

FAILURE ANALYSIS OF FIBRE REINFORCED COMPOSITE LAMINATES

1. USE OF THE PROGRAM

1.1 Introduction

1.1.1 General notes

This Item together with ESDUpac A8418 provides a Fortran computer program for the failure analysis of a fibre reinforced composite laminate subjected to consecutive systems of combined in-plane, moment and thermal loading. The program differentiates between individual layer matrix material failure, termed damage, and individual layer fibre failure or matrix material failure of all the layers, both termed laminate failure. The consecutive loading systems can be applied with either the damage of each loading system in turn carried over to the next or with each new loading system applied to the laminate as originally undamaged. If laminate failure does not occur under a particular loading system an assessment of the level at which failure would occur for that system is provided before the analysis returns to the next loading system. The program applies to balanced or unbalanced laminates that are initially unrestrained but also includes the effect of holding the unloaded laminate flat (for storage) if required. While thermal effects have been included in the analysis moisture effects have not because of the less certain, time dependent, long term nature of such effects. However, moisture degradation can be incorporated for each individual layer by providing reduced values of layer material properties and allowable stresses (X , Y and Q), particularly for the matrix material.

The first part of the Item gives details of the theoretical basis of the program. It gives guidance on the application of the program, instructions for its use and examples of input and output.

The second part of the Item gives supporting information on the organisation of the program and the method of analysis.

The program is available in two formats: (a) a Fortran source code with example input and output files, and (b) an executable program for PCs. Both versions can be found on the Compact Disc and on disk in the Sub-series Software Volume.

The failure assessment is based on a linear elastic layer-by-layer plate analysis of the laminate in which the stresses in each layer in turn are compared to the Puck Modified Criterion (see Data Item No. 83014*) which differentiates between fibre and matrix material failures. If a layer matrix failure occurs the matrix material properties of that layer are removed by assuming that its (in-plane) transverse direct and shear stiffnesses are zero. It is assumed that when this happens the fibre can still take load in its axial direction and that the laminate through-the-thickness shear integrity is retained. Therefore, during further computation, the layer longitudinal (fibre) stiffness properties are retained as is the allowance for the thickness of the layer. Because these layer matrix failures can lead to the progressive failure of other layers their development is traced through the gradual application of a loading system in which matrix material failures are present to provide a damage history under that system. This continues until either total matrix failure has occurred throughout the laminate or a single longitudinal (fibre) layer failure occurs, at which point total laminate failure is assumed.

The program provides a layer damage history for the laminate up to failure under the specified loading systems applied consecutively. It first gives an input data check. This is followed by an analysis of the effect of holding the laminate flat if this has been requested for which the required restraining moments, layer stresses and damage (if any) are recorded. Each loading system is then applied in turn to the

* Data Item No. 83014 "Failure criteria for an individual layer of a fibre reinforced composite laminate under in-plane loading".

unrestrained laminate incorporating any held flat damage if this has occurred. In each case this starts with the laminate under thermal loading only, for which layer stresses and damage (if any) are again recorded. The specified mechanical loading is then added to the thermal loading. If damage or failure occurs at this level of mechanical loading the loading is reduced to the level at which damage first occurs (maintaining ratios of component loads). The damage is then tracked back up to the specified load level or to the level of laminate failure if that occurs first. If laminate failure has not occurred when the specified load level is reached or, initially, no damage or failure has occurred when the specified load is first applied, then the specified loads are boosted in ratio to trace the layer damage until laminate failure does occur. Subsequent loading systems will then be applied as specified by the user either to (a) the laminate incorporating the layer damage sustained at the preceding specified load level (not the boosted load level) or to (b) the laminate as initially undamaged. Note that if the held flat condition has been specified in either case any resulting damage will be passed on, in the case of (a) to the first applied load system and in the case of (b) to each applied load system in turn.

A choice of three forms of output is given. First a full output of the damage/failure and stress analysis history of the laminate may be specified. Secondly a short output may be requested which gives only the initial conditions and the final layer damage at each specified loading and at laminate failure. Thirdly an extract of the analysis may be chosen which gives only the applied loads, failure loads and cause of failure for each load case. In the full and short forms of output the layer data may be given for all the layers or restricted to the layers approaching a critical level of damage specified by the user.

The program considers only failure within an individual layer and does not consider interlaminar and delamination effects; these may be significant at the edges of a plate, for such effects see Data Item No. 95028*. Since in practice such interlaminar effects are important and the matrix material stress-strain properties in particular are likely to be inelastic, the analysis should be used with caution and adequately supported by testing. Fibre reinforced laminates can fail in many ways and guidance on the failure modes of the laminates, including those not considered by this analysis, are given in Data Item No. 82025†. The program is likely to prove most useful in the initial assessment of the relative strengths of different lay-ups. Note that like any other non-linear load-stress analysis the results obtained cannot necessarily be factored for different load levels.

1.1.2 Scope of the program

Criteria

The program performs a linear elastic analysis of the stresses in the individual layers of a laminate based on the method given in Data Items Nos 94004‡ and 94003** and compares these stresses with the Puck Modified Criterion. This criterion treats layer failure in longitudinal tension or compression (1-direction, see Sketch 1.1), a fibre dominated mode, separately from the matrix material dominated transverse direct and shear failure. Laminate failure is judged to have occurred when any layer fails in the 1-direction (fibre failure) or all the layers have failed under a combination of transverse direct (2-direction) and shear stress.

Laminate constitution

The laminate is considered to be built up from orthotropic homogeneous layers which may have different material elastic and thermal properties, thicknesses and orientations of their principal axes of orthotropy. The material direct and shear stress-strain properties are assumed to be elastic (linear) to failure. Through-the-thickness (z-direction) forces and shears are neglected as are interlaminar effects including

* Data Item No. 95028 "Delamination and free edge stresses in composite laminates subjected to uniform prescribed axial strain and temperature change".

† Data Item No. 82025 "Failure modes of fibre reinforced laminates".

‡ Data Item No. 94004 "Stress analysis of laminated flat plates".

** Data Item No. 94003 "Stiffnesses of laminated flat plates".

delamination.

Laminate loading

The laminate may be subjected to any combination of moments and in-plane loads (see Sketch 1.1). Thermal loading is applied as the difference between the stress-free (cure) temperature and the layer working temperatures. The latter can either vary linearly from the outer to the centre layers of the laminate or be specified separately for each layer so that any thermal distribution can be simulated. The layers whether unrestrained or held flat are analysed at the working temperature level. The program will accept a sequence of thermal and mechanical loading systems, each loading system being applied consecutively to the laminate in an initially unrestrained condition although the user may specify whether or not it will include layer matrix material damage resulting from previous loading systems. It will provide a history of layer matrix material failures throughout that sequence until either matrix material failure has occurred in all the layers or a fibre failure has occurred in a single layer. Either of these events is assumed to constitute laminate failure. If no such failure has occurred after a particular loading system has been applied that system will be boosted, in ratio, to a level at which laminate failure (assessed as indicated) does occur, before then proceeding to the next system.

1.2 Notation

Attention is drawn to the sign convention used in this Item. The convention is that now in common use and differs from that used in the previous version (Amendment C) which this version supersedes. The sign convention for moments and curvatures has been changed. The convention used in this Item is consistent with that used in Data Items associated with ESDU programs for the analysis of composites.

Both SI and British Units are quoted but any coherent system of units may be used.

1.2.1 Coordinate system (see Sketch 1.1)

Note: It is implicit in the program that the $z = 0$ plane is midway between the upper and lower surface of the laminate.

$0(x, y, z)$	laminate reference axes
$0(1, 2)$	principal axes of orthotropy of layer

1.2.2 Sign convention for stresses

Tensile stresses are positive, compressive stresses are negative; the positive value is taken for all allowable stresses (X , Y and Q).

1.2.3 Stresses

Q	allowable shear stress of layer in 1, 2-plane (see Sketch 1.1)	N/m^2	lbf/in^2
X	allowable direct stress of layer in fibre direction	N/m^2	lbf/in^2
Y	allowable direct stress of layer normal to fibre (in-plane)	N/m^2	lbf/in^2

σ	stress	N/m ²	lbf/in ²
σ_1	layer direct stress in fibre direction (see Sketch 1.2)	N/m ²	lbf/in ²
σ_2	layer direct stress normal to fibre (in-plane) (see Sketch 1.2)	N/m ²	lbf/in ²
σ_6	layer shear stress in 1, 2-plane (see Sketch 1.2)	N/m ²	lbf/in ²

1.2.4 Loading (mechanical)

L	sequential identification numbers for loading systems (from 1 to L_{max})		
M_x, M_y, M_{xy}	column matrix of bending moment intensities acting in xz- and yz-planes and twisting moment acting about x- and y-axis respectively (see Sketch 1.1)	N m/m	lbf in/in
N_x, N_y, N_{xy}	column matrix of direct load intensities and shear load intensity referred to (x, y) coordinates (see Sketch 1.1)	N/m	lbf/in

1.2.5 Loading (thermal)

T_0	initial (cure) temperature at which laminate is stress free	°C	°C
T_k	final (working) temperature of layer	°C	°C
α_1, α_2	layer coefficients of linear thermal expansion in 1-direction and 2-direction respectively	°C ⁻¹	°C ⁻¹
T_{o1}	value of T_k at outside of laminate at layer 1	°C	°C
T_m	value of T_k for mid-plane ($z = 0$) of laminate	°C	°C
T_{on}	value of T_k at outside of laminate at layer n	°C	°C
δT	difference between initial and final temperature, $\delta T = T_0 - T_k$	°C	°C

1.2.6 Failure criteria

$R(1)$ ratio of layer direct stress in longitudinal (in-plane, fibre) 1-direction to respective allowable stress, derived from Puck Modified Criterion,

$$R(1) = \sigma_1 / X_t \text{ (if } \sigma_1 \text{ is positive, tensile)}$$

$$R(1) = \sigma_1 / -X_c \text{ (if } \sigma_1 \text{ is negative, compressive)}$$

Note: $R(1) \geq 1$ is assumed fibre failure

$R(2)$ relationship between layer transverse (in-plane) direct and shear stresses and respective allowable stresses, derived from Puck Modified Criterion,

$$R(2) = (\sigma_2^2 / Y_t Y_c) + (\sigma_2 (1/Y_t - 1/Y_c)) + (\sigma_6 / Q)^2$$

Note: $R(2) \geq 1$ is assumed matrix material failure

1.2.7 Moduli, stiffnesses, compliances and Poisson's ratios

A	in-plane stiffness matrix for laminate	N/m	lbf/in
B	coupled in-plane and flexural stiffness matrix for laminate	N	lbf
D	flexural stiffness matrix for laminate	N m	lbf in
E_1, E_2	modulus of elasticity of layer in 1- and 2-directions respectively, $E_1 = 1/S_{11}$ and $E_2 = 1/S_{22}$	N/m ²	lbf/in ²
G_{12}	shear modulus of layer, $G_{12} = 1/S_{66}$	N/m ²	lbf/in ²
S_{11}, S_{22} S_{12}, S_{21} S_{66}	compliances of layer material (see Data Item No. 94003) (note that $S_{12} = S_{21}$)	m ² /N	in ² /lbf
ν_{12}	longitudinal Poisson's ratio of layer, ratio of transverse (in-plane) strain to longitudinal (fibre direction) strain due to an applied longitudinal direct stress $\nu_{12} = -S_{21}/S_{11}$		
ν_{21}	transverse Poisson's ratio of layer, ratio of longitudinal strain to transverse strain due to an applied transverse direct stress, $\nu_{21} = -S_{12}/S_{22}$		

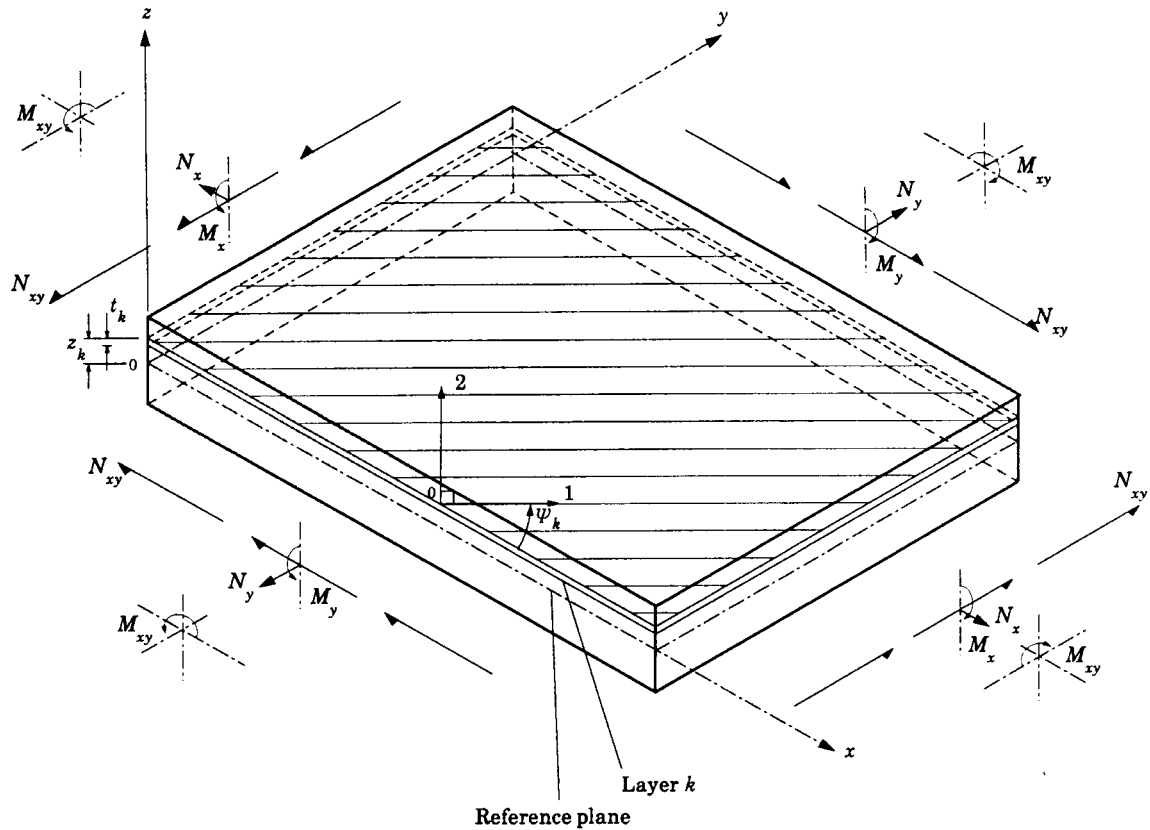
Copyright Engineering Sciences Data Unit

1.2.8 Laminate geometry

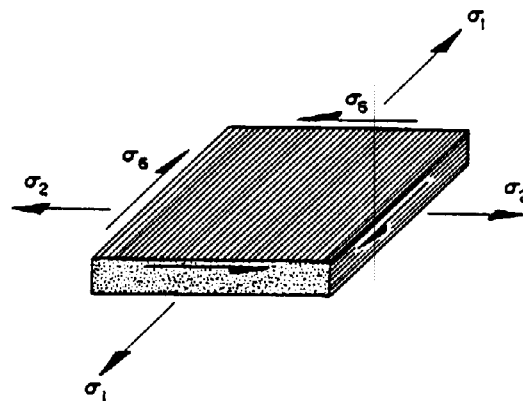
C	sequential identification number for layer configurations (from 1 to C_{max})		
cfr	chosen fraction for failure criteria $R(1)$ and $R(2)$ controlling layers which are printed out		
hf	identification for held flat condition		
k	layer identification		
n	number of layers in laminate		
op	identification of output form		
t	thickness of layer (see Sketch 1.1)	m	in
z	distance of layer middle surface from reference plane measured along z-axis (see Sketch 1.1)	m	in
ψ	angle of principal axis of orthotropy, 1-direction of layer measured from laminate reference axis (see Sketch 1.1)	degree	degree

1.2.9 Suffixes

c	compression
k	layer identification
max	maximum
t	tension
x, y, z	refer to laminate coordinate system (see Sketch 1.1)
1, 2, 6	refer to layer coordinate system (see Sketch 1.2)



Sketch 1.1 Sign convention for forces and moments



Sketch 1.2 Stress system aligned with principal (fibre) axis of orthotropy for individual layer in plane stress

1.3 References

The references are recommended as sources of information supplementary to that in this Item.

1. JONES, R.M. *Mechanics of composite materials.* McGraw Hill Book Co., New York, 1975.
2. TSAI, S.W. *Composite materials workbook.* Air Force Materials Laboratory, Wright-Patterson AFB, Ohio, AFML-TR-78-33, March 1978.
3. TSAI, S.W.
HAHN, H.T. *Introduction to composite materials.* Technomic Publishing Co., Westpoint, Connecticut, 1980.

1.4 Data Input Information

Many parameters are required to perform the failure analysis of a laminate and these are needed in the program input. Table 1.1 is given as a guide to the input for the Fortran program and an example input for this is given in Section 1.6.

Prior to the input of materials values 3 lines are provided for run identification details. These lines may be left blank or can carry up to 75 alphanumeric characters each. The contents of the lines appear in the output.

Also prior to the input of materials values, 2 lines are provided for the declaration of the units in which all the input data are to be supplied. These lines may be left blank or can carry up to 75 alphanumeric characters each. These lines also appear in the output. (Note that this is NOT an option to select units but simply the invitation to state the units used in the input data and to echo this statement in the output.)

Input data are required to define the properties of the materials, the orientation and lay-up sequence of the layers and the applied mechanical and thermal loading systems to which the laminate will be subjected. In addition a choice between full, short and extract forms of output (as specified in Section 1.5) must be made and a decision is required on whether or not the laminate is to be held-flat prior to application of the loading systems.

The input routine is arranged to avoid unnecessary repetition wherever possible. Layers having the same materials properties, thickness and fibre orientation (angle ψ , regardless of sign) are given a common configuration number for which the information is entered only once. It will be seen in Table 1.1 that the specific sequence in which particular layer configurations occur is later defined by entering the configuration numbers in sequence from the positive z surface of the laminate to the negative z surface. Reference to Sketch 1.1 will show the relationship between layer numbering and the direction of the loading. The number of separate layer configurations is limited to 50 and the total number of layers to 500.

The panel condition before mechanical loading is specified by choosing whether or not the laminate is to be held flat and providing the stress-free (cure) temperature. The choice is then made as to whether or not the damage sustained under each loading system is to be passed on to the next. If damage is to be passed on and the held flat facility is specified this will be applied only at the first working temperature and mechanical load level, which can therefore be used to analyse a storage condition. If damage is not to be passed on and the held flat facility is specified it will be repeated at the start of each new loading system. A single run specifying the held flat condition could be used to analyse a storage condition before a sequence of load cases is analysed. The specification of a fraction (*cfr*) denoting the proportion of the failure criteria, $R(1)$ and $R(2)$, for which the user requires layer data output is next required. This facility is provided because the full damage history of all the layers in a many layered laminate could result in extensive output. Only those layers for which $R(1)$ and $R(2) \geq cfr$ will feature in the data printed out.

The number of loading systems, L_{max} , (where $L_{max} \leq 20$) that are to be applied is specified followed by a choice indicating which form of output is required: full, short or extract. The loading systems to be applied to the laminate are entered in the order in which they are specified by the designer, regardless of relative magnitudes. Care should be taken to ensure that the sign convention shown in Sketch 1.1, which shows positive loads, moments and z-direction, is adhered to. It should be noted that if damage is to be passed on from one system to the next the order in which the loading systems are placed will significantly affect the occurrence of failure. The thermal loading of each layer is specified by entering the relevant values of T_k , the final (working) temperatures, for the particular applied loading system. They may be given as separate values of T_k for each layer or as three values, T_{o1} , T_m and T_{on} , which allow for a separate linear variation on each side of the middle surface (or layer) of the laminate. The applied (mechanical) loading for each system follows the thermal loading. For each new loading system the layer thermal loading will be the appropriate values of δT_k (see Notation, Section 1.2.5). Each new loading system is applied to the unrestrained laminate incorporating initial held flat damage and damage from previous load cases if specified.

Examples of input for the program in both free and fixed format are given in Section 1.6. Guidance on the tests necessary to provide values for the allowable stresses X_t , X_c , Y_t , Y_c and Q is given in Data Item No. 83014.

TABLE 1.1 PROGRAM INPUT DATA

Entry order	Enter the numerical values for the quantities indicated in free format. Each entry must be in the order given and made on a separate line with no blank lines in between (except Entries 1 and 2). The values given for each entry must have a space or comma between them. Some input systems may accept continuous data.
(1)	Enter run identification data, input file title or notes. Three lines 75 characters wide allowed. Lines may be left blank.
(2)	Enter description of units of input (see Section 1.4). Two lines 75 characters wide allowed. Lines may be left blank.
(3)	Number of separate layer configurations (limited to 50) Enter C_{max} (highest value of C), where $C_{max} \leq 50$.
(4)	Material properties and geometry of each layer configuration Enter $C \ \psi \ t \ E_1 \ E_2 \ G_{12} \ \nu_{12} \ \alpha_1 \ \alpha_2$
(5)	Enter $X_t \ X_c \ Y_t \ Y_c \ Q$
Repeat (4) and (5) as required	Repeat for each layer configuration. Note: enter $\psi \leq 90^\circ$ above; layers with an orientation between 0 and -90° are entered as a positive value, and the $\pm$ orientation is identified later (see (7) below). Where $-\psi$ has the same value as ψ for layers with the same properties only one entry is required. Also $1 \leq C \leq 50$.
(6)	Number of layers in laminate Enter n where $1 \leq n \leq 500$.
(7)	Sequence of layer configurations Enter C for each layer. Note: there must be n entries of the layer configuration identifier C , one for each layer starting with the most positive z layer. Where ψ_k is positive enter C , where ψ_k is negative enter $-C$. This angle should be compatible with the convention shown in Sketch 1.1. Limited to 25 entries per line, use new lines as required.
(8)	Number of loading systems Enter L_{max} where L_{max} is the number of loading systems (highest value of L). Note that $L_{max} \leq 20$.

TABLE 1.1 PROGRAM INPUT DATA (continued)

(9)	Form of output Enter op. Note: $op = 0$ requests short output $op = 1$ requests full output $op = 2$ requests extract output. } see Section 1.5.2.
(10)	Panel condition before mechanical loading Panel prior restraint Enter hf. Note: $hf = 0$ indicates laminate is not held flat before loading systems are applied and $hf = 1$ indicates laminate is held flat before loading systems are applied (see Section 2.2.1).
(11)	Panel stress-free (cure) temperature Enter T_0 (enter 0 if thermal loading is not required).
(12)	Progressive damage indicator Enter 0 or 1 as required. Note: 0 indicates layer damage is passed on from each loading system to the next. 1 indicates each loading system is applied to a laminate free of damage.
(13)	Critical layer failure fraction Enter cfr (fraction of failure criteria required). Note: Only data for layers with $R(1)$ and $R(2)$ equal to or more than this value will be printed out. If data for all the layers is required enter 0. If extract output has been specified enter 0.
Repeat (14) to (16) as required	Loading systems This complete section is repeated for each loading system in turn. Note: entries of the different systems where damage is to be passed on should be placed in order of application, not in order of magnitude. Details of the thermal loading must precede each entry for applied loading.
(14)	Layer thermal loading Enter 0 or 1 or 2 or 3 as required. Note: 0 indicates no thermal loading, (no difference between T_0 and T_k) 1 indicates linear variation of T_k through each half of laminate thickness 2 indicates T_k varies for each individual layer and 3 indicates repeat previous thermal loading.

TABLE 1.1 PROGRAM INPUT DATA (continued)

(15a)	If 0 or 3 was entered in (14) no entries are required for (15a) or (15b). If 1 was entered in (14) enter T_{o1}, T_m and T_{on}. (Note: $T_{o1} = T_m = T_{on}$ for constant temperature.)
or (15b)	If 2 was entered in (14) enter T_k for each layer in turn starting with the most positive z layer (+z). There must be n values. Limited to 10 entries per line; use new lines as required.
(16)	Applied (mechanical loading) Enter L N_x N_y N_{xy} M_x M_y M_{xy}. Signs of loads and moments should be compatible with the conventions shown in Sketch 1.1.

Note: A further entry of the letters “EOF” may be required when running the program in conjunction with certain compilers (e.g. Salford compiler).

1.5 Output Data Interpretation

1.5.1 Notes

The program ESDUpac A8418 can give a full layer damage history to laminate failure for a multilayered laminate under consecutive systems of thermal and mechanical loading with or without passing the damage from one loading system to the next. The data output for this could be considerable and may be reduced by choosing either the short output form, giving only the layer data for the final condition of each loading system and the ultimate failure, or an extract output form which gives only the applied loads, failure loads and cause of failure for each load. The full and short output forms can be further reduced by printing out data for only those layers reaching a chosen fraction of the value of the failure criteria, $R(1)$ and $R(2)$.

The output of the program comprises the following principal sections.

- (i) ESDU Header
- (ii) Input Data Check
- (iii) Results.

The header (i) gives the Data Item and Program titles and references. The input data check (ii) provides a detailed check of all the values of data input. If an error is detected an appropriate error message is given (see Section 1.5.2) and the program run terminated. If no error is detected the results of the analysis are given for each loading system in turn in full, short or extract form as specified.

The full output of the results commences with an analysis of the layer construction and layer thermal loading with the resultant **A**, **B**, and **D** stiffness matrices. If the laminate is held flat prior to loading, the moments required to do so are next given followed by the associated layer damage data (if any). Each thermal and mechanical loading system is then considered in turn for the laminate in an unrestrained condition, giving the layer stresses and layer damage history starting with the thermal loading only and then thermal and

mechanical loading together, until laminate failure occurs. If laminate failure does not occur due to a particular applied loading system the program will boost that loading system to a level where laminate failure does occur, recording matrix material failure levels in the process. It will then apply the next loading system to either the laminate unrestrained in the condition (damage state) that resulted from the application of that (previously unboosted) loading system or to the laminate in its initial stress free state (unrestrained or held flat), according to the user's choice.

The method by which the program performs the analysis is detailed in Section 2.2. If either the short form or the extract form of output is requested a full damage history will not be given. In the case of the short output the information given will be restricted to (1) input data check, laminate construction, stiffness matrices and loading, (2) held flat data, and (3) final mechanical and thermal loading layer stresses and criteria for each loading system, boosted if applicable. The extract form of output will give the laminate construction, the stiffness matrices, applied loads and failure loads and the cause of failure, for each loading system. It gives no layer data.

It should be noted that a matrix material failure is considered to have occurred when $R(2) = 1$ and this results in the removal of the transverse and shear stiffness properties of the layer concerned (damage). The fibre direction properties of layers are retained as is the allowance for the thickness of the layer. Whole laminate failure is considered to have occurred *at any point* in the computation when $R(2) \geq 1$ for all layers or $R(1) \geq 1$ for any layer. For any applied loading system the program tracks the proportionate load levels (with the component loads in strict ratio) causing layer damage, until laminate failure occurs. The damage analysis starts at the lowest load level causing a layer matrix material failure ($R(2) = 1$). If this first load level is below the applied load level the analysis then works its way up towards the applied load level. At each point at which layer matrix material failure occurs the transverse and shear properties of the damaged layer are removed and the layer stresses and criterion ratios $R(2)$ and $R(1)$ before and after their removal are printed. If a progressive failure occurs at this point the analysis will track that. If laminate failure has not occurred during the damage analysis, the program will record the layer stresses, failure criteria ratios and the numbers of failed layers at the applied load level and then boost the loads in ratio again tracking and recording the damage until a level at which laminate failure is reached. If damage has not occurred below the applied load level the program will go straight into the boosted load configuration.

1.5.2 Form of output

If FULL OUTPUT has been chosen this is followed by the results of the analysis in the form of the following output Segments (a) to (o) selected as appropriate to the problem input.

If SHORT OUTPUT has been chosen the selection will be made from the following output Segments (a) to (o) but leaving out the steps detailed in Segments (i) and (j) for reduced loading and (l) for boosted loading.

If EXTRACT OUTPUT has been chosen no layer stress or criteria data will be output. Segments (a), (b) and (e) (minus layer data) of the following output will be followed by the failure loading data extracted from Segments (j) and (m) and a statement as to whether total layer matrix failure or a particular layer fibre failure has caused laminate failure.

The full output of the program, an example of which is given in Section 1.6, takes the following form.

(a) Check of input data

INPUT DATA CHECK

The values input for each entry are checked to see if they are valid. If any value is in error the run is

terminated and an error message is given in one of the following forms.

[parameter] = [erroneous value]: must be [value] for [entry number]
 [parameter] = [erroneous value]: must be positive for [layer type number]

In addition the properties of each of the types of layers used are checked to ensure that they represent a valid elastic material by applying Equation (1.1). If this condition is not satisfied the run is terminated and an appropriate error message is printed out.

$$1 - \nu_{12}^2 E_2 / E_1 > 0 . \quad (1.1)$$

If no error is found a complete labelled copy of the input data is printed in the entry order including the loading systems.

(b) Output type requested

The output form chosen is confirmed by one of the following labels

FULL OUTPUT or SHORT OUTPUT or EXTRACT OUTPUT

as appropriate.

(c) Check of plate layer geometries, properties and thermal distribution (all output forms)

Details of the laminate geometry and thermal loading are preceded by this title:

PLATE CONSTRUCTION AND THERMAL DISTRIBUTION

Values are then given for the following quantities layer-by-layer through the laminate.

$k \quad t_k \quad z_k \quad E_{1k} \quad E_{2k} \quad G_{12k} \quad \nu_{1k} \quad \psi_k \quad \delta T_k$

(d) Laminate stiffness matrix (all output forms)

The stiffness matrix for the laminate before application of thermal loading, held flat moments or mechanical loading is given in the form specified in Data Item No. 94003 under this heading.

STIFFNESS MATRIX OF LAMINATE BEFORE LOADING (DATA ITEM 94003)

The values of the component sub-matrices are tabulated under their respective labels:

A B
B D

(e) Laminate condition before mechanical loading (all output forms)

If the held flat condition has not been specified the statement

LAMINATE NOT HELD FLAT

is given and the output moves on to Segment (f).

If the held flat condition has been specified the moments required to prevent curvature of the laminate under thermal loading, but not restricting in-plane displacements, will be given under the following headings.

LAMINATE HELD FLAT
THERMAL LOADING ONLY – APPLIED LOAD IS ZERO

MOMENTS REQUIRED TO HOLD LAMINATE FLAT

Those headings are followed by values for the moments

$$M_x \quad M_y \quad M_{xy}$$

This is followed by data on the layer stresses and criteria factors (not in extract output) titled:

LAYER STRESSES AND CRITERIA AFTER DAMAGE (IF ANY)

Values are then given for the following quantities for each layer for which $R(2)$ or $R(1) \geq cfr$ through the laminate thickness.

$$k \quad z_k \quad \sigma_{1k} \quad \sigma_{2k} \quad \sigma_{6k} \quad R(2)_k \quad R(1)_k$$

The presence of any layer matrix material failure is then noted.

NO LAYER FAILURE

or

THE MATRIX MATERIAL OF THE FOLLOWING
LAYER FAILS PROGRESSIVELY AT THIS LOAD LEVEL

LAYER

The layer numbers k are then given for any layers in which matrix material failure has occurred.

Note that if total laminate failure occurs at this stage it will be noted as shown in output Segment (m).

(f) First loading system (full output form)

The output for the first loading system commences with the following title.

LAMINATE UNDER LOADING SYSTEM 1

The layer stresses and criterion factors are first given for the unrestrained laminate with no applied (mechanical) loading and only the first thermal loading system present.

The data are presented under the following headings.