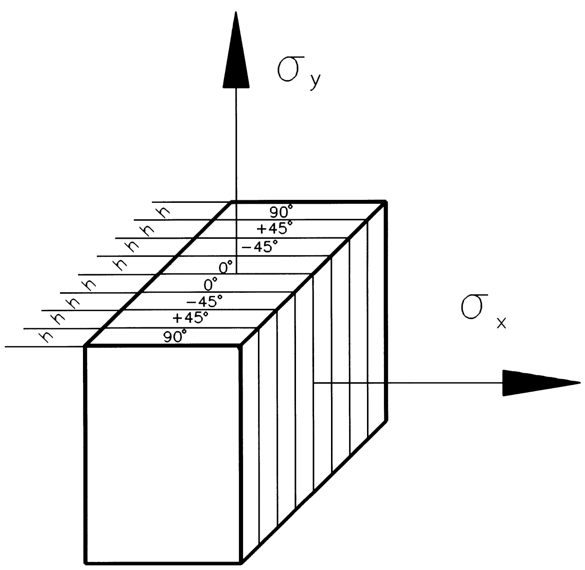

Fig. 12. Diagram showing the lay-up and loading configurations of the $(0°/\pm 45°/90°)_s$ laminate. Note that the total thickness of the laminate is 1·1 mm and all the layers have the same thickness.

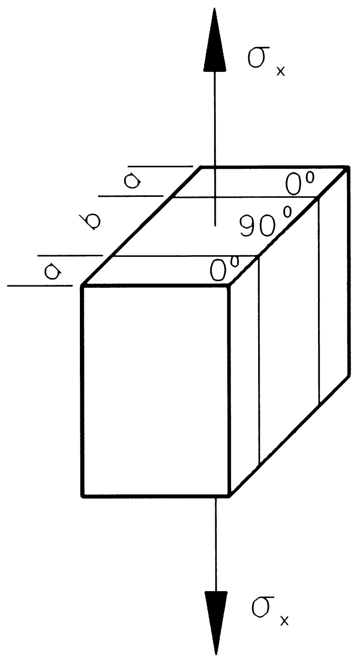

Fig. 14. Diagram showing the lay-up and loading configurations of the 0°/90°/0° laminate. Note the total thickness of the laminate is 1·04 mm, $b = 0{\cdot}52$ and $a = 0{\cdot}26$ mm.

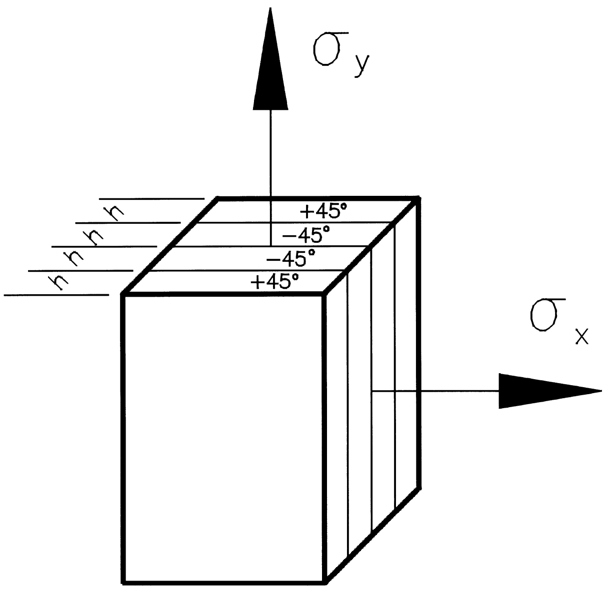

Fig. 15. Diagram showing the lay-up and loading configurations of the $\pm 45°$ laminate. Note that the total thickness of the laminate is 1 mm and all the layers have the same thickness.

curves under biaxial tension ($\sigma_y/\sigma_x = 2/1$) and the stress strain curves under uniaxial tensile loading ($\sigma_y/\sigma_x = 1/0$) which is expected to produce non linear response.

3.5 Selection of 0°/90° laminate

Cross-ply laminates consisting of layers oriented at 0° and 90° are a classical example used for studying the development of matrix cracking (transverse tension cracking) and its effect on the load carrying capacity of laminated composites. One of the simplest forms of cross ply laminates (Fig. 14) is made of plies oriented at 0°/90°/90°/0°, all of the same thickness. The case chosen for analysis in the exercise is that of 0°/90°/90°/0° laminate under uniaxial tension.

3.6 Selection of ($\pm 45°$) laminate

Experimental results are available on the behaviour of the $\pm 45°$ laminate under stress ratios $\sigma_y/\sigma_x = 1/1$ and $\sigma_y/\sigma_x = 1/-1$ (see Fig. 15) which could be regarded as equivalent to a 0°/90° laminate loaded under biaxial tension and pure shear, respectively. Hence, the theoretical solutions requested should provide an insight into the degree of understanding of 0°/90° laminates under loading cases other than uniaxial tension.

4 CONCLUDING REMARKS

- This paper presented details of the mechanical properties of the fibres, matrices and the unidirectional laminae used in the failure exercise.
- The materials selected have been widely used in practical applications and their properties are reasonably well characterised.
- Non-linear stress strain data has been presented as well as elastic constants for linear elastic analysis.
- In some cases, the literature gave a wide range of values for the same property and in other cases no data were available. The values chosen were in some cases arbitrary and inaccurate but this should not devalue the first part of this exercise as all the participants used exactly the same data.
- The six laminates chosen for analysis by the participants are considered to be representative of a wide range of composite laminates encountered in practical use in a variety of industries.
- A wide range of practical biaxial loading conditions were also specified which should produce a variety of modes of failure. In some cases a succession of failures may occur before the laminate can no longer carry load.
- In some cases the stress/strain behaviour of the laminates is expected to be linear and in some other cases highly non-linear.
- The solutions for this wide range of problems should help in stimulating researchers and engineers working in the area of composites to tackle the some of complex and challenging problems associated with design of composite laminates and should highlight some of major problems and gaps in current knowledge and practice.

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APPENDIX

Instructions to contributors

The instructions provided to each contributor are listed below in their original form.

The attached notes specify the unidirectional lamina properties, layer thicknesses, stacking sequences and loading for each of the laminates we would like you to analyse.

The in-plane loads (section stresses) should be applied in the x and y directions defined in the diagram provided for each laminate. The section stresses σ_x and σ_y are defined in the usual way as the in-plane loads per unit width divided by the total thickness of the laminate. In your calculations assume that the loads are increased monolonically, keeping the ratios of σ_x/σ_y, τ_{xy}/σ_x and τ_{xy}/σ_y constant.

Record and tabulate the magnitude of the section stresses (and if appropriate the type and location of failure) at which each failure is predicted.

Repeat the calculation to cover the range of stress ratios (2 or 4 quadrants) indicated by the graphs provided for each laminate.

Plot the results by using the scales provided for each laminate.

Draw curves through the results to represent the initial (inner) and final (outer) failure envelopes. Indicate any intermediate failure points. Plot the section stress vs strain curves as requested for particular laminates using the scales provided. It would be helpful if you would also send us your tables of results, but these will probably not be included in the paper. Results in the form of data files sent to us by E-mail or on floppy disks would be appreciated.

We are asking all contributors to use the same material properties even if you have reservations about the values provided.

Your theory may not require all the lamina properties provided (e.g. some software assumes linear elastic properties). In that case please employ your usual assumptions and neglect any information which is not needed.

If your theory requires additional (or different) information from that provided, please let us know as soon as possible and we will endeavour to provide that information. If you have default values for any missing parameters (e.g. interaction coefficients), we prefer you to use those.

In some cases the theory employed may not be intended to be applied to the whole range of laminates specified here. In that case, you may opt to analyse only some of the laminates but please explain the reasons for not analysing the other laminates in your paper.

The paper should describe Your failure theory and method of application to laminates in sufficient detail to allow your predictions to be reproduced by others, comment on the nature and effects of the failures predicted and, if appropriate, how your predictions could be used for design.

After receiving all the theoretical papers with your permission to publish the results, the experimental results will be superimposed on the theoretical predictions. The superimposed graphs will be sent back to you together *with tables of the experimental results for your future use and information on how the experimental results were obtained.*

The second paper (part B) would present graphs of superimposed results with any comment you may wish to make on the correlation between experiment and theory. You may choose to add a figure (or figures) to demonstrate refinement or particular features of your approach. You could indicate any future development to your theory which would allow you to consider a wider variety of laminates than those you are able to analyse immediately.

For those participants who have integrated failure analyses and structural analysis packages, details of the simple specimen geometry that you may opt to analyse as part of the second paper, will be sent as soon as you request them.