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On the guillotining of materials

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An analysis is presented for the mechanics of guillotining and experiments on a number of solids are described which agree with the theory. Irreversible work not associated with the cutting process (i.e. work of bending or plastic flow) is least when guillotining thin flexible sheets, and experiments on such materials permit determination of the specific work of fracture, once frictional effects have been compensated for. The results are compared with values of fracture toughness obtained by other methods. The analysis is extended to cover the formation of burrs at the cut edge of metal sheets. Comments are also made about the type of friction in guillotining and other scissor-type devices having "set" blades which scrape along one another during cutting.

1. Introduction

The process of guillotining appears to be, in the most general case, a complicated process of combined flow and fracture, with friction playing a superimposed role. Unlike the related processes of cropping, blanking and punching, where the cutting edge is in contact with the workpiece over the whole length or periphery to be severed, in guillotining the cutting blade is angled and makes progressive contact with the material along the line of cut (Fig. 1). At any instant therefore, the volume of material being deformed in guillotining is considerably smaller than in cropping and related processes. Clearly this affects the mechanics of the process, the working stroke of the blade of a guillotine (or scissors or tin-snips type of tool) being much greater for a given length of cut than that of a punch or bar-shearing device. Thus although the total work of flow and fracture may be similar in the different methods, forces in those methods of severing which involve progressive deformation are likely to be smaller than in the methods which deform the whole cut face simultaneously.

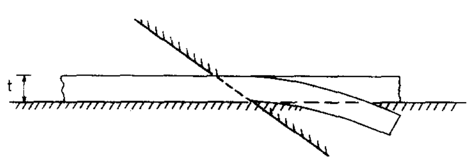

Figure 1 Progessive contact of blade and workpiece in guillotining.

There are many different designs of guillotine, but most have a flat rectangular base plate on which sits the workpiece material (paper, card, thin metal, thin polymer sheet and so on); sometimes there is provision for the workpiece material to be clamped near the cut edge. In the case of "workshop shears" for cutting sheetmetal, the supporting plate for the metal is quite narrow and the metal sheet is held horizontally in the hand rather than being pressed down flat as in the guillotining of paper. The guillotine blade may be spring-loaded in the sideways direction against the edge of the base plate, in which case the blade cuts in a skew fashion; the "setting" of scissor blades achieves a similar result. In such cases, the cutting edges scrape one another quite noticeably when the device is used without workpiece material; the scraping action profoundly affects the frictional behaviour of the device. The purpose of spring-loading and/or of setting blades is to try and ensure a clean cut by preventing the workpiece from bending over between baseplate and blade. The idea is used with devices intended for the cutting of materials possessing low stiffness which are more likely to be dragged down between blade and baseplate. Thus paper cutters have spring loaded set blades whereas metal shears, tin-snips and secateurs do not. In cutting metal some bending of the workpiece at the cut edge does occur which leads to burring; this seems difficult to prevent even when thin sheets of metal are cut on a spring-loaded guillotine, as described later in this paper. Extreme plastic bending of metal sheet at the cut edge is seen when using the older "levering" design of tin-opener, which also gives appreciable plastic buckling at the cut edge. These effects come about of course as there is no fixed baseplate or blade upon which to cut. The newer design of tin-opener which employs a blade pulled around the edge of the tin by means of a serrated wheel gives a somewhat better cut owing to the support of the lip of the tin.

The cutting angle (cross-section) of the blade varies with the device: scissors and paper cutters have blades which are flat on one side and the other edge angled out; sheet metal shears usually have 90° square profile cutting edges (or only perhaps slightly relieved square edges), with the blade and supporting bar being of similar widths. A 90° blade produces no sideways action, unlike a V-blade which pushes the workpiece to the side as it cuts through the thickness. In the case of paper and other low stiffness materials, the offcut can buckle away easily; with stiffer solids, such as metals, that is not possible and it may lead to unacceptable distortions. Given that zero angle blades are not practicable, actual choice of blade angle is a compromise between the strength of the cutting edge, the maintenance of sharpness and the level of the associated guillotining forces.

Other designs of paper-cutting guillotine employ a profiled wheel which is pushed along a bar parallel to the edge of the baseplate; such devices are not usually spring-loaded sideways, as there is less tendency for the resultant line of action of the force to bend down the workpiece. A similar device employing a driven cutting wheel is the bacon slicer, the only difference being that the work material is traversed to the wheel and not vice versa.

The present paper discusses the mechanics of guillotining, with particular reference to the cutting of low stiffness specimens where work of plastic flow (in metals) or other processes of irreversible deformation (in paper or polymers) are likely to be extremely small in comparison with the work of fracture. In such cases, when the total work of cutting is compensated for the work of friction (which, as described later, may reasonably be done very simply) estimates for the fracture toughness (R) are possible. Guillotining experiments are described for a variety of materials and the toughnesses obtained are related to other methods of measuring resistance to cracking or tearing.

2. Analysis

Consider a straight-bladed guillotine cutting as shown in Fig. 2, which is an idealization of actual cutting conditions; in practice the blade profile is usually curved.

The external force P is applied to the blade at some fixed distance r_2 from the pivot, and when the blade is at some generic angle α, the increment of external work done in a further rotation $d\alpha$ of the blade is

$$Pr_2 \sin \alpha \, d\alpha \tag{1}$$

In the same increment, the crack (i.e. the area of cut edge) increases by $(t/\cos \alpha) r_1 d\alpha$ where r_1 varies with α. Thus if R is the specific work of fracture, the associated toughness work is

$$Rtr_1 \, d\alpha / \cos \alpha \tag{2}$$

In the case of a blade spring-loaded against the baseplate with a sideways force S, the frictional force may perhaps be represented by μS, in which case the incremental frictional work is

$$\mu S r_1 \, d\alpha \tag{3}$$

Whether μ is the same coefficient of friction as in normal sliding will be discussed later in the light of the experimental results. It should be noted that in many guillotines, S may vary with α, owing to the form of spring-loading.

In low stiffness materials, the elastic strain energy may be neglected; again for those materials which suffer little plastic or other irreversible flow remote from the cut edge in guillotining, plastic work terms may also be neglected. Under these

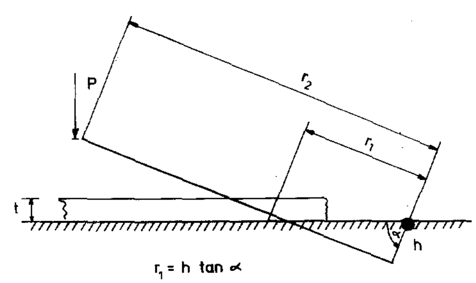

Figure 2 Geometry of blade and workpiece.

conditions the energy rate balance for guillotining becomes

$$Pr_2 \sin\alpha \, d\alpha = (Rtr_1/\cos\alpha)\, d\alpha + \mu S r_1 \, d\alpha \quad (4)$$

from which the cutting force is given by

$$P = Rt(r_1/r_2)\left(\frac{2}{\sin 2\alpha}\right) + \mu S(r_1/r_2)(1/\sin\alpha) \quad (5)$$

We note that $r_1 = h \tan\alpha$, so Equation 5 may be rewritten

$$P = \frac{Rth}{r_2} \times \frac{1}{\cos^2\alpha} + \frac{\mu Sh}{r_2} \times \frac{1}{\cos\alpha} \quad (6)$$

The experiments to be described were conducted on an Instron testing machine in compression, so that in place of α, the cross-head movement u will be given by

$$du = r_2 \sin\alpha \, d\alpha$$

or

$$u = r_2 (\cos\alpha_0 - \cos\alpha) \quad (7)$$

where α_0 is the angle of the blade at the start of the test. This, in turn, could be related to the length of cut if desired. Note that in an experiment on such a testing machine, the line of action of P remains fixed and does not move sideways as the blade descends as depicted in Fig. 2. However, when experiments are conducted with the blade almost closed, the associated changes in r_2 are insignificant and we may write

$$du = r_2 \, d\alpha$$

or

$$u = r_2(\alpha - \alpha_0) \quad (8)$$

Even with this simplification, it is not possible to recast Equation 6 into a simple P–u relation to predict the testing machine response. In schematic form the relation must be as shown in Fig. 3, where for simplicity the magnitudes of that part of the total force associated with friction and that part with cutting are assumed to have equal magnitudes. Also, we have assumed S to be constant, which was approximately true in the device used for the experiments. This comes about as follows: If the blade is spring-loaded against the baseplate by a leaf spring cantilevered out from the pivot, a plan view of the guillotine shows that when the blade is "open", it is set in a skewed fashion across the edge of the baseplate (Fig. 4). If such skewing may be represented by the angle β, the deflexion of the blade when a length of cut L has been made will be $L \tan\beta$. At that instant the sideways force

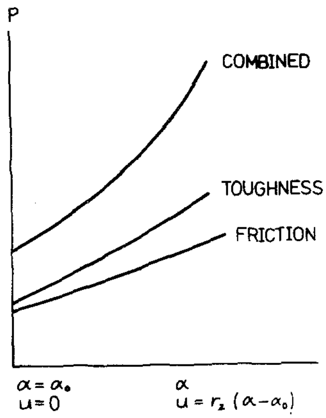

Figure 3 Load-deflexion relation for guillotining showing frictional and cutting components as predicted by Relation 6.

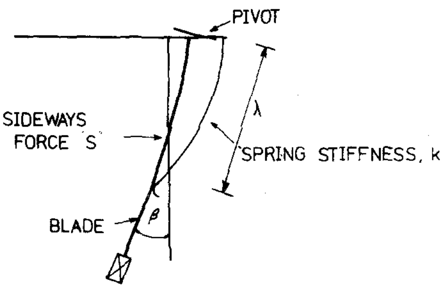

Figure 4 Plan view of guillotine showing sideways set of spring-loaded blade.

S gives a couple at the pivot of magnitude $SL \tan\beta$, which is counteracted by the couple provided by the spring loading device. If the spring has stiffness k, and if it is also deflected by $L \tan\beta$ when the cut is length L, the associated couple will be $(kL \tan\beta)\lambda$ where λ is the distance along the blade at which the spring bears against the blade. Thus

$$S = (k \tan\beta)\lambda \quad (9)$$

and according to this simplified picture, is constant.

In experiments which aim to determine values of the toughness R, it is possible to by-pass the details of the analysis if the work of friction can be partitioned off from the total work to give merely the work of fracture. Then R follows from the fracture work area and the associated length (area) of cut. This is demonstrated in Section 3, but there are instances where the details of the analysis are important such as when burrs are formed on the cut edge of thin metal sheets. A plastic work term has to be included in the analysis as discussed later. Again, in the cutting of thick metal sheets, there may be a period of indentation before cutting occurs, as in the shearing of metal bars [1]. This more complicated process of guillotining is not considered here.

3. Experiments and results

Experiments were performed on a Gestetner office guillotine, the total length of cut being some 500 mm, although only part of this was used. The materials investigated included various papers and card, sheet rubber and metal shimstock. Some experiments were performed on a number of the same sheets stacked together, as well as on single sheets.

The procedure was to cut the material over a known length, simultaneously producing a P–u trace on the testing machine. This gave the total guillotine force and total work. The cross-head was then run back to its position coinciding with the start of the cut, and the blade was swung upwards to contact the compression head again. The chart paper was also run back, so that a second P–u trace could then be picked up when the blade was driven down against the cut edge of the material and the baseplate of the guillotine. This second P–u trace represents the forces and work performed against fricton. Sometimes a third trace was obtained with the cut material being removed. For all practical purposes there was little difference between the second and third traces (particularly for the papers and cards), indicating that the principal frictional component comes from the blade scraping the baseplate, with only a minor contribution from rubbing the cut edge. For this reason, the frictional P–u traces were essentially the same for all materials, with the exception of waxed paper which gave about 75% of the friction forces shown by most other materials (including the metal sheets).

Sometimes interrupted cuts were made, or sometimes one long cut was made; an extra check on friction was sometimes taken after having performed interrupted cuts and having taken individual frictional traces, by taking a frictional trace along the whole cut edge. The cross-head velocity in all tests was 0.33 mm sec^{-1}, which gave a cutting velocity of about 3 mm sec^{-1} (the blade working between about $80° < \alpha < 86°$).

Fig. 5 shows P–u traces obtained in this way for a single layer of manila folder; the result was typical of all the more flexible materials. The general trends follow the predictions of Fig. 3. The local fluctuations in the guillotining force were caused by blade/baseplate interactions, it being observed that their periodicity coincided with the second or third frictional P–u traces. It was established that they did not arise from stick–slip at the contact between compression head and blade. As will be observed, there was a period of "bedding in" in the frictional traces obtained during interrupted cuts where the load took some displacement to attain the load it would have had in the absence of unloading. This seemed to be associated with springback in the blade and wear in the blade pivot. These portions of the P–u trace were ignored in the assessment of toughness.

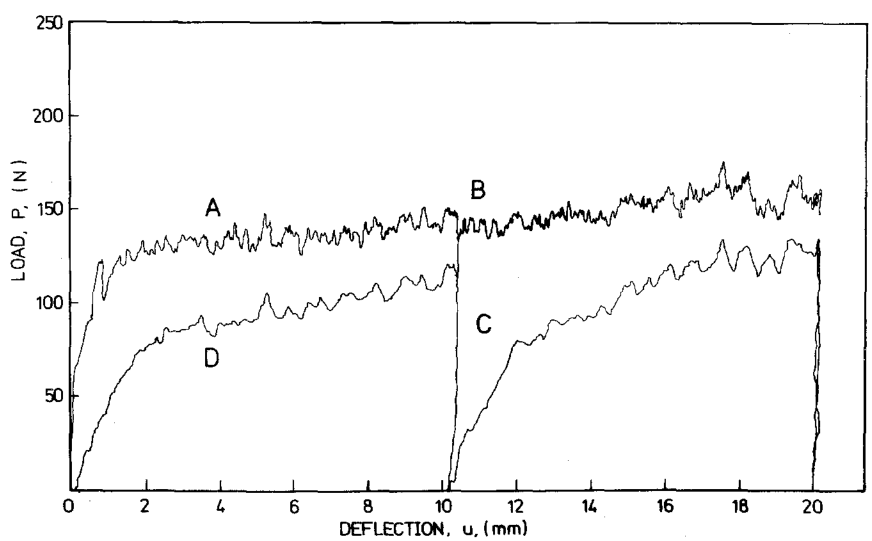

Figure 5 Load-deflexion traces for guillotining a single layer of manila folder, 0.26 mm thick.

TABLE I Fracture toughness values determined from guillotine experiments

Material	t(mm)	R(kJ m^{-2})	Remarks
Interleaving paper	0.06	16.93	1 layer
	0.24	10.32	4 layers
Copier paper	0.36	12.70	4 layers
Cardboard paper	0.48	13.60	
Drawing paper	0.27	18.50	0° angle of cut with fibre direction
		26.00	45° angle of cut with fibre direction
		29.00	90° angle of cut with fibre direction
Manila folder	0.26	15.16	1 layer
	0.52	13.63	2 layers
Waxed paper	0.18	15.10	2 layers
Rubber reinforced with cotton fabric	1.05	4.35	
Aluminium foil	0.105	10.68	8 layers
Shim brass	0.05	53.18	1 layer, ⊥ rolled direction
	0.10	33.38	2 layers, ⊥ rolled direction
	0.05	63.93	1 layer, ∥ rolled direction
	0.10	42.86	2 layers, ∥ rolled direction
	0.12	41.45	⊥ rolled direction
	0.11	41.39	∥ rolled direction
Copper foil	0.11	18.47	⊥ rolled direction
	0.11	25.95	∥ rolled direction
	0.22	21.41	2 layers, ⊥ rolled direction
	0.22	22.59	2 layers, ∥ rolled direction
Shim steel	0.16	42.06	⊥ rolled direction
	0.16	47.15	∥ rolled direction

The fracture toughness R may be determined from the differences in the work areas (ABCD) and the cut area given by Lt. The first part of Table I summarizes the results for various papers and a type of rubber sheet reinforced with cotton fabric.

In the case of the metal shimstock P–u traces were obtained which, although following the general trends of Figs. 3 and 5, showed some odd periodicities with the total loads falling (or at least not increasing at the same rate) as the cut progressed. Fig. 6 shows such a representative plot for 0.16 mm thick shim steel where it will be seen that the second or third (frictional) P–u trace carried on increasing in the anticipated manner even though the total P–u trace during cutting fell somewhat. At first sight this suggests for example a reduction in toughness with length of cut, as the incremental fracture work areas between the total P–u diagram and the frictional P–u diagram fall as u increases. However, the fluctuations in the P–u traces were found to coincide with burring at the cut edge – regions of greatest load occurring for the most severe burring – so that the plastic work required to form the burr appears as an increase in load.

We may model the formation of a burr as in Fig. 7, where the plastic bending-over or shearing is represented by the shear angle γ. $\gamma = u_0/w$ where u_0 is the movement of the blade below the top of the workpiece before cutting occurs and w is the "width" of the burr. The incremental plastic work done $d\Gamma$ in forming the burr as the cut progresses is given by

$$d\Gamma = (\bar{\tau}_y \gamma)\, d(\text{volume}) \qquad (10)$$

where $\bar{\tau}_y$ is some average shear yield stress and $d(\text{volume}) = w\ d(\text{cut area}) = w\,(t/\cos\alpha)\ r_1\, d\alpha = wth(\sin\alpha/\cos^2\alpha)\, d\alpha$.

Hence

$$d\Gamma = \bar{\tau}_y \gamma wth\,(\sin\alpha/\cos^2\alpha)\, d\alpha$$
$$= \bar{\tau}_y u_0 th\,(\sin\alpha/\cos^2\alpha)\, d\alpha. \qquad (11)$$

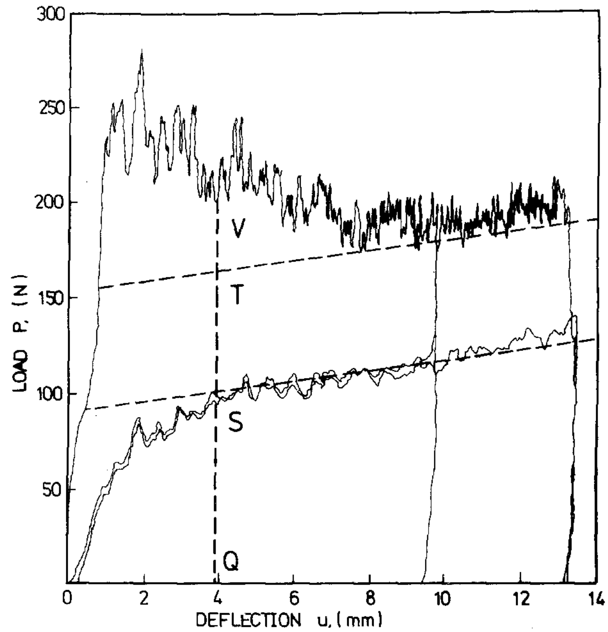

Figure 6 Load-deflexion trace for guillotining shim steel, 0.16 mm thick, perpendicular to rolled direction.

The total work relation, Equation 4, should now have $d\Gamma$ on the r.h.s., and we find

$$P = (R + \bar{\tau}_y u_0)th/(r_2 \cos^2 \alpha) + \mu Sh/(r_2 \cos \alpha) \quad (12)$$

The resistance to crack propagation has been effectively increased to $(R + \tau_y u_0)$ owing to burring. Note that the geometry of this particular combined flow and fracture problem leads to a coupling of the $R\mathrm{d}A$ and $\mathrm{d}\Gamma$ terms, as $\mathrm{d}\Gamma$ must be expressible in terms of $\mathrm{d}A$, i.e. it is not possible to produce a burr independently of cutting the edge.

The values for R given in the second half of Table I for the metal shimstock have been determined by taking the work area (shown dotted in Fig. 6) bounded by the lowest of the (rising) total P–u plots; these loads correspond to no (or smallest) burring at the cut edge. The reason why burrs occur at some regions and not others seems to be connected with the sharpness and smoothness of the cutting blade.

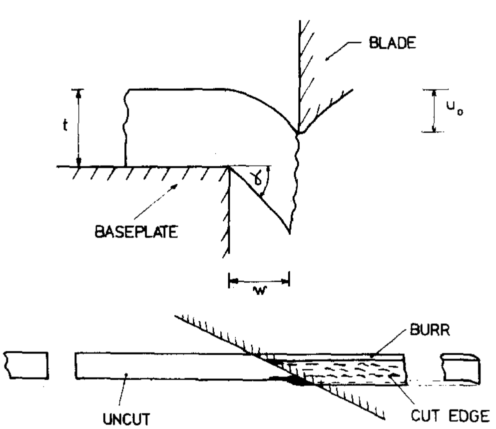

Figure 7 Geometry of burr formation in guillotining.

The $\bar{\tau}_y u_0$ term is represented by the likes of TV in Fig. 6, with R being proportional to ST. We may write

$$R/\tau_y u_0 = ST/TV. \quad (13)$$

The size of the burr (given by u_0) was measured at various locations. The greatest burr occurred at the start of the cut in the steel shimstock samples and was about 100 μm. ST/TV was smallest early in the cut and was of magnitude $\frac{4}{3}$ approximately. Using $R = 42\ \mathrm{kJ\,m^{-2}}$ we find that $\bar{\tau}_y \approx 310$ MPa from Relation 13. Later in the cut, where $ST/TV \approx 5$, $u_0 \approx 30\ \mu$m and $\bar{\tau}_y \approx 280$ MPa. The tensile yield strength of the steel sheet, determined independently was 550 MPa, so the model seems acceptable.

As regards the agreement between the analysis and the results for the frictional term, the general trend of the results follows the expression $\mu Sh/r_2 \cos \alpha$ given in Equations 6 or 12 with $S = (k \tan \beta)\lambda$, but rather large values of μ have to be used to make experiment and theory agree. For the particular guillotine employed, $k \approx 3.5\ \mathrm{kN\,m^{-1}}$, $\tan \beta = 1/15$, $\lambda = 300$ mm, $h = 15$ mm and $r_2 = 220$ mm (in order to fit the guillotine within the frame of the Instron testing machine, the guillotine blade could not be loaded at the handle, but at about half-way along the blade). The blade was cutting in the experiments when $\alpha \approx 80^\circ \sim 86^\circ$ so that

$$\frac{\mu S h}{r_2 \cos\alpha} \approx (27 \text{ to } 70)\mu$$

The frictional forces in the experiments were about 70 to 100 N, which gives $\mu = \sim 1$ to 4. Such values are, of course, an order of magnitude greater than the conventional coefficients for Coulomb friction. The geometry of contact between blade and baseplate (akin to a razor blade scraping across another razor blade) is, however, very unlike the usual geometries used to measure μ. Furthermore, it was observed that when the guillotine was operated for a few strokes without any workpiece material, noticeable metallic debris was generated at the regions of contact between blade and baseplate; wear fragments could be picked up by rubbing a finger along the (previously cleaned) edges. If the guillotine blade is indeed indenting the baseplate and cutting bits away, then Coulomb friction should not be expected to apply. An estimate for the relation between the frictional force (which is a microcutting force F) and the normal force S may be obtained from metal cutting theory, insofar as the geometries of conventional cutting apply to the guillotine/baseplate combination. We have as an order of magnitude for cutting the cast iron baseplate

$$F = (210 \text{ to } 420)A \qquad (14)$$

where A is the projected area of the cut (taken from Boston [2], in simplified form for cast irons of different hardnesses, and converted to SI units: F is in newtons for A in mm^2). From the mutual indentation of blade and baseplate [3], we have

$$A = S/9.81\,H \qquad (15)$$

where H is the hardness (kg mm^{-2}) and S is in newtons. Thus

$$F = \frac{(210 \text{ to } 420)S}{9.81\,H} \qquad (16)$$

The H values corresponding with the 210 to 420 coefficients are 130 to 240 BHN [2], so

$$F \approx 0.17S. \qquad (17)$$

The line of action of F is parallel to the edge of the baseplate, so that in place of $\mu S r_1\,d\alpha$ for the increment of friction work in Relation 3, we should have $F r_1\,d\alpha/\cos\alpha$ as $r_1\,d\alpha/\cos\alpha$ is the incremental displacement in the line of action of F. Consequently,

$$\mu S r_1\,d\alpha \equiv F r_1\,d\alpha/\cos\alpha$$

or

$$\mu \equiv F/S\cos\alpha, \qquad (18)$$

i.e.

$$\mu \equiv \frac{0.17}{\cos\alpha}$$

from Relation 17. In the experiments $80^\circ \lesssim \alpha \lesssim 86^\circ$, so $1 \lesssim \mu \lesssim 2.4$. The agreement with the values of μ required to make theory and experiment agree seems satisfactory.

4. Discussion and conclusions

The mode of fracture in guillotining is not altogether clear. In the ideal case it is presumably the antiplane mode III, but there may well be a mode I component as well. Blunt cutting blades will tend to bend over the workpiece between blade and baseplate which may lead to some tearing in mode I, and V-profile blades (even if sharp) push the offcut sideways which leads to an opening mode at the crack front, the magnitude of which will depend on the stiffness of the offcut. For these reasons we are reluctant to say that the cutting is definitely in mode III.

Independent measurements of the fracture toughness of the materials guillotined are available from the work of Ngan [4], Mai [5] and Seth and Page [6]. For example, Ngan gives $R = 10^6 t\ \text{kJ m}^{-2}$ for the antiplane tearing (trousers test) of shim brass of thickness t(m), at a rate of $170\,\mu\text{m sec}^{-1}$. The values agree well with those for the thinner brass shimstock in Table I. Ngan also gives $R = 4.6\ \text{kJ m}^{-2}$ for 3.8 mm thick cotton-fabric-reinforced rubber sheet pulled at $80\,\mu\text{m sec}^{-1}$.

In the case of paper it is well known that trousers tests produce ragged tearing, which is certainly not a simple mode III separation. Mode I values for toughness are however available in references [4] to [6]. The values of mode I fracture toughness for various types of paper (about 10 to $25\ \text{kJ m}^{-2}$ in all references) turn out to be comparable in magnitude with the values found in the present guillotining experiments. However there is a marked difference in the separated edges of paper pulled in mode I and cut on a guillotine – after all that is why scissors and guillotines are used – and even when a piece of paper is creased and subsequently pulled or torn the fractured edge is not clean. The ragged edges normally produced involve displacement irreversibilities and hysteresis loops [4, 5]. Consequently it is thought that, even though the toughnesses are comparable, in guillotining the work of fracture is more connected with cutting the cellulosic fibres than breaking the interfibre bonds and pulling out the fibres.

In the case of shim brass there is a significant difference between the guillotining and trousers test values of toughness and that in mode I, which was reported by Mai [7] to be about $20\,kJ\,m^{-2}$, i.e. about one half the guillotine value.

An advantage of guillotining over a simple antiplane tear test for metal sheets is that the local plastic buckling, which occurs in the path of the crack as tearing proceeds (readily observed in opening metal tins), is eliminated as the metal is forced to deform against the baseplate.

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