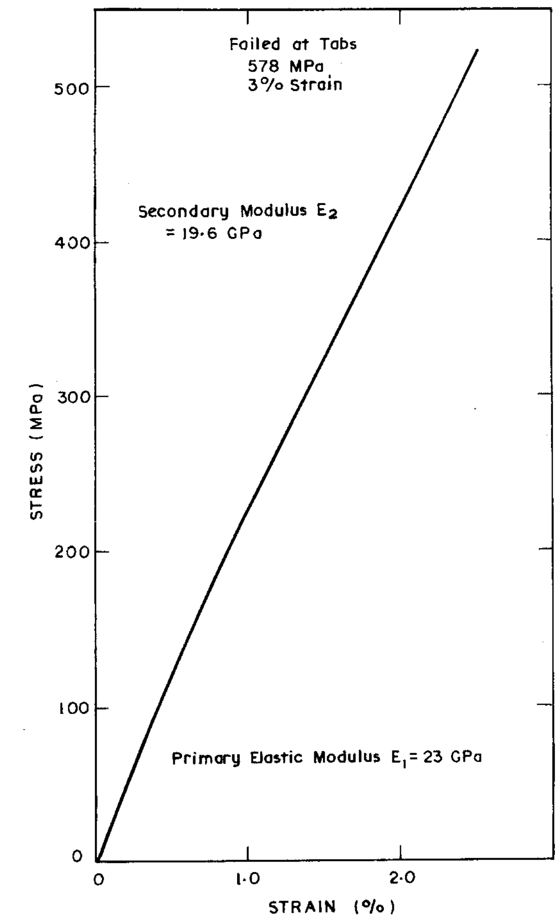

Figure 2 Stress–strain curve of bi-directional glass-fibre/epoxy resin laminate (20 end Ferro Unistrand glass fibre). Strain–rate $1.48 \times 10^{-4}\,\text{sec}^{-1}$, 30° C.

able for practical application (low glass transition temperature), the results indicate that resin development along the lines outlined above could result in fibre/resin composites with improved performance in multi-ply configurations.

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Contoured double cantilever beam specimens for fracture toughness measurement of adhesive joints

Contoured double cantilever beam specimens (CDCB) have been often used for fracture toughness (R) measurements and stress corrosion studies in adhesive joints [1–5]. The profiles of the cantilever beams are designed such that for quasi-static crack propagation to occur, the fracture load (X) is invariant in crack length (a) if R is a constant. Thus,

$$R = \frac{4X^2}{Et^2} m \tag{1}$$

where E is Young's modulus of the adherend; t the thickness of the adhesive; and m, which depicts the beam profile, is given by

$$m = \frac{3a^2}{h^3} + \frac{1}{h} \tag{2}$$

with h as the height of the beam at a given crack length (a). It may be realized from Equation 2 that when m is large, the CDCB specimens are slender; and when m is small they become stiff. In many fracture toughness experiments [1–4] for structural adhesive joints, m usually assumes very large values, typically of the order of $90\,\text{in.}^{-1}$ ($35.6\,\text{cm}^{-1}$). However, in the case of beams with small values of m, say 1 to $4\,\text{in.}^{-1}$ (0.394 to $1.575\,\text{cm}^{-1}$), because of crack tip effects and departure from simple beam theory [1], m has to be replaced by m' determined from accurate experimental compliance measurements. In this modified equation,

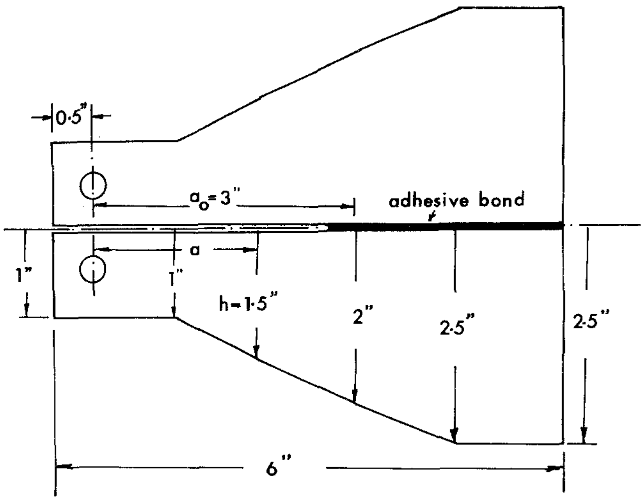

Figure 1 Specimen geometry of a CDCB testpiece with $m = 4\,\text{in.}^{-1}$, $t = 0.25$ in.

i.e. $R = 4X^2/Et^2\ m'$, if R is invariant in a, the fracture load should still remain constant during crack propagation.

In the present note, we relate some unexpected observations not previously reported for toughness measurements using CDCB specimens with $m = 4\,\text{in.}^{-1}$ ($1.575\,\text{cm}^{-1}$) (see Fig. 1). Except for a short range of crack length [6], where 1 in. $< a <$ 3 in. crack propagation does not take place at constant load even though R may be constant. Instead, crack spreading takes place at constant displacement (u) for constant R of the adhesive joint for crack lengths greater than 3 in.

Our conclusions are based on the following experimental results obtained from a Perspex/Tensol Cement 7 adhesive joint. Both the adherend and the adhesive are commercial products of I.C.I. Fig. 1 shows the CDCB specimen geometry and dimensions used for the fracture toughness determination of the adhesive joint. Note that $m = 4\,\text{in.}^{-1}$ ($1.575\,\text{cm}^{-1}$) in this specimen design, and the adhesive bond thickness is about $5 \times 10^{-3}\,\text{in.}^{-1}$ (0.127 mm). The starter crack length (a) is 3 in. (7.62 cm). A typical load–displacement (X–u) curve during quasi-static crack propagation in the adhesive joint is shown in Fig. 2. The fracture toughness values shown in the triangles are calculated according to the irreversible work area method of Gurney and co-workers [7–10]. It is apparent that with the exception of the first few millimeters (≈3.6 mm) of crack increment, the fracture load drops instantaneously at constant displacement as the crack spreads to the far end of the specimen. Thus, this fracture behaviour is at odds with that predicted by Equation 1, even though R during quasi-static spreading is quite consistent.

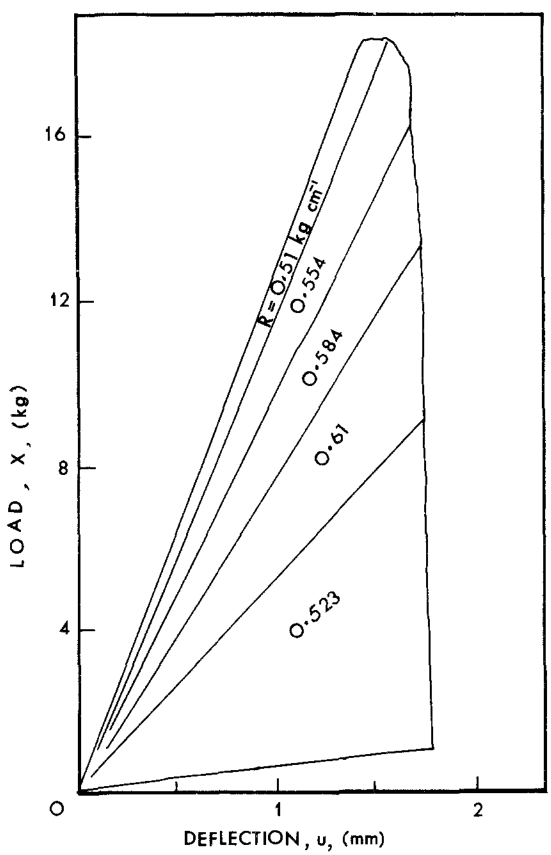

Figure 2 Quasi-static cracking in a Perspex/Tensol Cement 7 adhesive joint.

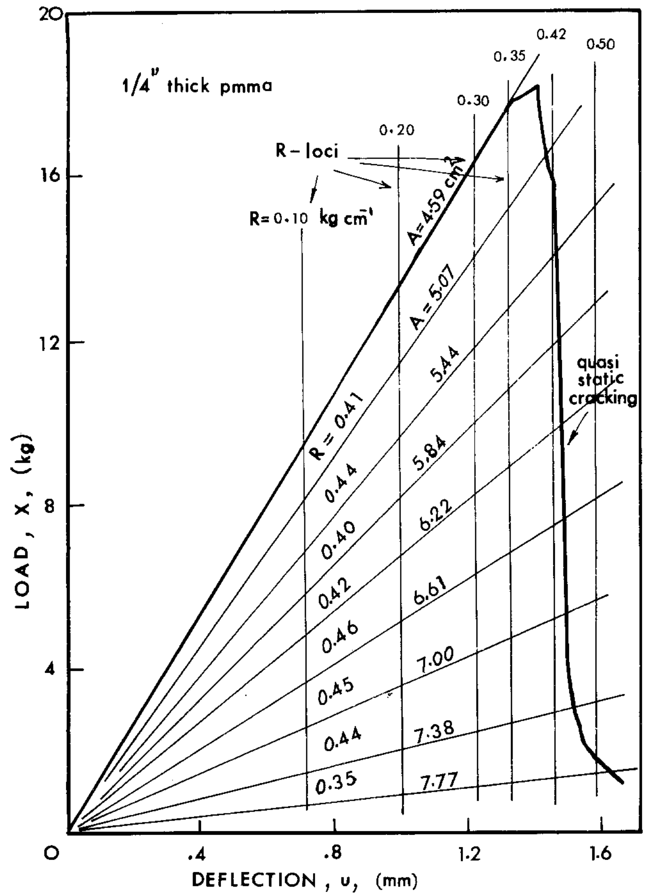

Figure 3 Quasi-static cracking in Perspex using a CDCB specimen with $m = 4\,\text{in.}^{-1}$.

To ensure that this observation is not peculiar to the anisotropic adhesive joints, we have run similar experiments on isotropic testpieces. Fig. 3 shows the load–displacement record of a similar CDCB specimen made entirely of Perspex. This result also confirms that crack propagation takes place essentially at *constant displacement* so that the fracture toughness values may be estimated from [7]

$$R = -\frac{u^2}{2t}\frac{\partial}{\partial a}\left(\frac{X}{u}\right) = -\frac{u^2}{2t}p; \quad \text{for} \quad a > 3\,\text{in.}; \tag{3}$$

where p is a constant, and represents the rate of change of stiffness (X/u) as the crack proceeds. Fig. 4 shows the stiffness measurements as function of crack area A $(=ta)$ for the CDCB specimens (i.e. both the plain Perspex testpiece and the Perspex/Tensol Cement 7 adhesive joint). A least square line to the experimental data gives

$$X = (319.7 - 40.3A)\,u; \quad \text{for} \quad 4 < A < 7.6; \tag{4}$$

where X is in kgf, u in cm and A in cm^2. These results give $p = -25.6\,\text{kg cm}^{-2}$, and $R = 20.15\,u^2$. Thus, the vertical constant u lines become the constant R-loci as shown in Fig. 4.

It is significant that these experimental results suggest alternate test methods for fatigue testing using hard or screw-driven machines in which displacement control is easier monitored than load control. Crack growth rates can thus be correlated with ΔR given by corresponding Δu in the usual way. In addition, these CDCB specimens with large crack lengths can also be used for stress corrosion experiments by wedge opening, instead of hanging with dead weights, to give various R values which are invariant with crack length.

Although the specimen is originally designed so that the rate of change of compliance with crack length is a constant (which is true only for 1 in. $<$ $a < 3$ in.), experimental compliance calibrations show that its reciprocal, i.e. the stiffness, is instead independent of change of crack length for $a < 3$ in. Therefore, if Equation 1 is used to calculate R of

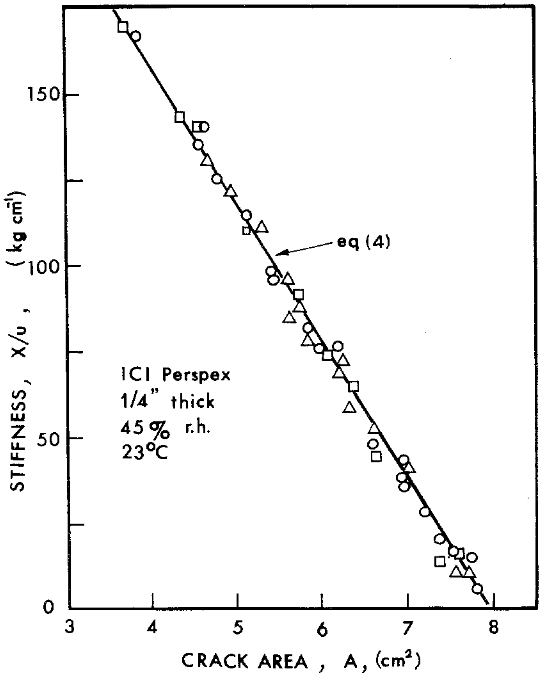

Figure 4 Variation of stiffness (X/u) with crack area (A) for the CDCB specimen with $m = 4$ in.$^{-1}$.

the adhesive joint, for low m specimen profiles and large crack lengths, by just using the load at fracture, this must necessarily give erroneous R-values. The correct R results can only be obtained using Equation 3. Of course, the irreversible work area method of Gurney [5, 7–10] is also valid for R measurements in this situation.

In view of the increasing use of these CDCB specimens with small m values (for improvement of beam stiffness and for avoidance of crack turning from the fracture plane), for fracture toughness determination of adhesive joints, we hope that this communication should be of some interest to experimentalists. A more detailed discussion on the stability of cracking in CDCB specimens has also been presented elsewhere [11, 12].

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Brittleness as an indentation size effect

It is well known that the mechanical response of certain solids can change dramatically with such variables as temperature, strain-rate, etc. The classic manifestation of this mechanical variability is the "ductile–brittle transition" evident in many engineering materials. Here we consider the influence of one largely unexplored variable, the scale of the overall deformation process, on the degree of brittleness. Standard indentation testing techniques provide a convenient basis for quantifying the effect.

The idea developed here derives from the observation that well defined hardness impressions may be produced in the hardest of solids at sufficiently low loads, but that the incidence of cracking about these impressions increases as the load level is raised. While considerable attention has been devoted to analysis of the residual