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Fracture mechanics of oilseed rape pods

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The basic theory of linear elastic fracture mechanics was applied to the fracture of pods from six genetic lines of oilseed rape (*Brassica napus*). An experiment was designed to allow the energetics of the fracture process to be accurately determined. The work of fracture, toughness and fracture toughness of five experimental varieties and one common commercial variety (Apex) were measured. The values for the toughness (0.006–0.271 kJ m^{-2}) and fracture toughness (0.026–0.233 MN m$^{-3/2}$) obtained from each line were distinct from each other but broadly similar to those of other brittle materials. The toughness and fracture toughness of Apex were approximately midway between the lowest and highest values measured. This result indicates that there is scope for improving the fracture resistance of oilseed rape crops so as to reduce seed loss before and during harvest. The approach described would be useful in selecting fracture-resistant genetic lines to help to develop such crops.

1. Introduction

Seed loss through pod shatter from oilseed rape plants during ripening and harvesting is high, typically 8–12% [1, 2] but can be over 20% if harvesting is only 1 week late [3]. This is a problem both in that the seed is lost and hence unavailable for oil extraction, and in the subsequent establishment of volunteer plants [4]. Rape seed can persist for a long time in the soil and is a concern both where rape is grown in rotation with other broad-leaved crops and in subsequent rape crops when rape of different qualities is grown in one rotation. Lines of rape for which the pods are more shatter resistant are therefore of commercial interest.

Shattering is a widespread phenomenon in dicotyledonous crops bearing many-seeded dry fruits, such as the *Brassica* species [5]. Tendency to shatter is the predisposition of the siliquae (pods) to dehisce and release seed. Such detachment and dehiscence is aided by the development of abscission layers, comprising cells that are mechanically weak, in the region of the junction of the valves of the fruits. The purpose of this study is to determine the extent to which the principles of fracture mechanics can be applied to the shatter of oilseed pods, and thence to investigate the range of shatter behaviour of five experimental lines and one commercial line of oilseed (*Brassica napus*).

2. Materials and methods

The major features of the siliqua are shown in Fig. 1. Shatter is generally initiated in the dehiscence zone at the point where the pedicel meets the replum at the base of the pod, or at the tip where the style is readily detached. Fracture continues along the dehiscence zone between the pericarp and the replum, allowing release of the seeds. Pods from six lines of *Brassica napus*, referred to as lines A–F, were supplied by the John Innes Centre, Norwich. Five of these were experimental varieties, and one (Apex) was a commercial variety from the National Institute of Agricultural Botany recommended list, 1996. Before testing, all samples were conditioned for at least 14 days in an environmentally controlled room at 20 °C and 50% relative humidity.

2.1. Determination of Young's modulus

Young's modulus E for each line of pods was determined independently for a strip of pod material excised from the wall. The strip was cut such that the wall material was tested in a direction parallel to the major axis of the pod. The test was repeated for each of three replicates for each line of pods.

2.2. Direct opening tests

The resistance of oilseed pods to fracture is generally determined in a cantilever bend test [5, 6]. Whilst this test provides a measure of the bending moment required to cause fracture, it is less useful in the determination of work of fracture and toughness as the deformation is not well controlled. The work of fracture is given by the difference in the stored elastic energy just before and just after fracture. In the cantilever bend test the latter is difficult to measure accurately, as the pod may not return to the start position or fragmentation may occur. To overcome these difficulties, a more controlled experiment was designed.

Each pod was mounted such that the replum was horizontal and the lower pericarp attached with an epoxy glue to a wooden board (Fig. 2). A small solder tag, with the loop bent to the vertical position and the

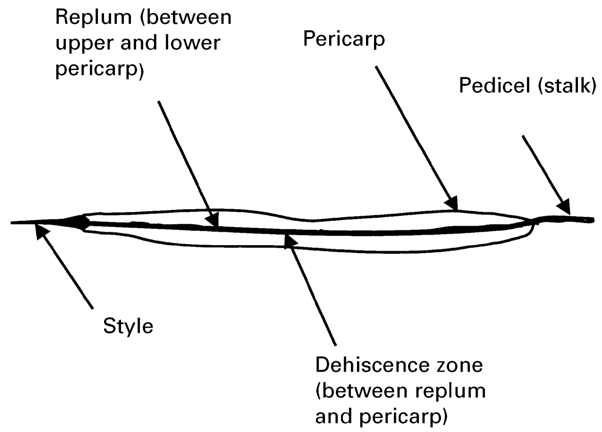

Figure 1 Essential features of an oilseed pod.

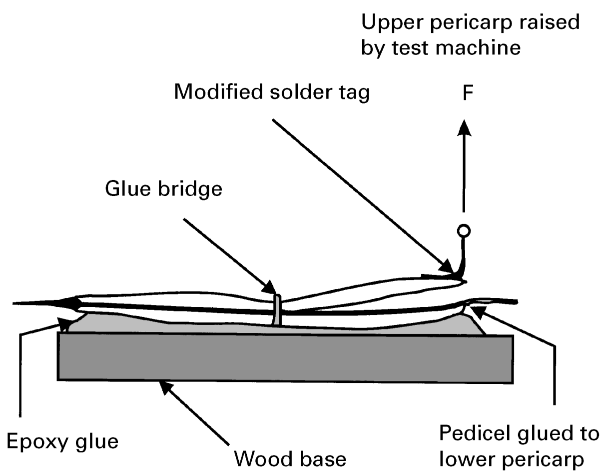

Figure 2 Method of mounting an oilseed pod for testing.

tag bent to match the curvature of the upper pericarp, was then attached to the upper pericarp at the base of the pod using a thixotropic cyanoacrylate adhesive. To ensure that fracture occurred only in the upper dehiscence zone, the pedicel was glued to the lower pericarp. Finally, a "glue bridge" was constructed by running a ring of epoxy glue around the cross-sectional perimeter of the pod at a distance of 25 mm from the base of the pod. A universal test machine (Davenport–Nene model DN10 fitted with a 10 N load cell) was used to open the pod at a constant rate of 0.5 mm min^{-1} and to record the force–deflection data. A long connection was used between the load cell and the pod such that, as the top of the pod lifted, the line of action of the opening force to the vertical did not exceed 0.1°.

For the first part of the test, the front end of the top pericarp was steadily lifted through 1.5 mm (Fig. 3, solid curve) and the force–deflection data recorded. At some point during this loading, a crack was initiated in the dehiscence zone which propagated with further lifting until arrested by the glue bridge. It was found that for all pods a vertical lift of 1.5 mm of the tag attached to the pericarp was sufficient to extend the crack fully. The direction of motion was then reversed and the pericarp lowered to the start position. To confirm that the crack had propagated to the glue bridge, and to measure energy losses due to plasticity of the pericarp, in the second part of the test the upper pericarp was raised and lowered through 2 mm (Fig. 3, broken curve). A trace of deflection increasing with load with no discontinuities in load indicated that no further fracture occurred, confirming that the crack had indeed reached the glue bridge after the initial deflection to 1.5 mm.

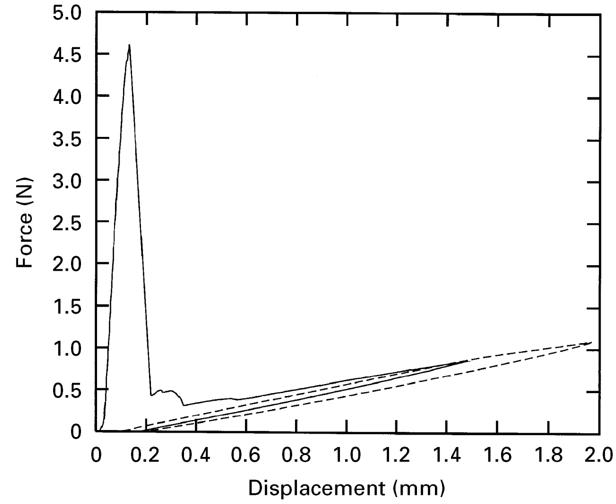

Figure 3 Force–deflection graph for pod opening. See text for key.

The flexural properties of the upper pericarp of each pod were calculated from the second part of the test (Fig. 3, broken curve). In the first part of the test a crack was initiated in the dehiscence zone and propagated to a fixed known point, defined by the position of the glue bridge. The top pericarp subsequently behaved as a cantilever constrained to zero deflection and zero slope at the glue bridge. Its flexural rigidity, EI, was calculated from

$$EI = \frac{Fl^3}{3\delta} \tag{1}$$

where F is the deflecting load, l the cantilever length and δ the end deflection.

The work of fracture R, was calculated by measuring the work done in raising the upper pericarp through the initial 1.5 mm, which included the fracture event, and subtracting from this the recovered elastic energy on returning to the start position. This work is given by the area bounded by the solid curve in Fig. 3.

To determine the toughness (also known as the critical strain energy release rate), G_c, it is necessary to know how the compliance of the pod changes with increasing crack length. The usual procedure of forming notches of different lengths and measuring compliance directly is not practicable, given the fragility of the specimens. However, having obtained the value for EI above and making the approximation that the cross-section of the pod was uniform along the length of the pod, the free length of the cantilever (and hence an estimate of the distance of propagation of the crack) could be calculated from Equation 1 for each point on the loading curve shown as a solid curve in Fig. 3. The toughness, G_c, was then calculated by the compliance calibration method (see, for example, [7, p. 350] or [8, p. 53]) from

$$G_c = \frac{1}{2}\frac{F_{max}^2}{l}\frac{\partial(1/M)}{\partial a} \quad (2)$$

where M is the stiffness of the cantilever in bending.

The fracture toughness (also known as the stress intensity factor), K_c, was then calculated from

$$K_c = \sigma\gamma a^{1/2} \quad (3)$$

where σ is the stress at failure, a is the (predicted) crack length and γ is the finite width correction factor. Conditions of plane stress were assumed as the width of the dehiscence layer (measured in the plane of the base and perpendicular to the major axis of the pod) is small compared with its length. In effect, two fracture processes (as the dehiscence zone runs down each side of the pod) were occurring simultaneously. Neglecting the curvature of the wall, which was large compared with the thickness of the dehiscence zone, the geometry of each side in the vicinity of the crack tip could be considered similar to that of a compact tension specimen. The appropriate value for γ was taken from [7, p. 359] for this case.

2.3. Cantilever bend tests

For comparison with the results from the direct opening test, cantilever bend tests were performed on five replicates from each line of pods as described in [6]. The stem of each pod was clamped such that the replum was in a horizontal plane, and the pod then deflected by pressing it vertically with a fine roller connected to the load cell at a moment arm of 30 mm and a speed of 8 mm min^{-1} until cracking occurred. The load–deflection curve was analysed to determine the bending moment required to initiate a crack in the pod.

3. Results and discussion

The basic theory of linear elastic fracture mechanics (LEFM) as used here is strictly applicable only to the fracture of isotropic homogeneous materials where the test piece has a well-defined geometry. Pod wall material is highly anisotropic, failure occurs at an interface between two distinct regions of the pod, and the geometry is complex. All these problems will be familiar to people who work with natural materials. It can nevertheless be illustrative to apply simple analytical techniques to such systems, provided that the simplifications and questionable assumptions which are made are held in mind. While a particular determined material property may be in error, its approximate value and the relationship between properties measured for different samples can be meaningful.

The main results are shown in Table I. Values obtained for R, G_c and K_c within each line of pods varied by a factor of about 2, but the distinction between lines was generally clear. Values obtained for the commercial variety Apex were in the lower to middle range of the results from the experimental lines, suggesting that improvements in shatter resistance of commercially grown rape crops may be possible. An exceptionally shatter-resistant pod may, however, present difficulties in the extraction of seed during threshing in the combine harvester. Figs 4, 5 and 6 show that R, G_c and K_c, all increased with increasing fracture force (the maximum force recorded on the load–deflection curve, which is the force required to initiate fast fracture). Results for pods from different lines tend to be gathered together into regions on these plots, but the relationship between R, G_c and K_c is consistent. This suggests that the mechanism of fracture operating is similar in each case.

In LEFM, K_c, E and G_c are related by [7, p. 353]

$$K_c = (EG_c)^{0.5}. \quad (4)$$

This equation can be used to give a measure of adherence of the results to the theory of LEFM. Plotting log K_c against log (EG_c) and fitting a regression line (Fig. 7) indicates for the experimental results that $K_c \propto (EG_c)^{0.51}$. The functional relationship between K_c and G_c is therefore close to that predicted (broken line in Fig. 7) by Equation 4. The vertical offset

TABLE I Results for the fracture testing of six lines of oilseed pods (values given are mean ± standard deviation); five replicates were used for each test, except for measurement of Young's modulus where three replicates were used

	Values for the following lines					
	Line A	Line B	Line C	Line D	Line E	Line F (Apex)
Nominal length of pod (mm)	61.6 ± 6.70	43.4 ± 1.93	41.6 ± 3.65	61.8 ± 2.01	55.8 ± 3.07	70.5 ± 4.9
Nominal width of pod (mm)	3.52 ± 0.11	3.45 ± 0.06	3.40 ± 0.24	2.99 ± 0.22	3.54 ± 0.16	2.89 ± 0.20
Length of dehiscence zone (mm)	51.8 ± 1.33	51.9 ± 1.48	52.6 ± 1.04	53.2 ± 1.72	52.6 ± 1.89	50.2 ± 2.69
Width of dehiscence zone (mm)	0.52 ± 0.05	0.39 ± 0.05	0.40 ± 0.05	0.52 ± 0.05	0.57 ± 0.08	0.42 ± 0.08
Maximum opening force, F_{max} (N)	0.58 ± 0.33	2.42 ± 1.31	3.34 ± 0.98	3.79 ± 0.89	5.90 ± 1.67	2.08 ± 0.66
Flexural rigidity, EI, of upper pericarp (N mm^2)	2.23 ± 0.575	1.33 ± 0.29	2.03 ± 0.57	1.88 ± 0.56	1.44 ± 0.48	1.96 ± 0.30
Young's modulus, E, of pericarp, measured along pod length (GPa)	0.64 ± 0.18	1.53 ± 0.22	0.55 ± 0.21	1.43 ± 0.64	0.72 ± 0.30	1.00 ± 0.91
Work of fracture, R (J m^{-2})	7.77 ± 1.31	14.86 ± 2.28	20.36 ± 5.22	28.46 ± 10.73	37.73 ± 7.49	16.85 ± 4.19
Toughness G_c (kJ m^{-2})	0.006 ± 0.002	0.054 ± 0.031	0.112 ± 0.066	0.153 ± 0.093	0.271 ± 0.168	0.05 ± 0.02
Fracture toughness K_c (MN $\text{m}^{-3/2}$)	0.026 ± 0.011	0.147 ± 0.076	0.195 ± 0.062	0.168 ± 0.043	0.233 ± 0.052	0.13 ± 0.05
Bending moment to cause fracture (N mm)	1.69 ± 0.63	2.69 ± 1.20	—	4.49 ± 0.74	8.58 ± 2.95	3.38 ± 0.62

between the experimental data (solid line) and the broken line gives a measure of the difference between the theoretical and calculated values of K_c. The experimentally determined values of K_c were approximately half those predicted from the theory. This agreement is good given the assumption of isotropy, which is certainly invalid, and the assumption that the longitudinal modulus of the pod wall is the same as that of the material in the dehiscence zone. Other errors arise from the approximations of homogeneity and of compact tension specimen geometry. Allowing for plasticity at the crack tip (which would increase the effective length of the crack for any given load and therefore increase the experimentally determined value of K_c) would result in closer agreement between the experimentally determined value of K_c and that obtained form Equation 4, but assuming that the size

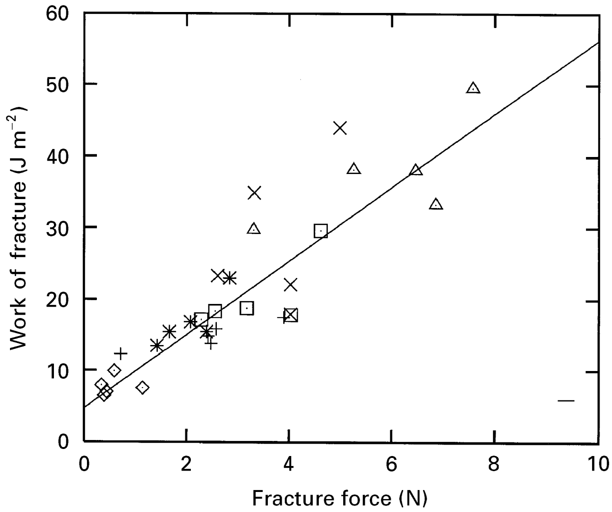

Figure 4 Work of fracture versus fracture force. (◇), line A; (+), line B; (⊡), line C; (×), line D; (△), line E; (∗), line F (Apex); (——), $y = 5.16x + 4.73$.

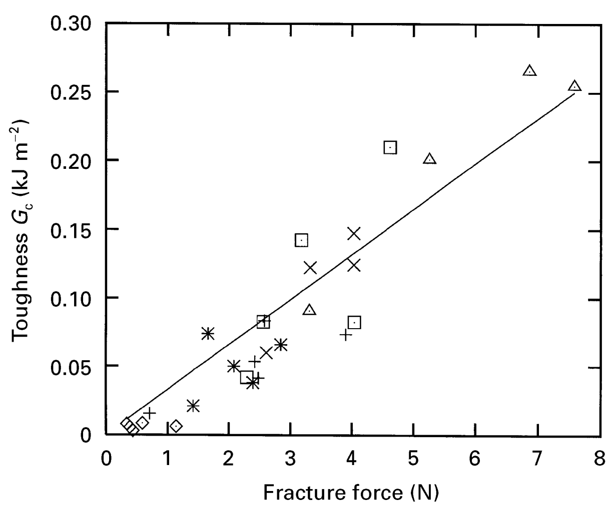

Figure 5 Toughness versus fracture force. (◇), line A; (+), line B; (⊡), line C; (×), line D; (△), line E; (∗), line F (Apex); (——), $y = 0.033x$.

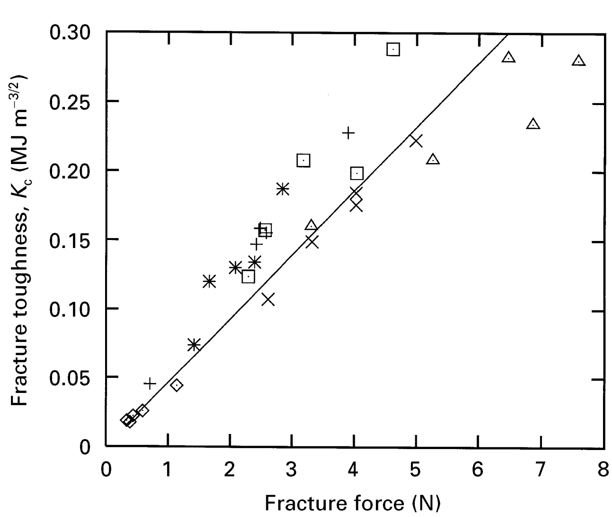

Figure 6 Fracture toughness versus fracture force. (◇), line A; (+), line B; (⊡), line C; (×), line D; (△), line E; (∗), line F (Apex); (——), $y = 0.046x$.

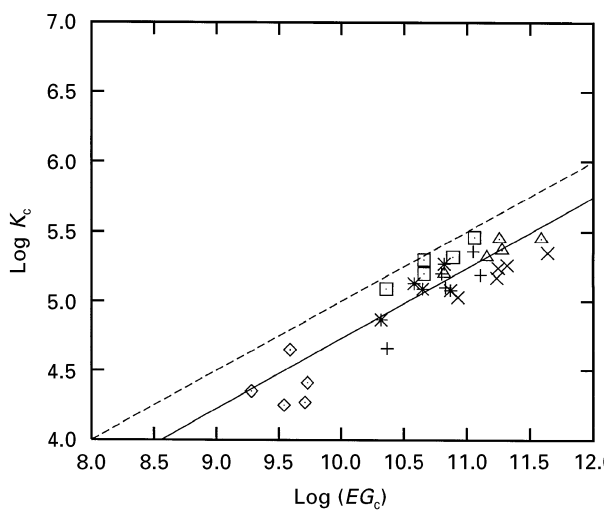

Figure 7 Relationship between fracture toughness, toughness and Young's modulus. (◇), line A; (+), line B; (⊡), line C; (×), line D; (△), line E; (∗), line F (Apex); (——), experimental data, $y = 0.51x - 0.34$; (- - -), theoretical relationship predicted by LEFM, $y = 0.5x$.

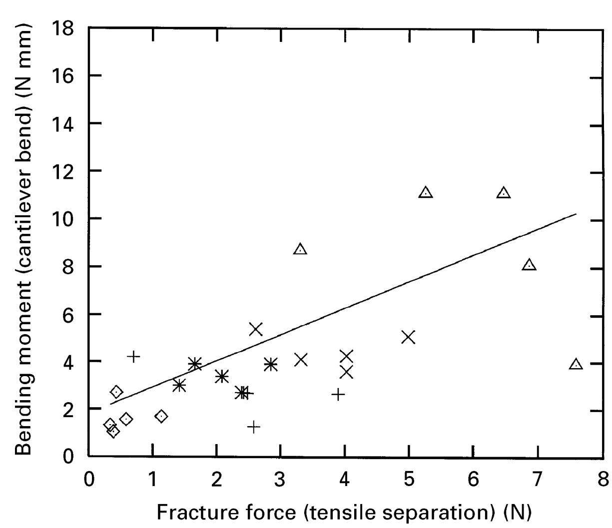

Figure 8 Comparison between the bending moment required to initiate fracture as measured from the cantilever bend test and the force required to initiate fracture in the direct opening test. (◇), line A; (+), line B; (×), line D; (△), line E; (∗), line F (Apex); (——), $y = 1.12x + 1.80$.

of the plastic zone cannot be greater than the thickness of the dehiscence layer changes the experimentally determined value of K_c by only 1–2%.

Previous work [2] has shown a correlation between observations of pod shatter in field and the maximum bending moment observed in a cantilever bend test. Fig. 8 shows the relationship between the bending moment (from the cantilever bend tests) and the force (from the direct opening tests) required to initiate pod fracture. This suggests that resistance to shatter in the field will be higher for those pods with higher measured values of R, G_c and K_c.

It is common to think of materials with a value of G_c below 1 kJ m^{-2} or K_c below 1 MN $m^{-3/2}$ as brittle. On this basis, the dehiscence zone of pods is brittle, which is confirmed by practical experience. The values for G_c and K_c are similar to those substances such as cement, glass, plaster and the less tough woods parallel to the grain, for example balsa and fir [9, p. 36].

4. Conclusions

The fracture behaviour of oilseed rape pods can be described by the basic theory of LEFM. Tests on pods from six different genetic lines gave substantially different values for work of fracture, toughness and fracture toughness. Values obtained for the commercial variety Apex were in the lower to middle range of the results from the experimental lines, suggesting that improvements in shatter resistance of commercially grown rape crops may be possible. The experimental procedure described here should enable evaluation of genetic lines for shatter resistance at an early stage when only a small number of pods may be available.

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