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Compressive failure of fibre-reinforced composites: buckling, kinking, and the role of the interphase

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Recent experimental studies of compressive failure in fibre-reinforced polymeric composites have been analysed. It is shown that the parametric basis for most compressive strength models, i.e. pure plastic buckling controlled by matrix shear strength and initial fibre misorientation, is probably incomplete. It is argued that, instead, failure is triggered by the initiation of an unstable kink band prior to buckling instability, and that additional parameters (interfacial shear stress/strain; fibre strength) are responsible for this transition in mechanisms.

1. Introduction

The compressive failure of fibre-reinforced polymeric matrix composites is often a crucial factor in their use. In particular, the failure of flexed structural composites panels frequently initiates on the compressive side, at a significantly lower stress level than that required to initiate tensile damage modes. Unfortunately, prediction of the onset of compressive breakdown has proved to be an elusive goal, due in large part to the complexity of the phenomenon. The purpose of this work was to address certain recent results that appear to show the problem to be even more complicated than heretofore generally appreciated. Specifically, the roles of the fibre–matrix interphase and fibre strength were considered.

2. Background

Generally, three different macroscopic failure modes are observed for unidirectionally reinforced composites [1]. In the first case, if the bond between fibre and matrix interface is weak, transverse forces generated by Poisson's ratio mismatches can initiate fracture at the fibre/matrix and induce longitudinal splitting. Because most engineering composite systems involve fairly strong interfaces, this usually is not the dominant mode of failure.

More common, and the focus of this paper, is the observation of compression failure via shear crippling [1], which is associated with fibre buckling and kinking. Typically the kink bands lie at an angle, β, of $20°$–$30°$ relative to the plane normal to the fibres, while the fibre segments within the kink are rotated by an angle, α (usually $\simeq 2\beta$), relative to the fibre direction (Fig. 1). For graphite and E-glass-reinforced systems, the kink band boundary usually is demarked by fibre fracture within a basically continuous polymer matrix (Fig. 2).

The third mode of failure is associated with pure compressive failure of the fibres themselves, i.e. fibre "crushing". This occurs when the axial strain within the composite attains a value equal to the critical crushing strain for the fibres. [2]. Owing to improvement in fibre performance, this highest strength failure mode is usually prevented by the occurrence of fibre kinking at lower stress levels.

Thus, current attention in regard to compressive failure of polymeric composites is focused on the phenomena which appear to control kinking. Most treatments of the problem derive from the work of Rosen [3] who, in 1965, analysed the elastic buckling (in both shear and transverse extension) of initially perfectly aligned fibres. Defining failure as the stress level corresponding to the onset of sinusoidal buckling instability, and computing the latter in terms of strain energy, the compressive strength turned out to be simply

$$\sigma_c = G_m/(1 - V_f) \tag{1}$$

where G_m is the shear modulus of the matrix and V_f is the volumetric fraction of fibres. It will be noted that the instability at failure is not yet a kink band; the latter is assumed (implicitly) to develop from collapse of the sinusoidal configuration, contributing nothing to the critical strength computation.

It was found that the above result was non-conservative, due principally to the fact that real composites do not contain perfectly aligned fibres. Non-aligned fibre enclaves constitute stress concentrations sufficient to cause local yielding of the matrix at stress levels well below the Rosen limit, and in 1972 Argon [4] showed, again by means of an energy-based argument, that collapse of a buckling instability ($\beta = 0$) ensued for a rigid–perfectly plastic composite when

$$\sigma_c = \tau_y / \bar{\phi} \tag{2}$$

where τ_y is the interlaminar matrix shear strength and $\bar{\phi}$ is the initial fibre misalignment with respect to the compression axis. It was noted by Argon that this computation actually describes the conditions needed

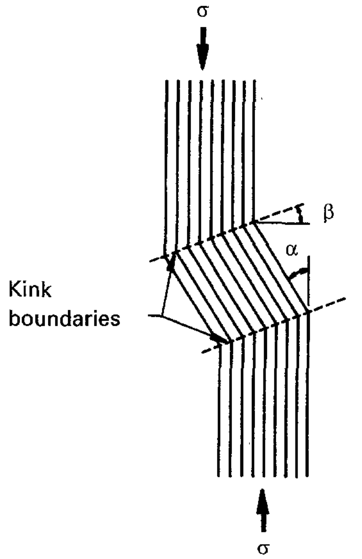

Figure 1 Schematic drawing indicating kink morphology; kink orientation, α, and the boundary orientation, β, are also indicated.

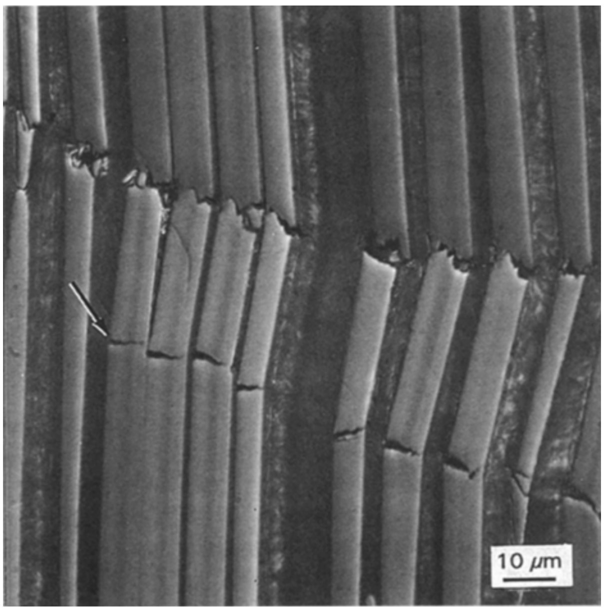

Figure 2 Kink band in 0° PAN graphite-reinforced PEEK, stress axis vertical. The lower boundary of band is arrested (arrow); the next fibre (left of arrow) has relaxed.

to generate a localized collapsed nucleus, which then spreads at a shear angle across the specimen to produce macroscopic failure.

Subsequently, many researchers [5–15] have refined the plastic buckling model. Budiansky [5] has extended the Argon formula to the more realistic (but still $\beta = 0$) elastic–perfectly plastic case, for which

$$\sigma_c = \tau_y/(\nu_y + \bar{\phi}) \tag{3}$$

where ν_y is the composite yield strain. This general approach has been further developed by Budiansky and Fleck [6], who have incorporated matrix strain hardening and finite fibre stiffness. The latter approach required the assumption that the kink exists *a priori*, i.e. the fibres already are broken at the two boundaries of the kink band, oriented at an initial (assumed) inclination angle $\beta > 0$.

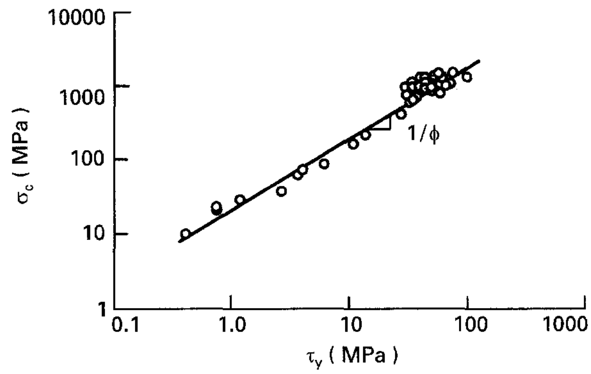

Figure 3 Composite compressive strength versus matrix shear yield strength [2]; $\phi \approx 3°$ from Equation 2.

Sensitivity analysis of expressions for σ_c that result from these types of buckling analyses indicate that easily the most dominant parameters are the matrix yield strength and the initial fibre misorientation [6]. Experiments by many researchers, summarized by Jelf and Fleck [2], support the conclusion that, for a variety of polymeric composites, σ_c is directly proportional to τ_y (Fig. 3), and the measured constant of proportionality suggests that $\bar{\phi}$ in the Argon analysis (Equation 2) is around 3°, which seems reasonable for current fibre lay-ups.

It should be noted, however, that these analyses do not really predict kinking, which was the original goal; they either represent the maximum compressive stress corresponding to buckling stability, following which kinking occurs as a post-failure event, or kinks are presumed to pre-exist (an unrealistic assumption). Specifically, the actual creation of the kink *per se*, i.e. fracture of the fibres, is explicitly assumed to make no contribution to the computation of σ_c. However there is actually no observational experimental evidence to prove that most engineering composites fail purely by buckling instability. While it is clear that some buckling deformation must precede compressive failure, it is perfectly possible that the latter is triggered by localized damage mechanisms superimposed on an otherwise stable buckled state. Recent experiments and microscopic observations appear to support this scenario; in fact, they seem to require it.

3. Recent developments

The importance of the fibre–matrix interphase in controlling the tensile and shear behaviour of polymeric composites has been well documented in the last few years. In addition, a few recent studies have explored the possibility of a similar role in regard to compressive strength.

Madhukar and Drzal [16], for example, have shown that by increasing interface strength (ISS) while maintaining constant matrix yield strength and nominal fibre misorientation, compressive strength increases proportionately while the failure mode changes from delamination to microbuckling (kinking) to fibre compressive failure (Fig. 4). Even more to the point is the work of Lesko *et al.* [17], who have varied interphase properties within the compressive

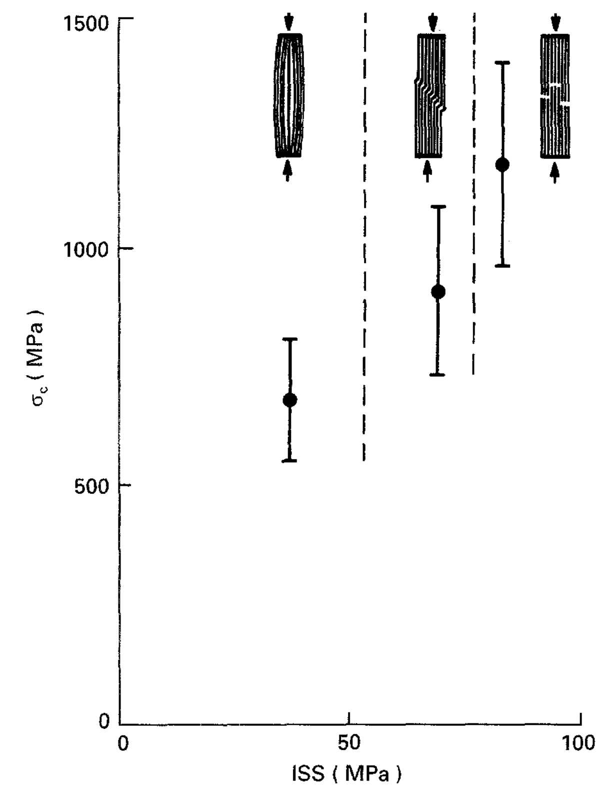

Figure 4 Compressive strength and failure mode versus interfacial shear strength for 0° PAN graphite-reinforced epoxy [16].

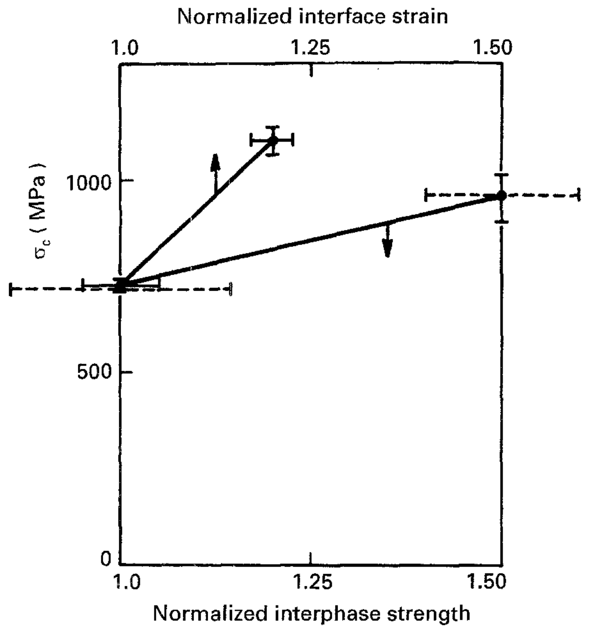

Figure 5 Compressive strength versus normalized interfacial strength (approximately constant interfacial strain) and versus normalized interfacial strain (at approximately constant normalized stress) [17]; matrix strength and lay-up are constant, and all failures occur via kinking.

strength regime dominated by kinking, again while maintaining τ_y and ϕ constant. Compressive strength increases significantly (Fig. 5) if either ISS or interfacial shear strain to failure are increased (while maintaining the other parameter essentially constant).

This is a surprising result, one not expected on the basis of the family of matrix shear strength and fibre misorientation-dominated theories outlined above.

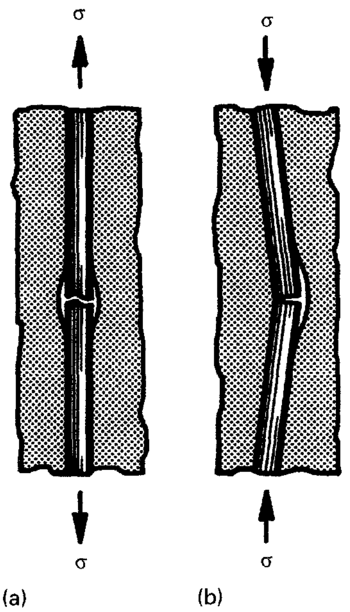

Figure 6 Schematic illustration of interfacial debonding induced by fibre fracture: (a) tensile loading (b) compressive loading.

Efforts have been made [7, 10] to consider the possible influence of the presence of the interphase upon buckling, and these, in fact, have shown that the effect should be small if the sole contribution arises from the deformation of the interphase. Realistic interphase are extremely thin (< 1 μm) relative to typical fibre thicknesses, in which case the change in compressive strength due to interface deformation is predicted to be negligible [10].

On the other hand, it is well known that the ISS controls tensile strength in a direct fashion via debonding and redistribution of local stress transfer following fibre fracture [18–20] (Fig. 6a). It should be emphasized that laser Raman spectroscopy (LRS) has demonstrated conclusively that for both epoxy [19] and thermoplastic [20] fibre-reinforced systems fibre–matrix debonding under tensile loading is preceded by fibre fracture. By analogy, similar ISS (or interfacial shear strain) controlled debonding should occur in compression, but only following fibre fracture (Fig. 6b).

If the latter process is important, it must be one that can manifest itself prior to pure buckling instability because, otherwise, subsequent kinking is just the end result of an unstable collapse, and the debonded fibre–matrix interface has no opportunity to exert its potential influence. Thus the question arises, does fibre fracture precede pure buckling collapse?

It can be shown that the answer is yes. As shown in Fig. 7, acoustic emission begins in carbon fibre-reinforced PEEK at stress levels well below the compressive strength, i.e. the point of structural instability. Only the fracture of a brittle fibre is likely to be responsible for this phenomenon. More concrete evidence is provided by SEM characterization of the process zone attending the tip of an arrested kink band in a 0° graphite/PEEK composite (Fig. 8). Here, the gently flexed fibre ensemble is riddled with microcracks nucleated on the tensile sides of many of the

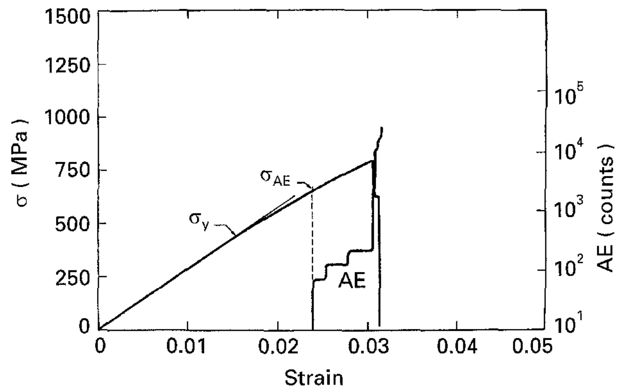

Figure 7 Compressive stress and acoustic emission versus strain in 0° PAN graphite fibre-reinforced PEEK.

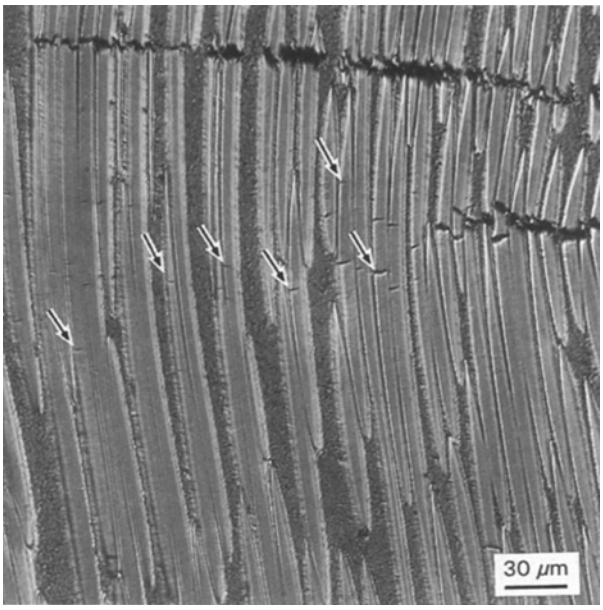

Figure 8 Flexed prekink zone preceding relaxed kink band, showing multi-fibre fractures (arrows) ahead of kink tip.

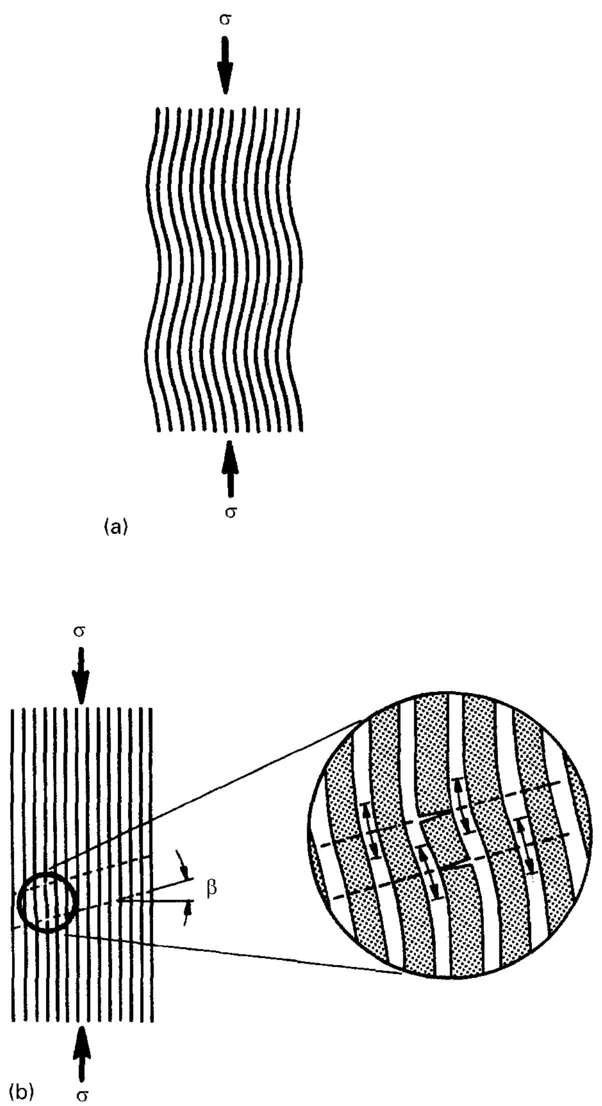

Figure 9 Schematic comparison of compression failure by macroscopic plastic buckle collapse versus microkink band development. (a) Homogeneous shear buckling instability. (b) Kink-band nucleation within a stable microbuckle.

fibres. This zone would be the precursor of any further kink band propagation; similarly, such a localized ensemble would serve, in the absence of the kink, as a kink nucleus. Based on the LRS evidence of debonding as the inevitable aftermath of pure tensile fibre fracture, it certainly seems reasonable to believe that at least partial debonding (as envisaged in Fig 6b) must be associated with the microcracks in Fig. 8.

It is this likelihood of prekink debonding at isolated fractured fibres that provides a mechanism for interfacial shear stress/strain to alter composite compressive strength as observed by Lesco *et al.* [17]. Recently, Chung and Weitsman [13] showed theoretically that random fibre spacings, combined with matrix non-linear plastic flow, introduces imbalances in the support provided by the matrix against fibre buckling, resulting in localized transverse/shear loads on the fibres. These, they note, could lead to premature fibre microkinking and thus to a transition from failure by unstable plastic buckling to collapse by macrokink band nucleation and propagation. This is essentially the present thesis, but with (fractured) fibre–matrix debonding substituting for (or added to) randomness in interfibre spacing as the origin of localized shear loadings against adjacent fibres.

Such a model can explain the fact that in real systems $\beta \neq 0$, contrary to current buckling models. In fact, experimental observation of engineering composites shows clearly that homogeneous sinusoidal buckling (Fig. 9a), generally does not occur, contrary to the usual theoretical assumption. Instead, buckling is localized, and usually occurs at the sites of initial shear offsets corresponding to lay-up imperfection (Fig. 9b). At enclaves such as these, tensile stresses are induced in fibres at local flexures whose range is delineated by the arrows. It is evident that the average probability of individual fibre failure will lie along two parallel shear bands oriented at $\beta > 0$, rather than normal to the reinforcement direction ($\beta = 0$).

Further, adding to the overall complexity of compressive failure is the microfracture process associated with the individual fibre. This is also a stable event, one capable of influencing the development of a kink band nucleus. Dobb *et al.* [21] have shown via recoil experiments that the compression fracture of a PAN

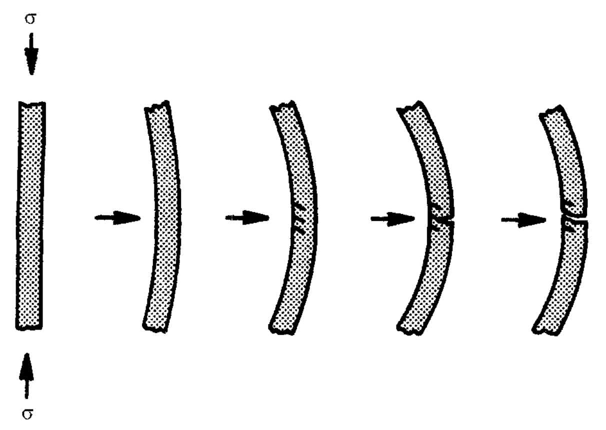

Figure 10 Schematic illustration of the sequence of events associated with fracture of a PAN graphite fibre under compressive loading; shear deformation bands nucleated on the inner (compressive) side of a curved fibre localize bending and induce fracture on the opposite (tensile) side.

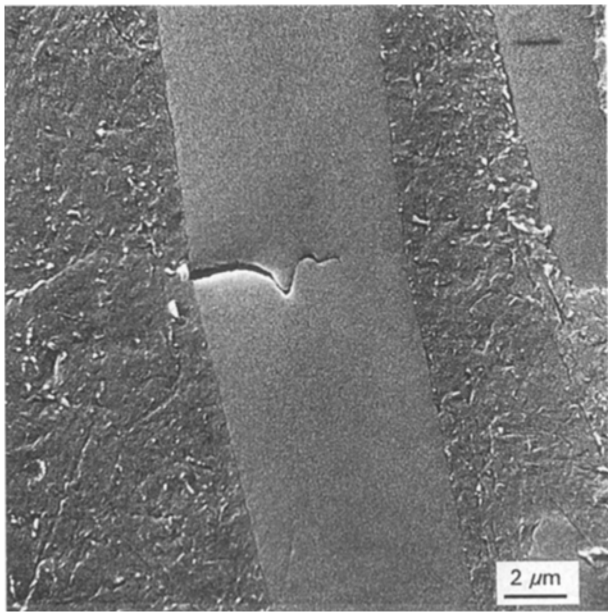

Figure 11 Tensile microcrack in flexed PAN graphite fibre in PEEK; compression axis is vertical.

carbon fibre takes place according to the discrete steps shown in Fig. 10, whereby the flexure of an initially straight fibre leads to the nucleation of shear deformation bands on the compressive side of the fibre; these, in turn, induce a tensile microcrack on the opposite side of the fibre, which links up with, and causes final failure along, the original shear bands. Shown in Fig. 11 is such a failure in progress at an arrested compression kink band in 0° PAN carbon fibre-reinforced PEEK; ion etching experiments [22] have proved that the unbroken section contains shear deformation bands. Thus, the transition from pure plastic buckling probably is a function not only of fibre matrix interfacial debonding, but of fibre failure mechanisms and flaw distribution as well.

Although most composite failure models predict collapse via plastic buckling as the critical event, this may be partly due to the fact that at least buckling can be modelled. The posited scenario certainly is much more difficult to handle analytically, suggesting that interfacial failure, corresponding local stress redistribution, fibre flaw distribution(s), and quasistable fibre fracture modes, must be included. On the other hand, it is encouraging that additional avenues other than matrix shear strength and fibre lay-up improvement may be available for the optimization of compressive performance.

It should be emphasized that others have previously suggested the potential relevance of a pre-buckling instability transition to kink band failure in compression. Weaver and Williams discussed the concept in their important 1975 paper [23], in which they imply (in the view of the present author) that plastic buckling could be essentially short-circuited by local tensile failure of flexed fibres and consequent kinking. Much the same conclusion was drawn by Hahn [24] in 1987, and as noted earlier, most recently by Chung and Weitsman [13].

Finally, there remains the nagging question as to how, if the development of a kink is so stable, the kink process in the absence of buckling instability can account for the dramatic instability associated with final compressive failure. This is answered in an elegant way in the recent theoretical development by Sutcliffe and Fleck [25], where it is shown that a kink band can be considered in terms of crack bridging fracture mechanics to be characterized by a compressive stress intensity factor, K_σ. Below a critical value, K_{IC}, of the latter, a kink can extend subcritically; however, once $K_\sigma = K_{IC}$, the kink propagates catastrophically, and the specimen fails.

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