

FAILURE MODES OF FIBRE REINFORCED LAMINATES

1. NOTATION

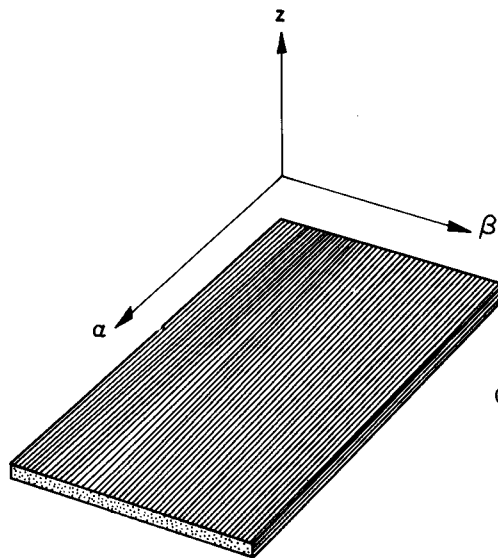
x, y, z	coordinates of laminate (see Sketch 3.1b)
α, β, z	coordinates of individual layer (see Sketch 3.1a)
ψ	orientation of fibre to chosen reference x -axis (see Sketch 3.1b)

2. INTRODUCTION

This Item presents the failure modes of fibre reinforced laminates in which the individual layers consist of continuous fibres that are strong and stiff along their length in a more flexible surrounding matrix. The fibres and matrix are designed to perform complementary functions and therefore react to the various loading conditions in different ways. Additionally the orientation of the fibres usually varies from layer to layer through the laminate thickness. Consequently there are many more potential failure modes for these laminates than for metallic materials. There are two principal ways of considering the failure of such laminates: (1) based on the behaviour of the individual layers and the interfaces between them, (2) based on the laminate as a whole. This Data Item deals with the first of these approaches.

3. GENERAL COMMENT ON FAILURE MODES

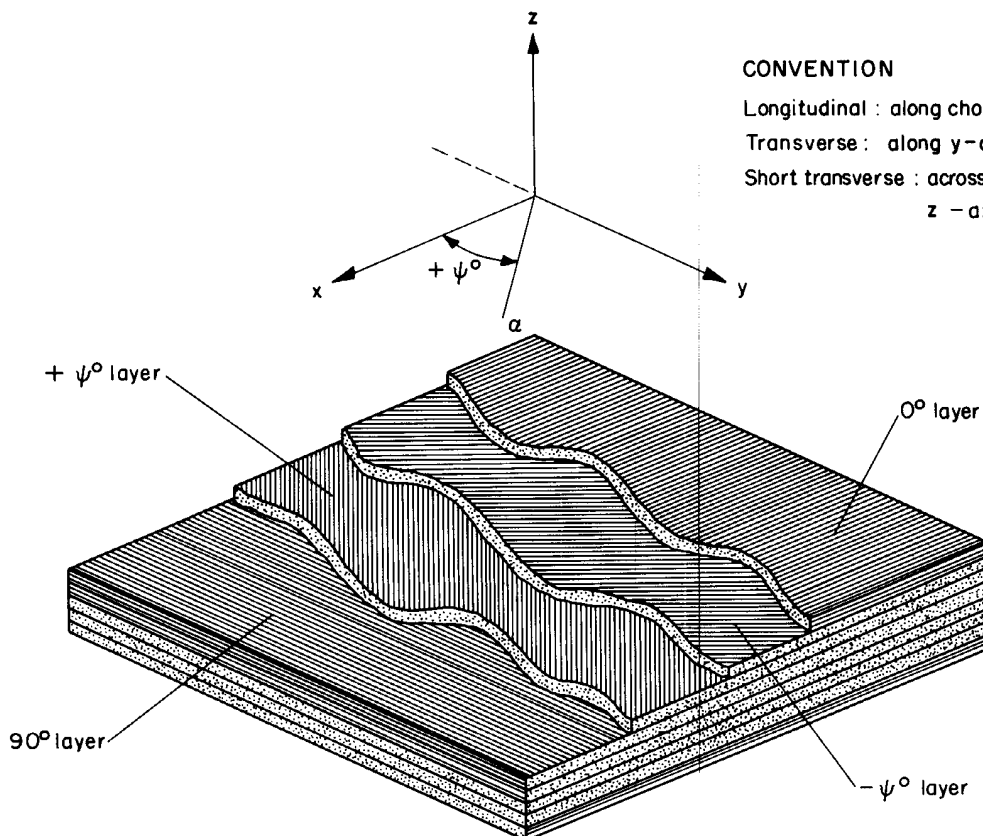
In each layer of a laminate the principal function of the fibre is to transmit loads in its longitudinal direction (α , see Sketch 3.1a) although it will also transmit transverse and shear loads. The resin matrix connects the fibres, maintaining their relative position while distributing the load among the fibres and ensuring continuity of transverse and shear loading in the laminate. The typical laminate will be composed of a number of individual layers, as shown in Sketch 3.1b. The laminate may be subjected to any combination of loading though the layers are most efficient taking in-plane longitudinal direct load. The failure modes are best understood by dealing first with the modes for a single layer under simple loading, as given in Section 4, and then relating these to more complex configurations, as given in Section 5. It should be noted that laminate strength may be significantly affected by the residual stresses that are present after curing. These stresses can be high enough to cause premature cracking of the matrix. Voids may also be present as a result of imperfect manufacturing processes and these will affect the stresses in the laminate. In addition the effect of environmental conditions, particularly of the temperature and moisture content, will also significantly affect the matrix behaviour and consequently those modes that are heavily matrix dependent. (References 5, 6, 7, 9 and 10.)



CONVENTION

Longitudinal: along fibre direction, α -axis
 Transverse: across layer width, β -axis
 Short transverse: across layer thickness, z -axis, (normal)

Sketch 3.1a Individual layer



CONVENTION

Longitudinal: along chosen reference axis, x -axis
 Transverse: along y -axis
 Short transverse: across laminate thickness, z -axis, (normal)

Sketch 3.1b Multidirectional laminate

4. UNIDIRECTIONAL LAMINATES AND INDIVIDUAL LAYERS UNDER SIMPLE LOADING

The failure modes for unidirectional laminates under uniaxial direct and shear loading are presented in Table 4.1. The following notes amplify the information therein. The information given in Table 4.1 applies also to individual layers. Interlaminar and delamination effects, though not strictly applicable to an individual layer, will be applicable to it in the practical case where layers are combined. Some of the modes listed in Table 4.1 are much more likely to occur than others; modes 1, 2, 3, 4, 10 and 11 are such modes.

TABLE 4.1 Failure Modes of Unidirectional Laminates

This table applies to individual layers as well as laminates (except for interlaminar effects).

<i>Mode of failure</i>	<i>Nature of loading</i>	<i>Primary factors</i>	<i>Secondary factors</i>	<i>Notes</i>
1. Fibre failure transmitted laterally (brittle failure)	Longitudinal tension	(-) Fibre tensile strength (-) Fibre volume fraction (+) Matrix stiffness and strength (+) Interface bond strength	(-) Cure shrinkage stresses	See Section 4.1.1 and Sketch 4.1
2. Fibre failure transmitted longitudinally and laterally (brushing)		(-) Fibre tensile strength (-) Fibre volume fraction (-) Matrix stiffness and strength (-) Interface bond strength (+) Cure shrinkage stresses	(+) Fibre strength variability	See Section 4.1.1 and Sketch 4.2
3. Brittle fibre failure (inclined shear)	Longitudinal compression	(-) Fibre Strength and volume fraction (+) Local and overall stability (-) Local distortion/eccentricity		See Section 4.1.2 and Sketch 4.3
4. Kink band failure (timber-like)		(-) Matrix shear stiffness (+) Local distortion/eccentricity (-) Fibre diameter	(-) Fibre shear stiffness (-) Fibre volume fraction (+) Moisture and temperature (matrix)	See Section 4.1.2 and Sketch 4.4.
5. Fibre microbuckling		(-) Matrix transverse stiffness (-) Fibre diameter and volume fraction (-) Fibre Young's modulus	(+) Moisture and temperature (matrix)	See Section 4.1.2 and Sketches 4.5a and 4.5b
6. Locally originated delamination		(+) Local distortion/eccentricity (-) Fibre diameter and modulus (-) Matrix tensile strength	(-) Matrix shear stiffness (+) Moisture and temperature (matrix)	See Section 4.1.2
7. Matrix/bond-line tension fracture	Transverse tension	(-) Matrix/fibre average failing strain (-) Fibre/matrix bond strength (+) Cure shrinkage stresses	(+) Disparity between fibre and matrix stiffnesses (-) Matrix strength (+) Fibre distribution irregularity (+) Fibre volume fraction	See Section 4.1.3
As above (delamination possible)	Short transverse tension (normal)	As above (+) Curved laminate bending	As above	See Section 4.1.3
8. Matrix/bond-line (inclined shear) fracture	Transverse compression	As for mode 7	As for mode 7	See Section 4.1.3
9. Transverse layer buckling		(-) Matrix/fibre transverse modulus (-) Matrix/fibre shear modulus	(+) Fibre volume fraction	
10. Shear in matrix, fibre/matrix debonding, interlaminar shear in laminate	Longitudinal/short transverse shear	(-) Matrix shear strength (-) Fibre-matrix adhesion (+) Moisture and temperature (resin)	(+) Fibre volume fraction (+) Cure shrinkage stresses	See Section 4.1.4 and Sketch 4.6a
11. Shear in matrix, interlaminar shear in laminate	Longitudinal/transverse shear	(-) Matrix shear strength	(+) Cure shrinkage stresses (+) Moisture and temperature (matrix)	See Section 4.1.4 and Sketch 4.6b
12. Shear in matrix (cross fibre shear), interlaminar shear in laminate	Transverse/short transverse shear	As for mode 10	As for mode 10	See Section 4.1.4 and Sketch 4.6c

(+) the greater the quantity, the more likely the failure.

(-) the lower the quantity, the more likely the failure.

4.1 Notes on Table 4.1

4.1.1 Longitudinal tension failure modes 1 and 2

As the tensile load develops fibre fractures occur. Initially the matrix is able to cope with this by redistributing individual fibre loading by matrix shear across the fibre gap to the same fibre and to adjacent fibres. When a number of such fibre failures are grouped in transverse alignment a crack starts to grow in the layer. If the matrix is capable of containing the local shear stresses the crack spreads across the layer as a clean continuous tensile failure of the fibres and matrix, as shown by Sketch 4.1. If the matrix is unable to take the local shear stresses it fails in shear in a direction parallel to the fibres. In addition fibre-matrix debonding may occur. By linking up with other transverse fibre failure groups the crack spreads in an erratic fashion across the width of the layer as a total brush type failure, as shown by Sketch 4.2. If the matrix is comparatively brittle the cracks can also cause matrix disintegration; in this case the unsupported fibres fracture under local distortions and total brittle matrix failure results. Identification of brittle matrix failure as a third primary tensile failure mode is considered in detail in Reference 9. (For additional information on failure modes 1 and 2, see References 4, 5, 7 and 10.)

4.1.2 Longitudinal compression failure modes 3, 4, 5 and 6

If the fibre is relatively thick (typically boron fibres) and rigidly supported, the usual (metallic) shear compression failure can occur in individual fibres (mode 3, see Sketch 4.3) followed by matrix disintegration. More usually under longitudinal compression load the fibres start to buckle. This initially takes the form of a short wavelength instability which is known as microbuckling. Here the fibres may be considered to act as infinite columns upon an elastic foundation. Two forms of microbuckling model are usually considered: (1) in-phase buckling, in which the matrix shear stiffness is inadequate and the whole layer shears sideways (see Sketch 4.5b) and (2) out-of-phase buckling in which the matrix direct transverse extensional stiffness is inadequate (see Sketch 4.5a). In practice, while (1) is more likely to occur, the ultimate failure mode is usually a gross form of instability known as 'kink band' failure, where a whole block of the layer material shears sideways across either the width or thickness of the layer (see Sketch 4.4). This may be initiated by fibre microbuckling or local defects, voids and eccentricities. For certain fibre/matrix combinations fibre microbuckling (mode 5 similar to Sketch 4.5a) will lead to layer collapse. In multilayer laminates, particularly where local distortions or offset loading is present, delamination may consequently occur (mode 6) though this is unusual in unidirectional laminates. (For additional information on failure modes 3, 4, 5 and 6, see References 5, 6, 8, 10 and 11.)

4.1.3 Transverse and short transverse tension and compression failure modes 7, 8 and 9

The effects of transverse tension or compression are taken principally by the matrix. In the case of transverse tensile loading (mode 7) the failure occurs as a through layer crack running parallel to the fibres which may be initiated by a matrix stress concentration and/or local matrix-fibre debonding. The effects of short transverse tension, usually induced by curvature or bending, are similar though in this case delamination may occur. Transverse compression loading, where the layer or laminate is stiff enough to resist buckling, will result in transverse shear failure (mode 8) or matrix disintegration (which may occur at a load level much greater than that for transverse tension). Short transverse compression will have a similar effect. When the layer or laminate is not stiff, transverse compression loading is likely to result in transverse overall buckling (mode 9).