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Some Observations on the Nature of Fibre Reinforced Plastics and the Implications for Structural Design [and Discussion]

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Some observations on the nature of fibre reinforced plastics and the implications for structural design

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[Plates 1 and 2]

Fibre reinforced plastics exhibit many phenomena not found in conventional construction materials and these can have a marked effect both on the performance of structures made from them and, by implication, on the way in which such structures are designed. This paper considers three of the more interesting phenomena, namely compressive behaviour, tensile notch sensitivity and transverse cracking in multidirectional laminates. The latter two phenomena both involve failure of the matrix or fibre/matrix interface which, perhaps paradoxically, has a beneficial effect in one case but is detrimental in the other. Although the paper refers primarily to carbon fibre–epoxy resin composites, the conclusions and design implications relate to a wide range of fibre reinforced materials.

1. Introduction

The nature of fibre reinforced plastics – the properties that make them what they are – continues to be the subject of considerable study and with good reason. Most fibre reinforced plastics exhibit phenomena not found in the more conventional, isotropic materials they are likely to replace, and these can have a marked effect both on the performance of structural components made from them and, by implication, on the way in which such components are designed. While some of the phenomena arise simply from the anisotropy associated with most fibre reinforced materials, others result from relatively complex interactions between two (or more) constituent materials having very different physical and mechanical properties.

In recent years there has been an increased realization that the operational environment has a significant effect on the performance of fibre reinforced plastic components, and this has led to a greater emphasis being placed on understanding the way in which the many environmental factors affect basic properties. It is well known, for example, that both heat and moisture adversely affect the properties of a range of plastics commonly used as matrices, but the significance can be fully appreciated only when the effects of matrix properties on modes of failure of the reinforced plastic as a whole, and on fibre/matrix interface behaviour in particular, are properly understood.

In the present paper we have chosen to look at three of the more interesting phenomena associated with carbon fibre reinforced plastics (c.f.r.p.), namely longitudinal compressive behaviour of unidirectional material, and transverse cracking and tensile notch-sensitivity of multidirectional material. In each case, the phenomenon is described and the various factors governing behaviour are discussed. Consequent implications for structural design are also indicated so that the relation between the nature of fibre reinforced plastics and the design of efficient structural components might be better appreciated.

2. Longitudinal compressive behaviour

(a) *The mechanism of failure*

The mechanism of longitudinal compressive failure in unidirectional fibre reinforced materials has been the subject of study and debate for more than two decades. During the earlier part of the period, most theoretical treatments were based on one suggested by Dow & Grunfest (1960) in which failure is attributed to fibre instability within an essentially elastic matrix. Simplified instability equations, using a two dimensional model due to Rosen (1965), were modified by a succession of workers to allow for a number of effects including matrix plasticity (see, for example, Hayashi 1970), out-of-plane buckling (see, for example, Lager & June 1969), poor fibre alignment and voids (see, for example, Greszczuk 1967). However, with one or two notable exceptions (see, particularly, Moncunill de Ferran & Harris 1970), agreement between experiment and theory for a wide range of fibres (or filaments) and matrices was poor. In the case of unidirectional c.f.r.p. agreement was particularly poor, theory overestimating measured values by factors varying between 1.5 and 4.0 depending mainly on carbon fibre type.

In 1973 new light was thrown on the compressive behaviour of unidirectional c.f.r.p. by Ewins & Ham (1974) when it was shown that, while fibre instability could cause failure, a more usual mode of failure for carbon fibres in an epoxy matrix, particularly at or below room temperature, was one depending on the compressive strength of the fibres themselves. Furthermore, it was concluded that the mechanism of failure is by shear across both fibres and matrix on a plane of near-maximum shear stress. Measured compressive strengths under this mode of failure for a range of different carbon fibre types also showed a constant relation to fibre tensile strength, and it was suggested that shear-initiated failure at fibre flaws, proposed by Reynolds & Sharp (1973) as a possible tensile failure mechanism, was a mechanism common to tension and compression. (This is not to say that subsequent propagation of failure occurs via a common mechanism, since other factors not common to tensile and compressive behaviour are clearly important.)

While the fibre strength-dominated mode sets an upper bound on compressive strength, it does not preclude the occurrence of other failure modes at lower stresses under different circumstances. It is well known, for example, that both poor interlaminar shear strength (see, for example, Ewins 1970) and high void content (see, for example, Fried 1965) can depress compressive strengths substantially and it can be assumed that these might also reflect a change in failure mode. Matrix stiffness, especially shear modulus, is a major parameter in many stability analyses and, again, there is evidence (Ewins & Ham 1974) that quite moderate temperatures, say 100 °C, will cause sufficient reduction in matrix stiffness to allow instability modes to dominate and compressive strengths to be substantially reduced. Photomicrographs of the fracture surfaces of typical unidirectional c.f.r.p. compressive test specimens (figure 1, plate 1) show clearly the differences between shear and fibre instability failure modes.

(b) *Design implications*

A picture of compressive strength of unidirectional c.f.r.p. emerges, in which an upper bound is governed by a failure mode strongly dependent on fibre strength but which can be significantly reduced by a change in mode to one governed ultimately by fibre instability. What then are the implications for structural design, particularly where structural performance is critically dependent on compressive strength and/or stability?

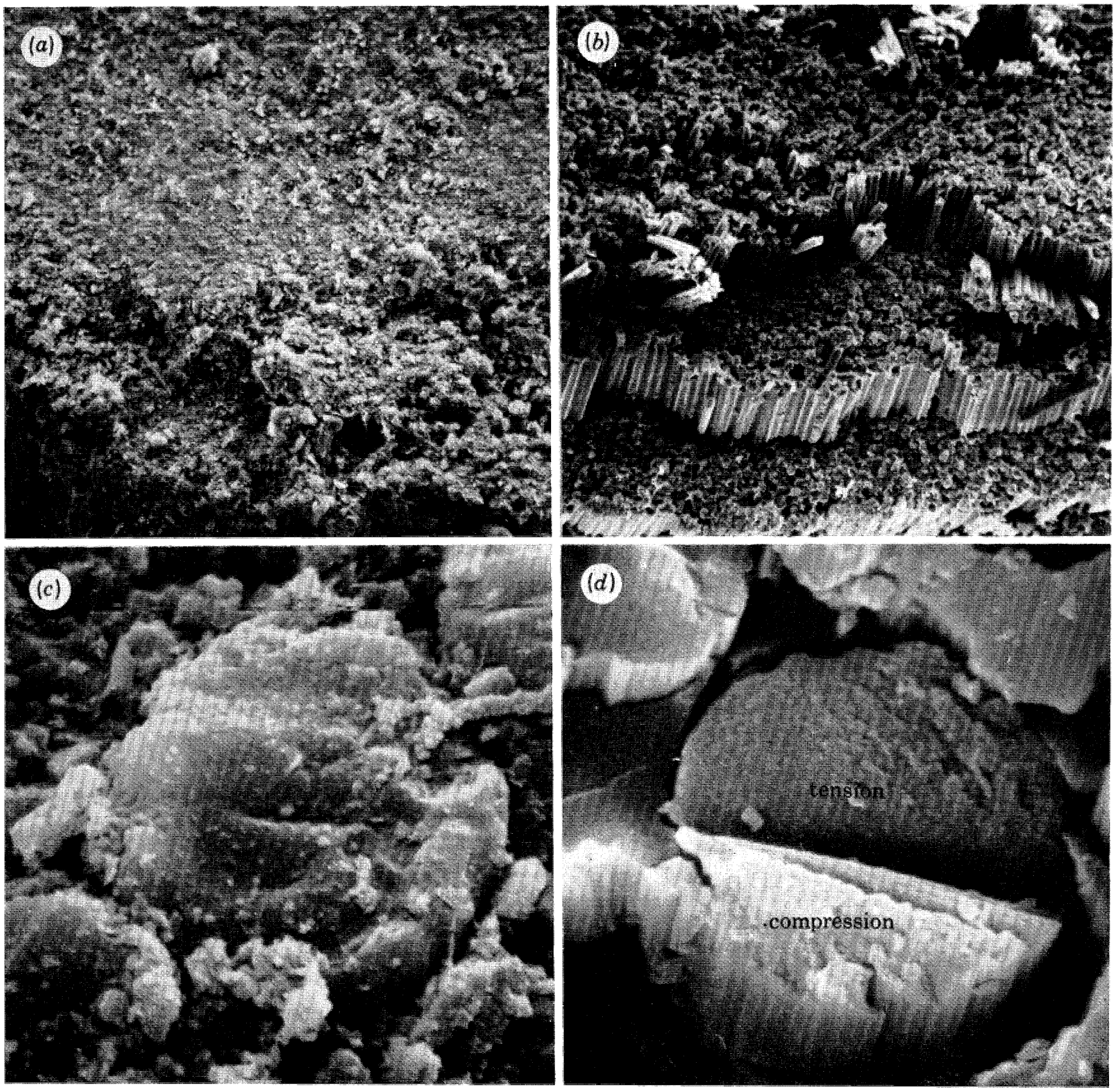

FIGURE 1. Longitudinal compressive failure modes (HM-S carbon fibre reinforced epoxy). (*a*) shear mode (magnification $\times 200$); (*b*) fibre instability mode (magnification $\times 200$); (*c*) shear mode (magnification $\times 7000$); (*d*) fibre instability mode (magnification $\times 8000$).

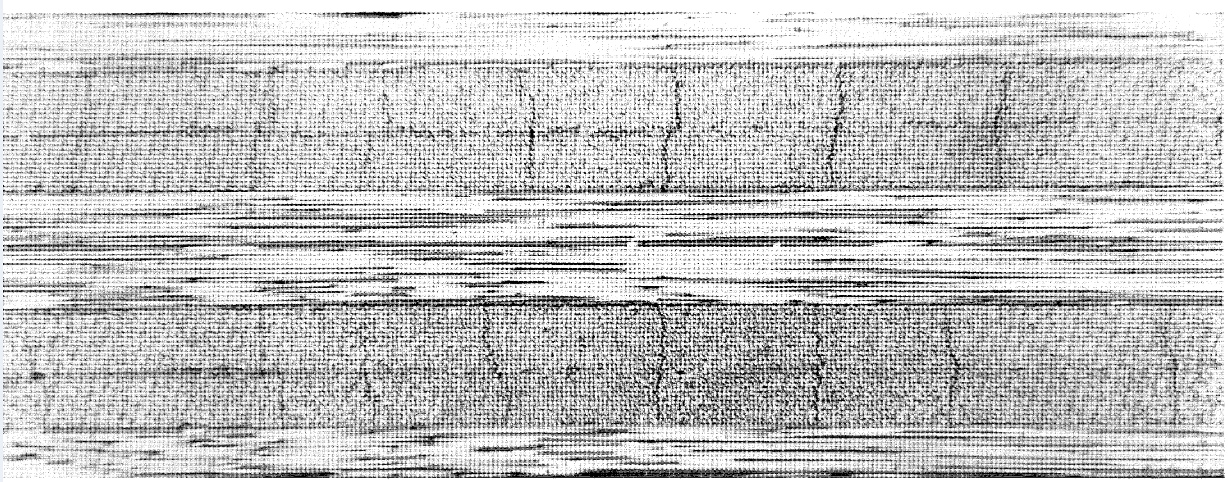

FIGURE 4. Transverse tensile cracks in a symmetric 8-ply (0°, 90°) laminate (HT-S carbon fibre reinforced epoxy).

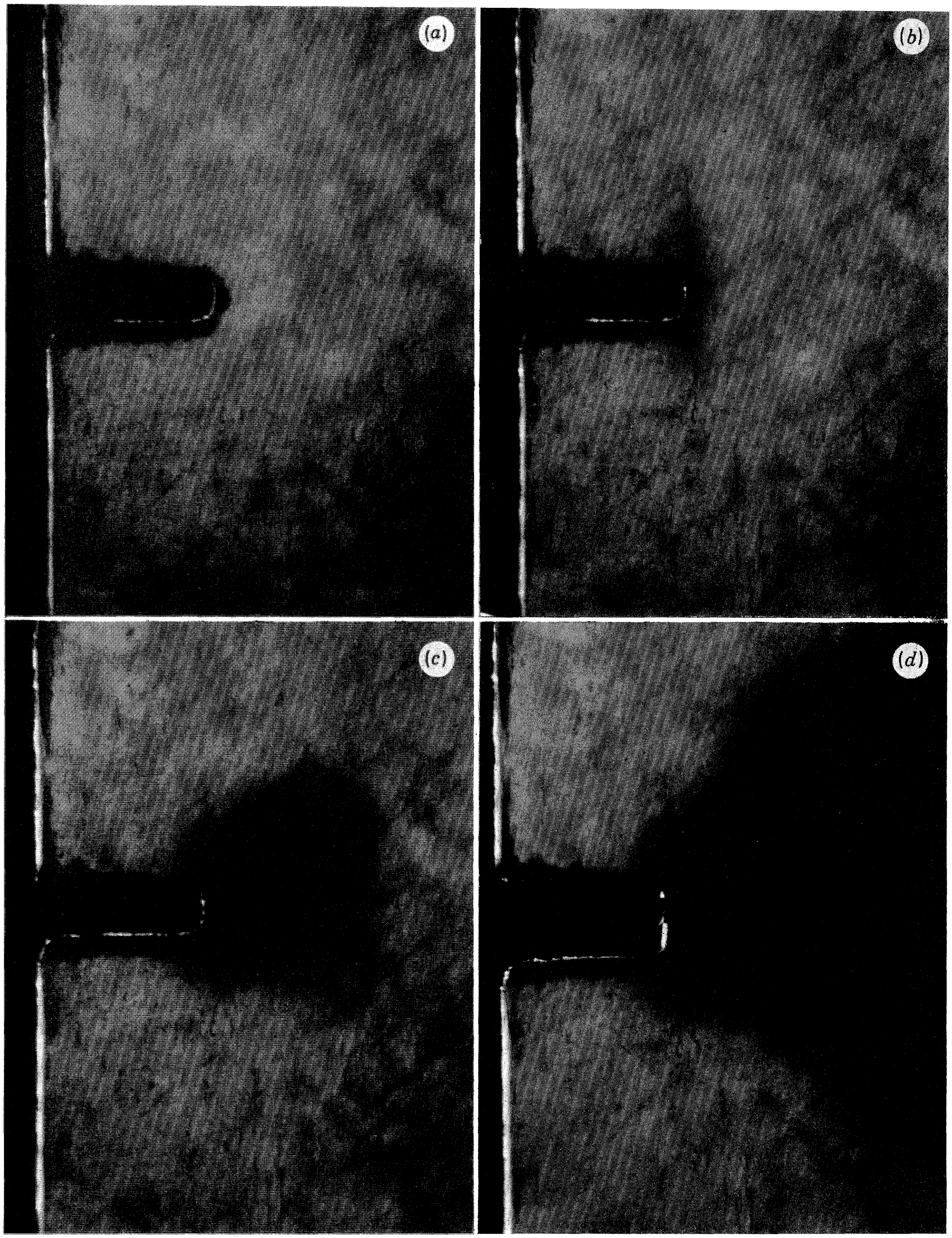

FIGURE 7. Growth of a damage zone in a (0°, ±45°) laminate (glass fibre reinforced epoxy).

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First, consider the temperature range over which a structure might be required to operate, say −50 to +120 °C, and the effect of changes in temperature over such a range. For a full understanding it is necessary to consider not simply the effect on compressive strength directly but more particularly the effect on certain properties of fibre, matrix and fibre–matrix bond on which compressive strength depends. For example, provided the mode of failure based on fibre strength (shear mode) remains dominant, compressive strength will decrease only slightly with increased temperature, probably due to a decrease in the contribution to strength of the matrix. However, as temperature increases, matrix shear modulus and fibre–matrix bond strength decrease and at some critical temperature the failure mode will change to one governed primarily by fibre instability. Since the rate of change of matrix shear modulus with temperature is relatively large, particularly at higher temperatures, the reduction in compressive strength as a function of temperature will be considerably more marked after the change in mode. Figure 2, which shows the experimentally determined variation of compressive strength with temperature for a typical unidirectional carbon fibre reinforced plastic, serves to illustrate the point.

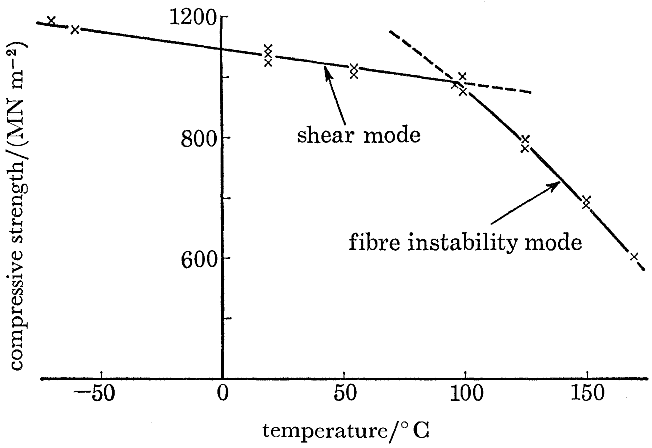

FIGURE 2. Experimentally determined variation of compressive strength with temperature (HT-S carbon fibre reinforced epoxy).

Consider now the effect of environmental exposure and particularly the effect of moisture. Whether the environment implies constant exposure, such as would be encountered in tropical climates, or cyclic exposure, as would be typical for an aircraft operating under normal service conditions, the long-term effect on compressive strength is likely to be deleterious (Augl 1977). Although the principal cause is a reduction in matrix modulus caused by moisture absorption and consequent matrix plasticization (Browning 1977), other changes such as a reduction in fibre–matrix bond strength may also be important. Again, following a mode change to one of fibre instability, further mositure absorption and a corresponding reduction in shear modulus are likely to result in a rapid reduction in compressive strength.

Of course, the effect of temperature and moisture absorption cannot be treated in isolation and the results of combining the two are illustrated in figure 3. It is worth noting that the combined effect might be greater than suggested by a simple summation of the two effects and that it will be further worsened by the inclusion of load cycling, particularly if the matrix is strained beyond its elastic limit.

Consider finally the possible effects on a structure loaded in compression of interactions

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between material and structural modes of failure. Interaction between structural instability modes, say local and overall buckling, is known (Koiter & Skaloud 1962) to cause structural collapse at stresses significantly below those relating to individual modes, but with fibre reinforced plastics there is the added possibility of instability modes occurring within the material itself. If, for example, a structure is designed to allow local buckling before overall collapse then, as a result of mode interaction, local fibre instability may be triggered at stresses lower than those normally expected for the material with consequent premature failure of the structure. Early failure might also be initiated by the existence of secondary loads such as in-plane shear; indeed, there is some evidence that quite small shear strains can reduce substantially the compressive strength of unidirectional c.f.r.p., probably by causing early fibre instability. It is of particular importance therefore that critical material and structural failure modes be established for any design so that interaction effects can be properly assessed and allowed for.

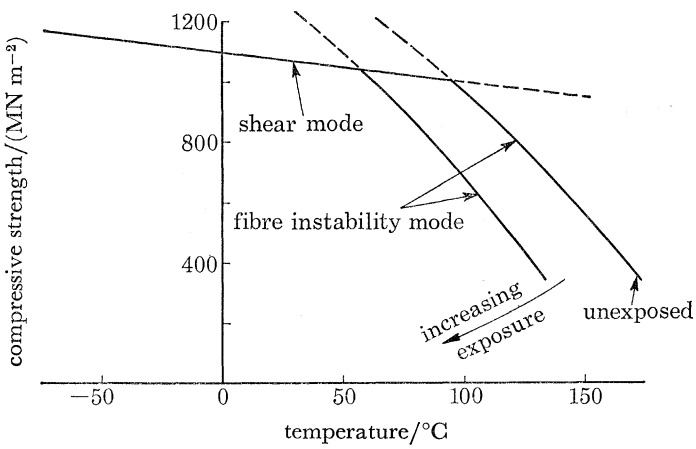

FIGURE 3. Variation of compressive strength with temperature and humidity exposure (HT-S carbon fibre reinforced epoxy).

3. TRANSVERSE CRACKING

Transverse cracking, that is cracking parallel to the fibre direction, in individual plies of multidirectional laminates has been widely observed (see, for example, Garrett & Bailey 1977), and over a range of commonly used carbon fibre–epoxy laminates is likely to occur at values of strain significantly below the failure strain of the fibres themselves. In general it is caused by a combination of mechanical and thermal strains, although in extreme cases the induced thermal strains on cooling from laminate cure temperatures (typically 170 °C) to a low ambient temperature (say −40 °C) are alone sufficient to cause spontaneous cracking. Figure 4 (plate 1) shows a photomicrograph of typical transverse cracks in the cross section of a symmetric, 8-ply (0 °, 90 °) c.f.r.p. laminate, and of particular note is the regularity of crack spacing.

Whether transverse cracking will occur before failure of the fibres (longitudinal failure), and whether thermal strains are alone sufficient to cause cracking, will depend not only on the difference between cure temperature (taken here to be approximately equal to the laminate thermal stress-free temperature) and minimum ambient temperature but also on the difference between properties in the two principal directions of individual plies. The three most significant of these are (*a*) strain to failure, (*b*) the Young modulus and (*c*) coefficient of thermal expansion; it should be noted that all are, to a greater or lesser extent, themselves functions of temperature.

It is also worth noting that transverse strain to failure is generally governed by the fibre–matrix bond strength and not by the strain to failure of the matrix.

Experimental and theoretical analysis (Parvizi *et al.* 1978) has shown that, for a balanced multidirectional laminate of given ply orientations in given proportions, overall strain at which cracking first occurs is dependent also on ply thickness and ply stacking sequence. The results, which show that the strain at which cracks are first initiated increases both with decreasing ply thickness and with increasing dispersion of plies in a given orientation, are not surprising but none the less have clear implications for design. Propagation of cracks and the formation of secondary and subsequent cracks have also been studied, and the strains at which they occur, together with crack spacing, have been accurately predicted (Garrett & Bailey 1977).

It is clear that the phenomenon of transverse cracking is complex and merits further study, but from the design point of view the mere probability of transverse cracking occurring in multidirectional laminates gives rise to an obvious dilemma. If, on the one hand, the onset of cracking is taken to be 'failure' of the laminate as a whole – a reasonable criterion under conditions where, say, gas or liquid under relatively high pressure has to be contained – then the efficiency of fibre reinforced structures will be less than indicated by single-ply properties alone. For c.f.r.p., where transverse strains resulting from cooling of the cured multidirectional laminate are always tensile and the transverse strain to failure is generally less than longitudinal strain to failure, transverse cracking will occur at strains substantially lower than the longitudinal failing strain, and efficiency will be correspondingly reduced.

If, on the other hand, transverse cracking is permitted, the effect on properties, particularly during and after exposure to adverse environments, could be severe. A single example will serve to illustrate the point. Much large but relatively thin multidirectional sheet material, such as would be found on an aircraft wing or fuselage, is subject not only to in-plane direct (tensile or compressive) loads but also to in-plane shear and normal pressure loads. The presence of transverse cracks could give rise to a change in shear stress–strain behaviour or reduce the failing strain in fibre directions by causing a stress concentration. These effects act both directly in causing a reduction in the values of important design properties and indirectly in that they may introduce unexpected failure modes. While subject solely to static load, transverse cracks do not generally lead to delamination, but under fatigue load partial delamination is known to occur. Under compressive load, failure may change from a strength-dominated mode to one of local ply instability and failure might occur at stresses far below expected values.

Many of these effects are likely to be aggravated by an adverse environment. Moisture is absorbed by cracks to a substantially greater degree than the normal equilibrium level for the matrix (Browning 1977) and a rapidly changing temperature might well subject the moisture to a freeze–boil–freeze cycle with consequent disastrous effects.

Thus it is clear that, for any particular application in which transverse cracking is likely, the effect on both short and long term properties needs to be assessed and a considered and well understood design philosophy established.

4. Tensile notch sensitivity

(a) *The mechanism of failure*

Tensile notch sensitivity occurs in multidirectional fibre reinforced plastics when the laminate strength is governed by tensile failure of fibres. This is illustrated by figure 5, which shows the

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variation with orientation of the net tensile strength of both notched and plain specimens taken from a (0°, ±45°) c.f.r.p. laminate. Within a few degrees of each fibre axis the composite strength is governed by the tensile failure of fibres (see, for example, Snell 1977), and notch sensitivity is readily apparent; at other angles laminate failure occurs by transverse tensile or shear failure of the individual fibre plies and notch sensitivity disappears.

For a laminate loaded in tension parallel to one of the fibre axes it has been shown (Potter 1978) that a notch may precipitate failure only by inducing the sequential failure of the tensile load-bearing fibres. Such a process, which in effect constitutes the propagation of a *trans*-fibre crack, is initiated by the transfer of tensile load from the fibres which fail at the notch tip into the adjacent unbroken fibres. However, the magnitude of the fibre stress concentration which may be induced by such load transfer is limited by the relative weakness of the matrix and the

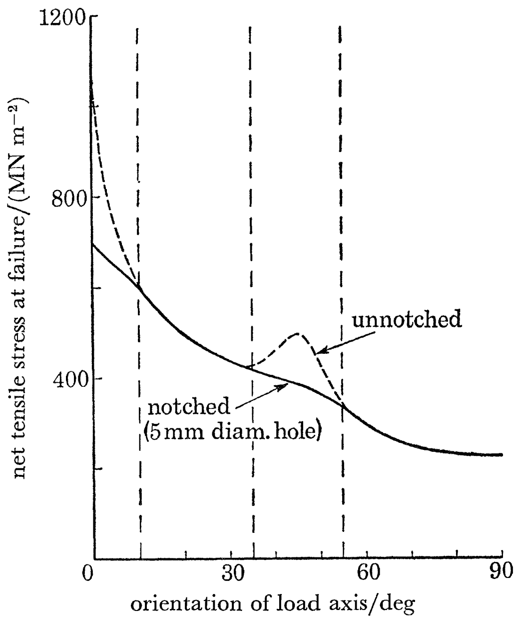

FIGURE 5. Variation of net tensile stress at failure with orientation for a (0°, ±45°) laminate HT-S carbon fibre reinforced epoxy).

fibre–matrix bond. It follows that the initiation of a *trans*-fibre crack may be inhibited if, as a result of the stress distribution due to the notch, the initial difference in stress between a fibre which fails at the notch tip and the adjacent unbroken fibre is sufficiently large.

This interaction between the macroscopic stress distribution due to the notch and the microscopic stress concentration due to inter-fibre load transfer leads to a notch size effect, such as is illustrated in figure 6 for circular notches in a (0°, ±45°) c.f.r.p. laminate. Large notches give rise to a large perturbed stress field such that the difference in stress between adjacent fibres at the notch tip is small. Thus, when a fibre fails at the tip of a large notch (that is, a notch of greater than 30 mm radius in the example), inter-fibre load transfer sufficient to initiate a *trans*-fibre crack may occur without overstressing the matrix. The laminate fails in a brittle manner and the stress at failure may be deduced simply from the macroscopic stress distribution and the unnotched tensile strength. For small notches the perturbed stress field is highly localized so that, although fibre failures may occur at the notch tip, *trans*-fibre crack propagation is inhibited by plastic flow or failure of the matrix or fibre–matrix bond. As the applied load is increased, the overstressing of the matrix leads to the growth of cracks parallel to the fibres. These cracks, together with transverse cracks in the angle plies, are often referred to as a damage zone (see, for example, Mandell *et al.* 1975). The growth of the damage zone with applied load, which may be directly observed in Kevlar or glass reinforced plastics (see figure 7, plate 2), modifies the stress distribution at the notch tip by degrading the local material properties. This process continues until the modified stress distribution is such that any additional fibre failure will precipitate a *trans*-fibre crack. The smaller the notch, the more highly localized the perturbed stress field and the greater the applied stress necessary to create the conditions under which *trans*-fibre propagation may occur. It is of particular interest to note that damage zones tend to obscure the effects of notch tip geometry so that, while the fracture stresses of laminates containing large notches will be dependent upon notch shape, those of laminates containing small notches will be generally independent of notch shape.

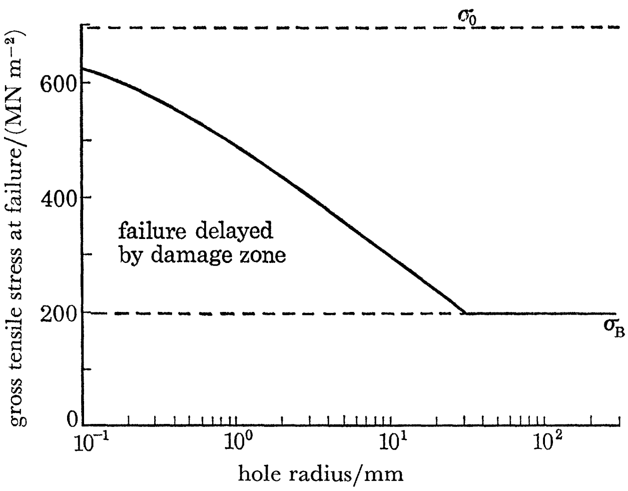

FIGURE 6. Effect of notch size (hole radius) on gross tensile stress at failure (HT-S carbon fibre reinforced epoxy). $\sigma_B = \sigma_0/C$, where C = (elastic) tensile stress concentarion factor. σ_0 denotes unnotched strength; σ_B denotes brittle fracture strength (for circular holes).

In the past, the notch sensitivity of fibre reinforced plastics has been quoted in terms of the reduction in strength due to small notches of arbitrary size and shape in laminates of arbitrary lay-up. However, in view of the present understanding of the fracture mechanism, a more fundamental parameter to quantify notch sensitivity is the maximum value of the fibre stress concentration that can result from failure of a single fibre, since this is the parameter that ultimately determines the conditions under which tensile fracture may occur. To derive this parameter from the strength reduction due to a notch requires some assumption concerning the relation between fibre strength and laminate strength. For example, employing a model in which the fibres are of uniform strength such that the laminate strength may be derived by a simple mixture rule, it has been shown (Potter 1978) that for c.f.r.p. the maximum stress increase in any fibre due to the failure of an adjacent fibre is, perhaps surprisingly, of the order of only 0.1 % of the effective fibre strength. It should be noted, however, that this apparently low value corresponds to a laminate stress gradient due to a notch of at least 10 % (of the laminate unnotched strength) per millimetre if *trans*-fibre crack propagation is to be inhibited.

While the concept of such a fibre stress concentration and the model upon which it is based are sufficient for the accurate prediction of notch sensitivity effects, they remain an idealization of the microstructural fracture process. In practice, the fibre strength is length dependent, being governed by the random occurrence of flaws (see, for example, Watt 1970). Furthermore, analyses such as those due to Hedgepeth & Van Dyke (1967) or Fukuda & Kawata (1976) suggest that, in reality, the fibre stress concentration must be substantially greater than that indicated above. However, when a flawed fibre breaks there is a high probability that the adjacent fibres will have local strengths significantly greater than that of the broken fibre, owing to the distribution and variation in severity of flaws. As a result the effect of the fibre stress concentration on laminate failure stress is much less severe than if the fibres were of virtually uniform strength. It is this balance between the true fibre stress concentration and the fibre strength characteristics that determines both the relation between fibre and laminate strengths (see, for example, Rosen 1970) and the tensile notch sensitivity of the laminate. Indeed, the two effects are essentially one since the laminate strength is largely governed by its own sensitivity to inherent defects.

(*b*) *Design implications*

Notch sensitivity will have considerable implications for the structural design of fibre reinforced plastic components. However, in contrast to the behaviour of metallic structural materials in which the effects of adverse environments and loading history tend to exacerbate the effects of stress raisers, the most severe notch sensitivity effects in fibre reinforced plastics will, in general, be observed in quasi-static tensile tests conducted in the research laboratory. The physical explanation of this difference in behaviour is simply that stress-induced microcracks in an isotropic material tend to form at right angles to the principal stress direction and act as concentrators of tensile stress whereas in fibre reinforced plastics the relative weakness of the matrix and fibre–matrix bond encourages the formation of cracks parallel to the tensile load-bearing fibres and these act as relievers of tensile stress.

It is clear that any factor that affects the redistribution of load from a broken fibre may influence both the tensile strength and notch sensitivity of fibre reinforced plastics. At the more fundamental level these might include fibre surface treatment, resin formulation and state of cure, and fibre alignment and fibre distribution, while of particular significance from the design point of view are service environment and loading history.

Consider, for example, the effects of fatigue. A consequence of the susceptibility of the matrix to fatigue damage is that the fatigue properties of c.f.r.p. loaded in tension parallel to the fibres (see, for example, Owen & Morris 1970) are considerably better than the corresponding properties when loaded in shear (see, for example, Phillips & Scott 1978). Thus, in a notched laminate subjected to a fluctuating tensile stress, the single-ply properties will be rapidly degraded in regions of high shear stress which are induced both by the notch itself and, if the tensile stress is sufficiently high, by the failed fibres at the notch tip. The resultant fatigue-induced damage zone will be larger than that induced by quasi-static loading and the beneficial effect on the tensile fracture stress will be correspondingly greater. In consequence the residual strength of a notched laminate generally increases with the number of fatigue cycles until it approaches the residual strength of the corresponding unnotched laminate (see, for example, Kulkarni *et al.* 1977) after which the behaviour of notched and unnotched laminates is the same.

Fatigue-induced damage zones must also grow around naturally occurring defects in unnotched laminates and again this will tend to increase the residual strength. However, the growth of damage zones leads also to an increasing probability of defect interaction which will tend to reduce the residual strength. The balance between these two effects is determined by the distribution of defects and the extent and rate of growth of matrix damage. At practical working stress levels, laminates containing high modulus carbon fibres will experience lesser cyclic strain amplitudes than laminates containing high strength carbon fibres and this will lead to less extensive damage zones. In consequence, increases in the residual strength of unnotched laminates are generally observed only in laminates containing high modulus carbon fibres (see, for example, Sturgeon 1973).

The static perfomance of notched fibre reinforced plastics is affected in this unconventional manner not only by fatigue but also by any other factor that degrades the matrix or fibre–matrix bond. Clearly, the combined effects on notch sensitivity of such factors as fatigue, elevated temperature and humidity need to be fully understood and allowed for if the full potential of the material is to be realized.

5. Concluding remarks

While the desirable properties of fibre reinforced plastics stem largely from those of the reinforcing fibres themselves, the preceding discussion of compressive strength, transverse cracking and tensile notch sensitivity shows that the efficiency with which these properties can be exploited depends to a large extent both on the properties of the matrix and the nature of the fibre–matrix bond. It is therefore an interesting paradox that degradation of the matrix, or fibre–matrix bond, which is generally regarded as detrimental can, under certain circumstances, be positively beneficial. While, for example, the effect on the matrix of elevated temperature and humidity can lead to a marked reduction in compressive strength, it can also lead to an advantageous reduction in tensile notch sensitivity. Likewise, laminate cracking, which is very much a function of the fibre–matrix bond strength, can, on the one hand, lead to substantial design limitations or loss of material integrity and yet, on the other, be the very mechanism by which notch sensitivity is reduced.

Clearly, in an attempt to meet the ever increasing demands of reliability, damage tolerance and long life in a harsh environment, it is inadequate, if not impracticable, to design fibre reinforced plastic structures simply by using a set of design data in a conventional way. What is also required of the designer is an understanding of the nature of fibre reinforced plastics and, particularly, a knowledge of how various properties and failure mechanisms are interrelated.

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Discussion

Sarah M. Bishop (*Materials Department, Royal Aircraft Establishment, Farnborough, Hampshire, U.K.*). In a multidirectional composite the fracture mechanisms involved in the formation of a damage zone at the tip of a notch are complex. They involve cracking within layers and interactions between layers which depend on lay-up, layer thickness, stacking sequence and fibre–matrix bond strength. A damage zone is made up of shear cracks parallel to $0°$ fibres, cracks parallel to fibres orientated at $\pm\theta°$ to the $0°$ direction, delamination and sometimes other modes of failure. Whereas $0°$ cracks reduce the stress concentration on the $0°$ layers, crack opening or shear along a crack orientated at $\theta°$ in one layer can produce large stresses in a neighbouring $0°$ layer which may result in failure of the $0°$ layer along the $\theta°$ direction instead of a transverse failure. A failure criterion for notched composites must take account of all possible fracture mechanisms. It is important that a parameter is found for predicting failure of such composites and thus it is instructive to look at models which may describe their behaviour. However many more data must be obtained and more supporting evidence found before a micromechanical parameter based on fibre failure can be extended to the prediction of macroscopic failure stress.

R. T. Potter. Dr Bishop is correct in her observation that the micromechanical events occurring in a notch tip damage zone are many and various. Furthermore, the stress-reducing effects of cracks parallel to the $0°$ fibres are fundamental to the tensile fracture criterion which has been developed (Potter 1978). However, there is a good deal of evidence that, contrary to Dr Bishop's suggestion, cracks in the $\theta°$ plies do not of themselves produce large stress concentrations in the $0°$ plies. First, failure of the $0°$ fibres along the line of a crack in the $\theta°$ plies is not inevitable; in practice we find this is observed in only about half of the specimens tested, while the failure stress is essentially constant. Secondly, we have shown that, in spite of the presence of cracks in the $\theta°$ plies, the longitudinal failure strain of an unnotched ($0°$, $\pm\theta$) laminate is not significantly different from that of the unidirectional composite. More important, in notched laminates we have shown that, again, in spite of the presence of cracks in the $\theta°$ plies, the failure of a significant number of $0°$ fibres does not occur until the longitudinal tensile strain of the laminate has locally exceeded the failure strain of the unidirectional composite. It is evident therefore that although cracks occur in the $\theta°$ plies in both notched and unnotched laminates they do not cause the premature failure of the $0°$ fibres.

This discussion of the magnitude of the stress concentration due to cracks in the $\theta°$ plies is, however, in any event irrelevant to the general applicability of the tensile fracture criterion. Laminate failure is governed by the tensile failure of the 0° plies and, for simplicity, we have described the stress concentration in the unbroken 0° fibres as being principally due to the tensile failure of 0° fibres nearer the notch. However, since both the composite tensile strength (σ_x') and the maximum achieveable fibre stress concentration (δ) in the 0° plies are determined directly from experimental observations of the notched and unnotched strengths of the laminate, all sources of stress concentration in the 0° plies are taken into account. Detailed consideration of the potential effects of all the various micromechanical events occurring at a notch tip, including those referred to by Dr Bishop, would be necessary only if an attempt were made to calculate σ_x' and δ directly from the properties of the fibre and matrix alone.

P. J. Worthington (*C.E.R.L., Kelvin Avenue, Leatherhead, Surrey, U.K.*). What was the fibre volume fraction of the carbon fibre–epoxy material and what is the effect of fibre spacing on notch sensitivity and failure modes? The reason behind this question is that, although one may aim to make composite components with an optimum fibre volume fraction, there will be regions where this is not so. Thus, one could perhaps form a large crack in an *abnormal region* which can then propagate through normal material.

R. T. Potter. The fibre volume fraction of the composites referred to in our paper was about 0.6. Fibre volume fractions which differ substantially from this value are not readily attainable from current commercially manufactured pre-impregnate and therefore information about volume fraction effects is limited to a range of about 0.55 to 0.65, within which no marked change in fracture behaviour has been observed.

Since local variations in volume fraction will cause variations in the stress distribution in addition to their potential effects on notch sensitivity it is not possible at this stage to speculate meaningfully about the formation and propagation of cracks due to 'abnormal' regions.

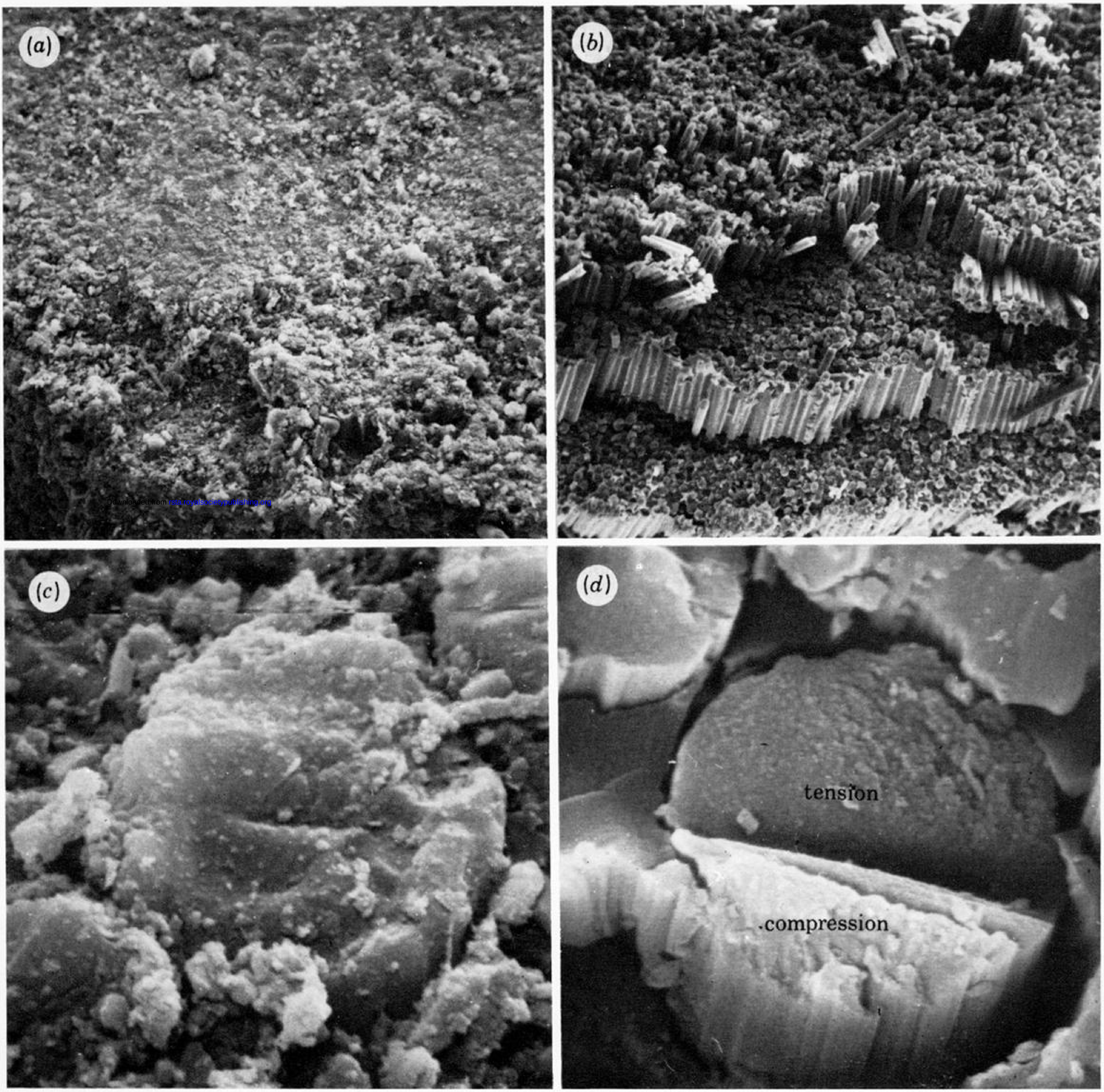

FIGURE 1. Longitudinal compressive failure modes (HM-S carbon fibre reinforced epoxy). (*a*) shear mode (magnification ×200); (*b*) fibre instability mode (magnification ×200); (*c*) shear mode (magnification ×7000); (*d*) fibre instability mode (magnification ×8000).

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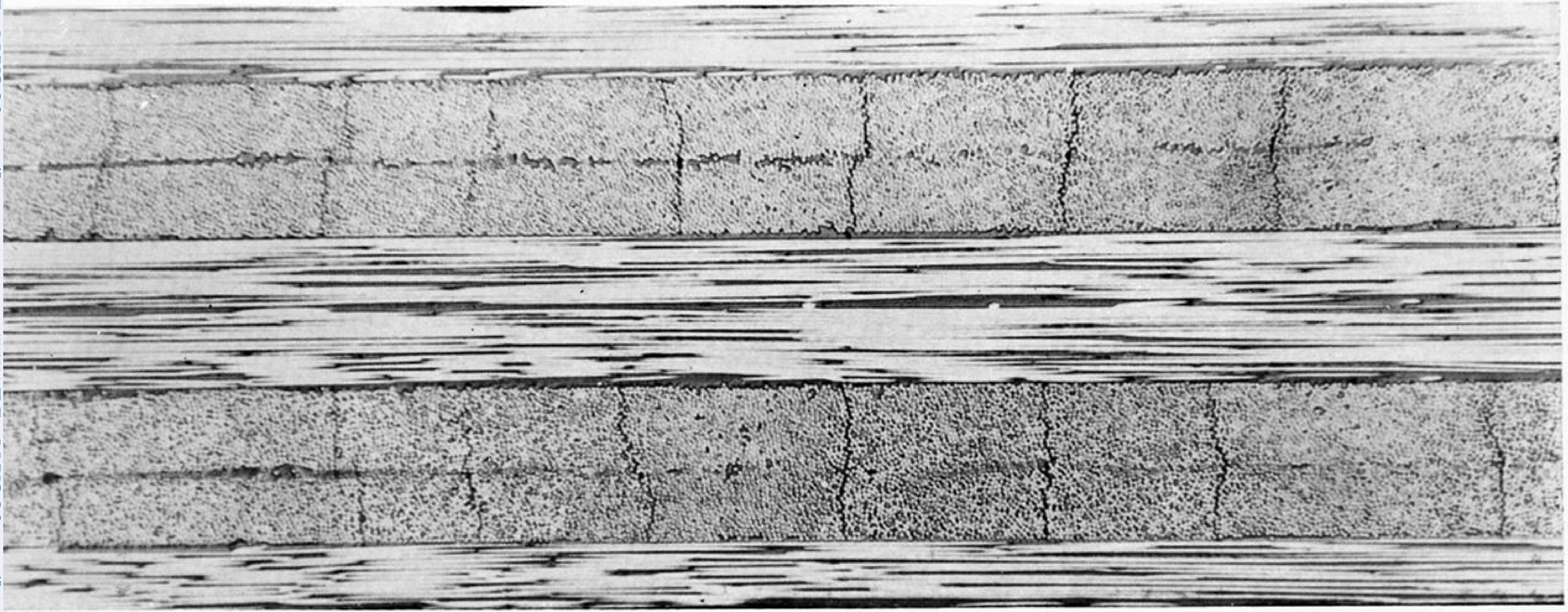

FIGURE 4. Transverse tensile cracks in a symmetric 8-ply (0°, 90°) laminate (HT-S carbon fibre reinforced epoxy).

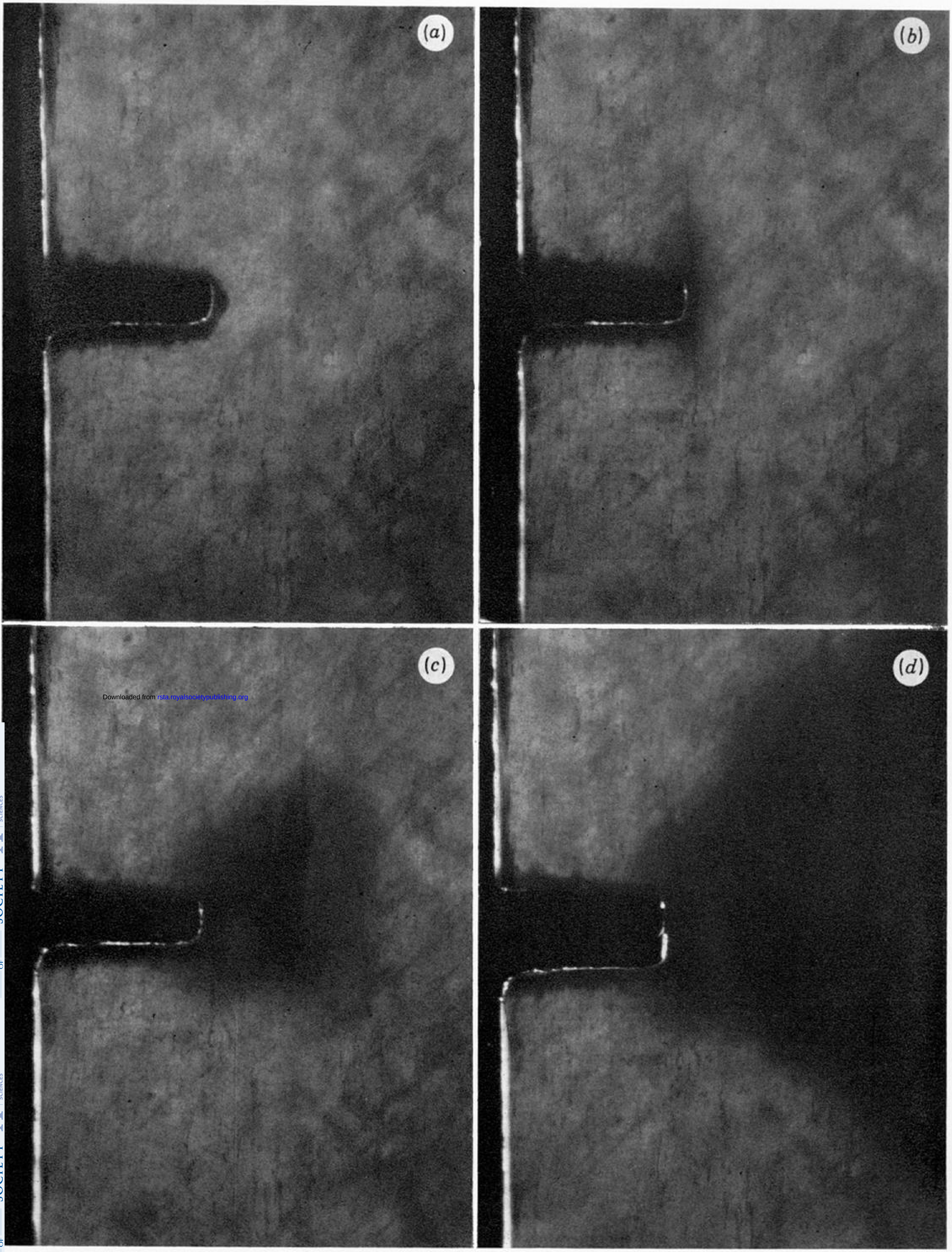

FIGURE 7. Growth of a damage zone in a (0°, ±45°) laminate (glass fibre reinforced epoxy).

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