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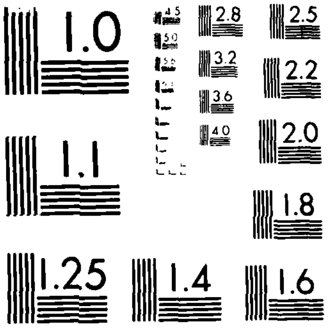

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Technical Report No. 2

CONTRIBUTION OF BENDING ENERGY LOSSES TO THE APPARENT TEAR ENERGY

by

A. N. Gent and Jongkoo Jeong

Institute of Polymer Science
The University of Akron
Akron, Ohio 44325

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When a strip is torn, energy is expended both in tearing it and in propagating a bend along each torn section. Estimates are given of the contribution of bending energy losses to the apparent tear energy. Experiments with highly-dissipative semi-crystalline polymers, torn with controlled amounts of bending, are then described. The bending energy losses ranged from 5 to 70 percent of the total tear energy, depending upon the degree of bending imposed, the thickness of the strip, and the extent to which it had been partly cut through before tearing. These results were in satisfactory agreement with approximate theoretical estimates. When the torn strips were allowed to take up naturally bent configurations under the action of the tearing force, then the contribution of bending energy losses to the apparent tear energy became rather independent of the strip dimensions and depended principally upon the dissipative nature of the material, represented by the fraction H of deformation energy that is not recovered. A general relationshi is proposed between the apparent (G'_c) and true (G_c) tear energies in this case: $G'_c = G_c/(1 - H)$. Values of H for the materials examined ranged from 30 to 70 percent. Thus, bending energy losses are expected to increase the tear energy by a factor of 1.4x to 3.3x for unconstrained tearing of these semi-crystalline polymers. Somewhat smaller increases were actually observed, ranging from 1.1x to 2x.

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Keywords: fracture energy; plastics; rubber,

1. Introduction

When a strip is torn apart it undergoes a bending deformation in the neighborhood of the tear tip and straightens again as the tear passes on, Figure 1. Some energy is lost in inelastic processes during bending and recovery; it is supplied by the applied tear force F and is generally included in the apparent fracture energy G_c', defined as the total energy required to tear through unit area of material. When the torn parts of the strip are not stretched significantly by the tear force F, so that the energy expended in stretching them can be neglected in comparison, then G_c' is given by (1)

$$G_c' = 2F/t \tag{1}$$

where t is the width of the tear path, Figure 1.

Now it is not known what contribution is made to G_c' from energy dissipated in bending and recovery, denoted G_b here, and what contribution is made from the energy required solely for tear propagation, denoted G_c. Although it has commonly been assumed that G_b is small, this may not be true for markedly inelastic materials. An attempt has therefore been made to evaluate G_b quantitatively and to establish the conditions under which it is negligible.

Similar measurements have been reported recently by Kinloch and Tod (2), for sheets of a rubbery-composite propellant formulation containing 87 percent w/w of solid particles dispersed in a polybutadiene binder. They concluded that as much as 50 - 70 percent of the measured fracture energy could be assigned to energy losses in bending together with an additional term due to the changing weight of the torn leg. (The latter term is insignificant in the experiments described here because the tear forces are considerably larger.)

Experiments have now been carried out with strips of semi-crystalline polymers, mainly polyethylene, which are both strong and markedly inelastic. They have been torn with controlled amounts of bending, enabling the contribution $\underline{G_b}$ to the apparent fracture energy to be determined for test strips of various thickness, and compared with theoretical estimates. Finally, some measurements on unconstrained strips, where the degree of bending is determined by the tear strength itself, are reported and analyzed.

2. Experimental

(a) Materials

A crosslinkable low-density polyethylene (LDPE) was obtained from Nisseki Chemical Co., Japan. It was denoted Rexlon W2040, and had a melt index of 1 g/10 min and a density of 0.92 Mg/m^3. It contained a few percent of dicumyl peroxide. Crosslinked sheets were prepared by molding for 1 h at 160°C; they were then cooled rapidly to room temperature. The degree of crystallinity and melting temperature were determined by differential scanning microscopy to be 29 percent and 103°C, respectively.

High-density polyethylene (HDPE) was obtained from Asahi-Kasei Industries, Japan. It was denoted R340P and had a melt index of 7g/10 min and a density of 0.955 Mg/m^3. Sheets were prepared by molding for 1 h at 160°C; they were then cooled rapidly to room temperature. The degree of crystallinity was found to be 64 percent and the melting temperature was 128°C.

Trans-polyisoprene (TPI) was obtained from Polysar Ltd., Canada, denoted TP-301. It was mixed with 1 percent of dicumyl peroxide and 1 percent of Antioxidant 2246 (American Cyanamid Company), pressed into sheets and crosslinked lightly by heating for 1 h at 150°C. The crosslinked sheets were then allowed to crystallize at 40°C for 20 h. The degree of crystallinity and melting temperature were found to be 37 percent and 59°C, respectively, by differential scanning calorimetry.

(b) Measurement of bending energy losses

Test strips, 10 mm wide and 200 mm long, were cut from the prepared sheets and subjected to bending with the experimental arrangement shown in Figure 2. Two strips were placed vertically in the gap between two closely-spaced rollers and the upper parts bent around each roller into a horizontal plane. Inextensible strings fastened to the horizontal sections passed over pulleys and were secured to fixed points. Thus, on raising the roller and pulley assembly, the vertical parts of the strips were forced to pass through the gap between the rollers and bend through 90°. In this way a bend of specified severity, governed by the radius R of the rollers, was propagated along each strip. A weight M was attached to the lower end of the strips to force them to conform to the radius of the rollers during bending.

The work expended in propagating the bend can be obtained from the applied vertical force $2F$. We note that

$$2F = 2F_s + M, \tag{2}$$

where F_s denotes the tension in each string, and

$$F_s = F_b + M/2, \qquad (3)$$

where F_b denotes the force required to propagate the bend. From equations 2 and 3, the bending force F_b is given by

$$F_b = F - M. \qquad (4)$$

In separate experiments, the frictional force required to rotate the rollers was determined, and subtracted from the total force. It was found to be only about 2 percent of the total force.

Measurements were made of the total force F, and hence, by means of equation 4, of the bend propagation force F_b, for strips of various thickness using rollers of different diameter. All measurements were made at 24 ± 2°C and at a velocity of about 1 mm/s.

(c) Tear tests

Strips were cut from the prepared sheets, 20 mm wide and 200 mm long. A cut was made along the center of one side to a depth between 10 and 90 percent of the sheet thickness t_o, leaving the remainder of the sheet thickness t to be torn through. Values of t were determined by direct observation of the torn surfaces subsequently.

Tearing was carried out using the same roller and pulley arrangement as before, with an added weight M sufficient to bring the major part of the bent regions into contact with the rollers, Figure 2. In this case the total force $2F$ represented the sum of the forces $2F_c$ for tear propagation and $2F_b$ for bend propagation, plus the added weight M. As the bending forces could be determined separately on the torn strips,

using the procedure described in the preceding section, the force $\underline{F_c}$ required solely to propagate the tear was obtained by subtraction and hence the true tear energy $G_c = 2F_c/t$.
(The apparent tear energy $\underline{G_c'}$ is given by $2(F_c+F_b)/t = (2F-M)/t$.)

3. Bending Energy Losses

Measured values of the force $\underline{F_b}$ required to propagate a bend in strips of LDPE are plotted in Figure 3 against the added weight $\underline{M}$. When $\underline{M}$ was small, the strips did not conform well to the roller diameter but bent through 90° more gradually. The bending force $\underline{F_b}$ was correspondingly small. Above a certain value of $\underline{M}$, however, the strips conformed closely to the roller diameter and the force $\underline{F_b}$ then became largely independent of $\underline{M}$.

The energy dissipated per unit cross-sectional area and per unit length of strip is given by $\underline{W_b = F_b/wt_o}$, where $\underline{w}$ denotes the width of the strip and $\underline{t_o}$ its thickness. Values of $\underline{W_b}$ for strips that conformed closely to the roller diameter are given in Table 1 for various thicknesses and for various degrees of bending, represented by the roller radius $\underline{R}$. As might be expected, greater energy was required to propagate a bend of given radius in thicker strips. As $\underline{t_o}$ was increased from 0.3 mm to 2 mm, $\underline{W_b}$ increased from abcut 10 kJ/m^3 to about 80 kJ/m^3. Also, as the radius $\underline{R}$ of the roller was decreased from 9 mm to 2.5 mm, $\underline{W_b}$ increased from about 10 kJ/m^3 to about 90 kJ/m^3

for a strip of thickness $t_o = 0.5$ mm.

Approximate values of W_b can be calculated from the theory of elastic bending, using certain simplifying assumptions about the deformation and the dissipative processes. The center line of the bent strip is assumed to be the neutral axis, Figure 4, as would be the case in the absence of friction at the roller surface, and the material is assumed to follow a linear relation between stress and strain, both in tension and compression, with an elastic modulus E. Thus, the total energy stored in the bent portion of the strip is given by $wt_o E\, e_m^2/6$, where e_m is the maximum strain set up in the outer layers of the strip, given by

$$e_m = t_o/2R\ . \tag{5}$$

If it is assumed that a fraction H of the deformation energy is lost in dissipative processes, then the energy required to propagate the bend by unit distance is given by

$$W_b = HE\, t_o^2/24\, R^2\ . \tag{6}$$

The maximum possible value of W_b is obtained when $H = 1$ and the radius R of curvature of the neutral axis takes its minimum possible value, $t_o/2$. Under these circumstances,

$$W_{b,max} = E/6\ . \tag{7}$$

Thus, when the elastic modulus E is given the representative value 100 MPa, the corresponding maximum value of W_b is obtained as about 16 MJ/m^3, i.e., about 20X the largest value measured in the present experiments.

Measurements were made of the hysteresis fraction H in tension, using long strips of LDPE stretched at a strain rate of 0.01 s^{-1}. Values of H were calculated from the areas under the loading and unloading stress-strain relations. They were found to increase from about 0.3 at low strains up to about 0.5 at strains close to the yield strain. Values corresponding to the maximum strains set up in the bending experiments are given in Table 1. Values of the amount $\underline{W_b}$ of energy dissipated in bending per unit cross-sectional area and per unit length of strip were then calculated by means of Equation 6. They are given in the final column of Table 1 and are compared with experimentally-determined values both there and in Figure 5. Reasonable [redacted] agreement is seen to hold between the measured and calculated values of $\underline{W_b}$ except at small degrees of bending. Other contributions to the observed energy dissipation probably become significant then; for example, frictional sliding of the surfaces of the strip in contact with the rollers.

4. Contribution of Bending Energy Losses to the Tear Energy

(a) Forced bending

Tearing experiments were carried out with the same roller arrangement. When the added weight M was small, the torn parts of the strip did not conform closely to the roller diameter, Figure 6a. When a larger weight was used, then the strips were brought into close contact with the rollers except in a small region near the tear tip, Figure 6b. The added weight was made sufficiently large to achieve this condition in all of the tearing experiments carried out with forced bending.

The amount of energy dissipated in bending as unit length of the strip was torn through is given by $2F_b = 2wt_oW_b$, where $2w$ is the width of the test strip and t_o is its thickness. The amount of energy required solely to propagate the tear is given by $2F_c = tG_c$, where t is the thickness of the strip actually torn through, generally smaller than t_o because the strip was partly cut through initially along the center line. The total energy expended is then given by $2F_b + 2F_c$. Thus, the apparent tear energy G_c' is given by

$$G_c' = G_c + G_b \tag{8}$$

where

$$G_b = 2wt_oW_b/t \tag{9}$$

Measurements were made of the apparent tear energy for test strips of LDPE cut initially to various depths so that the ratio t_o/t was varied. In each case, the force $2F_b$ was also determined by measurements on the torn strips. Values of the apparent tear energy G_c' and true tear energy G_c, obtained by subtracting the force contribution $2F_b$ due to bending energy losses from the total tear force, are given in Table 2 and plotted against the thickness ratio t_0/t in Figure 7. For each value of torn thickness t, the true tear energy was found to be independent of the total thickness t_0 of the strip. However, the apparent tear energy increased strongly with the total thickness t_0, reflecting an increasing contribution from bending energy losses, equations 6 and 9. When the total thickness t_0 was 10x the actual thickness torn through, then the apparent tear energy was about three times the true value.

On the other hand, as the thickness of the sheet was decreased relative to the torn thickness and the ratio t_0/t approached unity, then the apparent tear energy approached the true value. ~~Thus, for these sheets, torn whilst being bent around rollers of 9 mm radius, the contribution of bending energy losses to the apparent tear energy was small when the total thickness t_0 was only 1 - 2 times the torn thickness.~~

It should be noted in Table 2 and Figure 7 that the true tear energy is itself dependent upon the torn thickness t, as discussed elsewhere (3,4). This dependence cannot be attributed to bending energy losses because they have now been taken into account. It is attributed instead to plastic deformation in a small region around the tear tip whose size is governed by t (3,4).

(b) Unconstrained bending: theoretical considerations

When the torn parts of the strip are allowed to take up their naturally bent configurations under the action of the tear force F, then the corresponding value of the minimum radius R of curvature will depend upon the modulus of elasticity E, and the width w and thickness t_0 of the torn sections. An approximate value of R can be deduced from elementary bending theory (5):

$$R^2 = Ewt_0^3/24F. \qquad (10)$$

From equations 6 and 9, the resulting contribution $\underline{G_b}$ to the observed tear energy from bending energy losses is obtained as

$$G_b = 2HF/t = HG_c'. \qquad (11)$$

Note that all terms in the strip dimensions and modulus cancel. Thus, the apparent tear energy is given in terms of the true tear energy by the simple relationship:

$$G_c' = G_c/(1 - H). \qquad (12)$$

It seems probable, in view of its simple form, that this result is independent of the particular mode of deformation undergone by the torn sections and would apply to other deformations also, provided that they are brought about by the force causing fracture. A similar relation was proposed by Burns (6) and Burns and Webb (7) to correct the observed fracture energy for energy dissipation arising from the motion of dislocations during cleavage of inorganic crystals.

(c) Unconstrained tearing: effect of thickness $\underline{t}$

Measurements were made of the apparent tear energy for strips of LDPE of different thickness $\underline{t_o}$, having an initial groove cut in them in each case to a depth of about one-half of the thickness so that $\underline{t = t_o/2}$. The values obtained for $\underline{G_c'}$ are plotted in Figure 8 against the thickness $\underline{t}$ torn through and are seen to increase as $\underline{t}$ increases, almost in direct proportion. When a correction was made in each case for the contribution $\underline{G_b}$ due to bending energy losses, the true tear energy was still found to increase in proportion to $\underline{t}$,

Figure 8, but with a somewhat lower slope, about 78 percent of the original value. Thus, for these strips of LDPE, about 20 percent of the effect of increasing the thickness of the test strip is due to increased energy losses in bending. Now equation 12 does not predict any direct effect of the strip thickness upon the apparent tear energy but an indirect effect might well be expected. Higher bending strains will be developed under the much higher forces that are required to tear thicker strips, Figure 8, and the energy dissipation ratio $\underline{H}$ was found to increase significantly with increasing maximum strain, Table 1.

However, the main effect of increased thickness is attributed to an increase in size of the region around the tear tip undergoing plastic deformation, as discussed before, and this feature is independent of the degree of bending.

(d) Unconstrained tearing: effect of energy dissipation ratio $\underline{H}$

Measurements were made of the apparent tear energy $\underline{G_c'}$ of a number of semi-crystalline materials, differing in their energy-dissipating characteristics. One sample of HDPE was annealed for 2 h at 120°C, a procedure which renders this material rather brittle, with low tear energy (3). Another sample of HDPE was compounded with 35 wt percent of powdered talc, making it both weaker and more dissipative. In all cases the true tear energy $\underline{G_c}$ was also determined using large-diameter rollers to minimize the degree of bending. The results are given in Table 3.

Effective values of the dissipation ratio $\underline{H}$ were calculated from the ratios of the two tear energies $\underline{G_c'/G_c}$ by means of equation 12. They are compared in Table 3 with values of $\underline{H}$ determined experimentally for the same materials using long strips in simple extension. A maximum strain of about 10 percent was imposed.

Good correlation is seen to hold between inferred and measured values of the dissipation ratio $\underline{H}$ for materials whose true tear energies ranged from 10 to 50 kJ/m^2. This correlation is particularly notable because there is no parallel correlation with the tear energy itself. Thus, there are instances of weak, highly-dissipative materials and of stronger, less dissipative-ones, but in all cases the effect of bending energy losses upon the observed tear energy correlates well with the measured dissipation ratio.

However, the numerical agreement is poor, the inferred values of H being only about one-half to one-third of the directly-measured values. Some part of this discrepancy may be due to the use of unrealistically high strain levels in the measurement of H. The mean strains in bent strips are probably much smaller than 10 percent and the values of H will be correspondingly less. The calculated values are also quite sensitive to the values chosen for G_c' and G_c, especially when these are similar in magnitude, so that small errors in determining the fracture energies can lead to relatively large errors in H. Careful experiments with materials having dissipation properties less sensitive to the applied strain level and covering a wider range of values seem desirable at this point.

5. Conclusions

The following conclusions are obtained:

(i) The force required to propagate a bend of controlled magnitude in strips of semi-crystalline polymers can be estimated with reasonable success from elementary bending theory, assuming that a fraction H of the deformation energy is dissipated in inelastic processes.

(ii) When strips are torn between two rollers, in such a way that the torn sections are forced to conform to the roller diameter, the measured tear force is increased by the force required to propagate the bend in each torn section. The apparent tear energy is thus larger for thicker strips, and for stiffer materials, and when they are made to bend more sharply. It is also larger when the sheet is partially cut through initially, so that the thickness torn through is smaller than the actual thickness, although in this case a direct effect of the torn thickness is also present. And, of course, the tear energy is increased in proportion to the dissipation ratio $\underline{H}$.

(iii) On the other hand, when strips are torn without constraint, so that the torn sections take up their naturally bent configurations under the action of the tear forces alone, then it is inferred that the strip dimensions and modulus have no direct effect upon the apparent tear energy $\underline{G_c'}$. It is suggested that $\underline{G_c'}$ is now related to the true tear energy $\underline{G_c}$ by the relation

$$G_c/G_c' = 1 - H, \tag{13}$$

similar to that proposed by Burns (6) and Burns and Webb (7) for the cleavage fracture energy of inorganic crystals.

(iv) Measurements on several semi-crystalline polymeric materials, having a range of values for $\underline{G_c}$ and $\underline{H}$, were found to be in good qualitative agreement with equation 13. However, the numerical agreement is relatively poor, measured values of $\underline{H}$ being much greater, 2x to 3x, than those inferred from equation 13. This is probably because of experimental difficulties in determining $\underline{G_c}$ and $\underline{H}$ with sufficient precision.

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Table 1: Work W_b per unit volume expended in propagating a bend in strips of LDPE of thickness t_o using rollers of radius R.

t_o(mm)	R(mm)	e_m(%) calculated from eq. 5	W_b(kJ/m^3) measured	H	W_b(kJ/m^3) calculated from eq. 6
0.28	9.1	1.5	17 ± 7	0.32	1.2
0.53	9.1	2.8	11 ± 2	0.37	4.8
0.53	5.6	4.5	17 ± 6	0.42	14.2
0.53	2.5	9.7	93 ± 10	0.51	80.0
1.13	9.1	5.8	39 ± 5	0.45	25.2
1.75	9.1	8.8	56 ± 4	0.49	63.2
2.05	9.1	10.1	72 ± 7	0.52	88.4
2.10	9.1	10.3	76 ± 14	0.52	91.9

Table 2: Apparent tear energy $\underline{G_c'}$ of LDPE, measured under forced bending conditions (R = 9.1 mm), and true tear energy $\underline{G_c}$ corrected for bending energy losses.

$\underline{t}$ (mm)	$\underline{t_o/t}$	$\underline{2(F_c + F_b)}$ (N)	$\underline{G_c'}$ (kJ/m^2)	$\underline{2F_c}$ (N)	$\underline{G_c}$ (kJ/m^2)
0.16	1.55	1.5±0.2	9.4±1.2	1.5±0.3	9.4±1.9
	3.15	1.8±0.3	11.3±1.9	1.6±0.4	10.0±2.5
	4.45	1.8±0.3	11.3±1.9	1.4±0.6	8.8±2.5
	6.8	2.7±0.4	16.9±2.5	1.8±0.6	11.3±3.8
	9.5	4.5±0.4	28.1±2.5	1.3±0.8	8.1±5.0
0.26	3.1	4.8±0.3	18.5±1.2	3.6±0.4	13.8±1.5
	7.0	7.6±0.3	29.2±1.2	3.6±0.5	13.8±1.9
	8.1	9.8±0.4	37.7±1.5	3.3±0.6	12.7±2.3
0.55	1.1	12.8±0.2	23.3±0.4	12.0±0.3	21.8±0.5
	1.5	13.0±0.5	23.6±0.9	11.8±0.5	21.5±0.9
	3.05	14.5±0.5	26.4±0.9	10.5±0.7	19.1±1.3
	3.75	18.9±0.5	34.4±0.9	12.4±0.7	22.5±1.3

Table 3: Apparent tear energies $\underline{G'_c}$ from unconstrained tearing experiments and true tear energies $\underline{G_c}$ corrected for bending energy losses. Strip thickness $\underline{t_o}$ = 1.1 mm, torn thickness $\underline{t}$ = 0.6 mm.

Material	$\underline{G'_c}$ (kJ/m^2)	$\underline{G_c}$ (kJ/m^2)	$\underline{H}$ (from eq. 12)	$\underline{H}$ (measured)
TPI	19.7±2.2	18.1±1.4	0.08	0.40
LDPE	25.4±2.3	21.8±1.2	0.14	0.45
HDPE	63.6±7.6	52.8±4.2	0.17	0.45
Annealed HDPE	12.3±2.1	9.4±2.5	0.24	0.65
Talc-filled HDPE	22.6±1.8	11.9±3.7	0.47	0.75

FIGURE LEGENDS

Figure 1. (a) Tear test

(b) Test piece cross-section

(c) Cross-section after tearing.

Figure 2. Experimental arrangement for tearing or bending strips with controlled curvature.

Figure 3. Force F_b per unit width required to propagate a bend in strips of LDPE of various thickness t_o, plotted against the added weight M.

t_o = 2.1 mm, R = 9.1 mm, O;

t_o = 1.1 mm, R = 9.1 mm, ●;

t_o = 0.5 mm, R = 9.1 mm, ◐;

t_o = 0.5 mm, R = 2.5 mm, ◑;

Figure 4. Sketch of a strip passing round a roller showing strains e set up by bending.

Figure 5. Comparison of measured and calculated values of the work W_b dissipated per unit volume in LDPE strips bent around rollers (Table 1).

Figure 6. Photographs of LDPE strips being torn around rollers. t_o = 1.1 mm

(a) Added load M = 5 N; (b) M = 30 N

Figure 7. Apparent tear energy $\underline{G_c'}$, represented by open symbols, and true tear energy $\underline{G_c}$, represented by filled-in symbols, for strips of LDPE of various thickness $\underline{t_o}$, cut partway through initially so that only a distance $\underline{t}$ remained to be torn through.

$\underline{t}$ = 0.55 mm, O,●;

$\underline{t}$ = 0.26 mm, □,■;

$\underline{t}$ = 0.16 mm, Δ,▲.

Figure 8. Apparent tear energy $\underline{G_c'}$(O) and true tear energy $\underline{G_c}$(□) for strips of LDPE plotted against the tear path width $\underline{t}$. The total thickness $\underline{t_o}$ was about $\underline{2t}$.

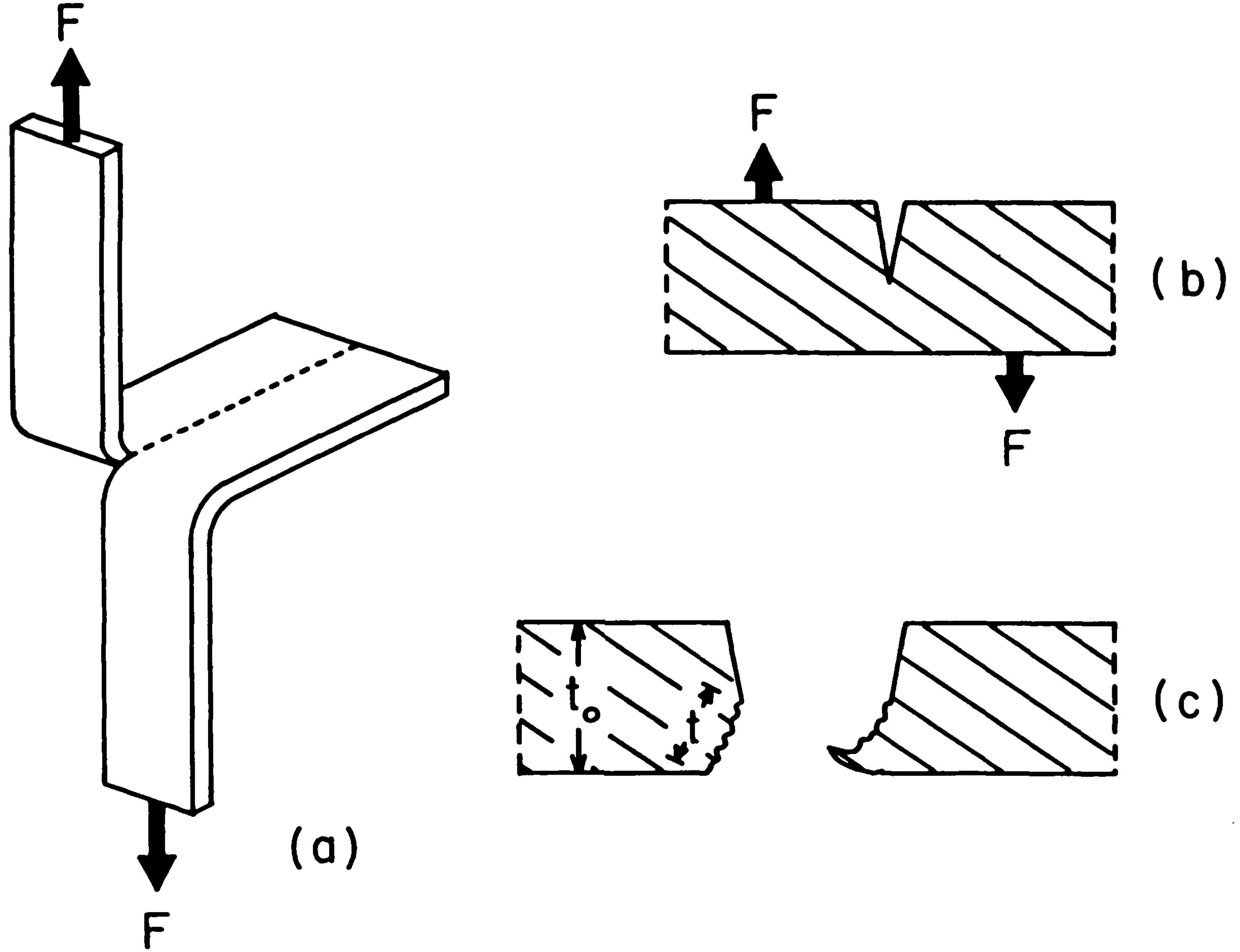

Figure 1

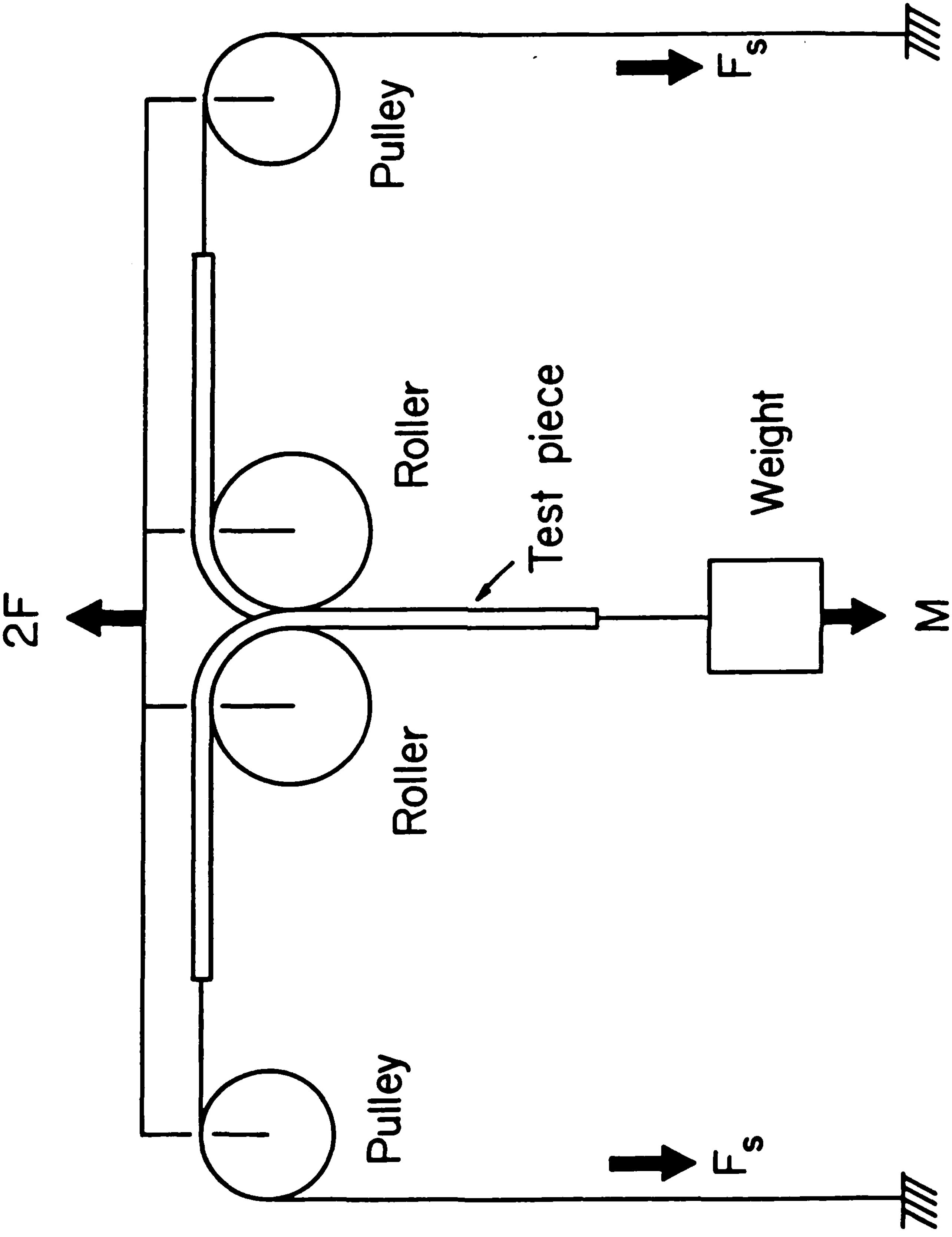

Figure 2

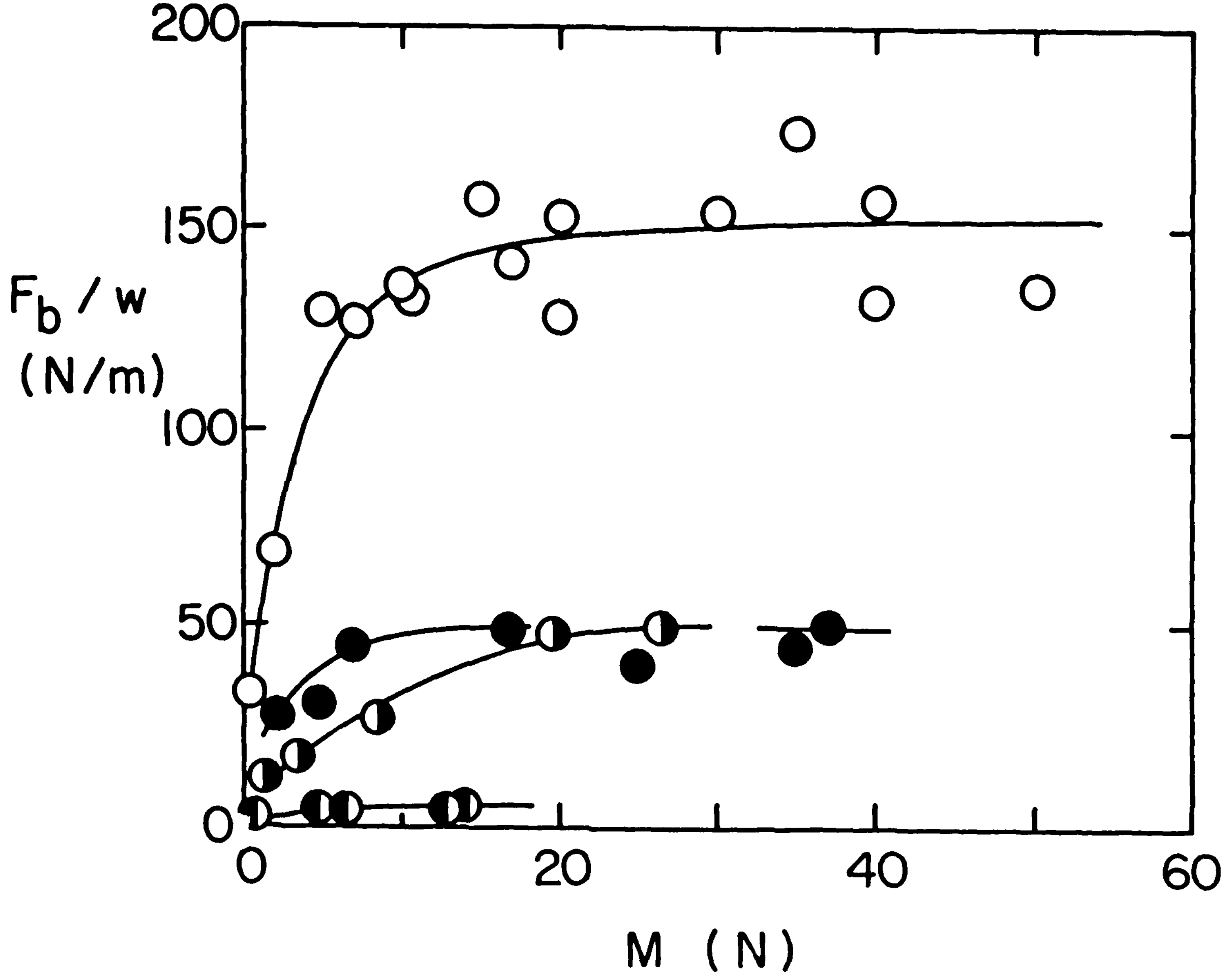

Figure 3

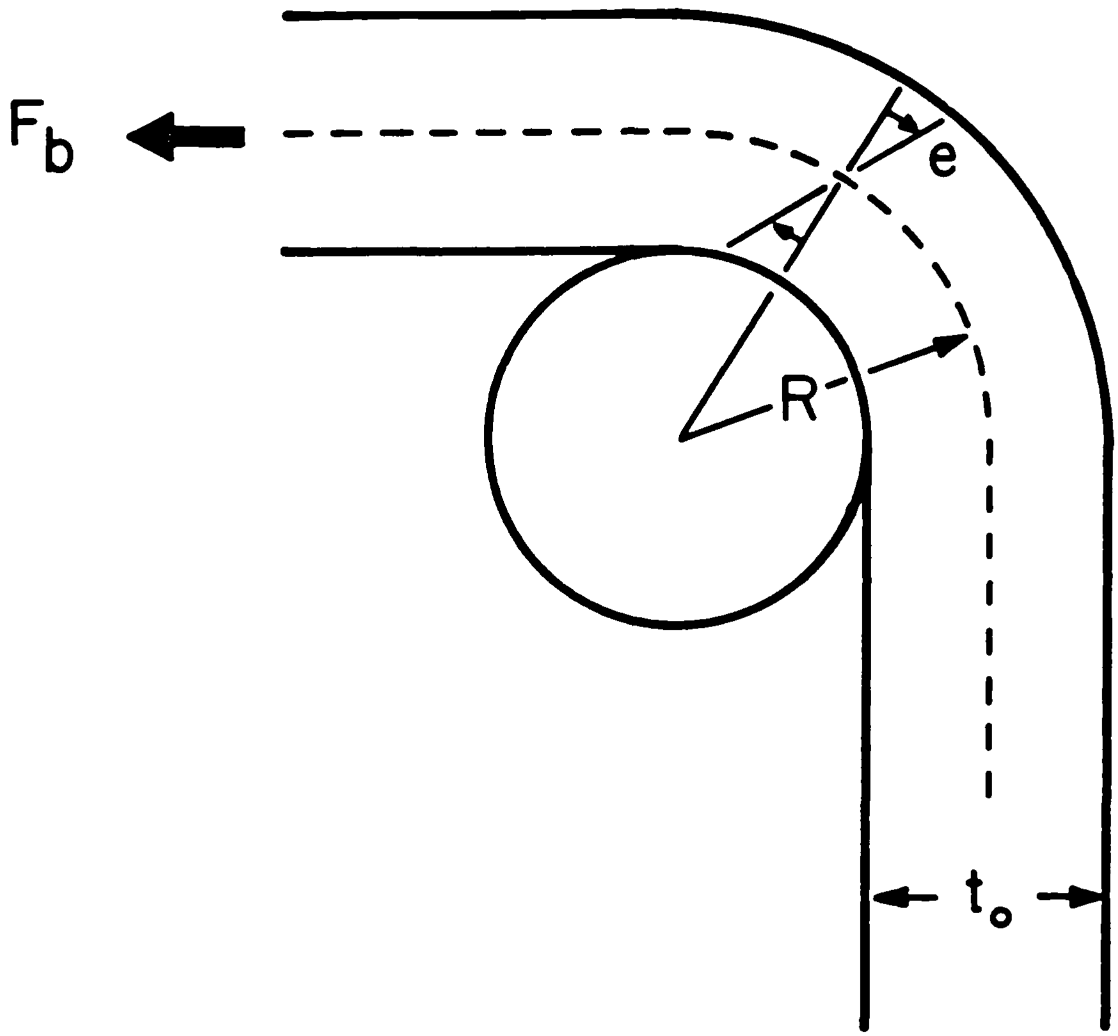

Figure 4

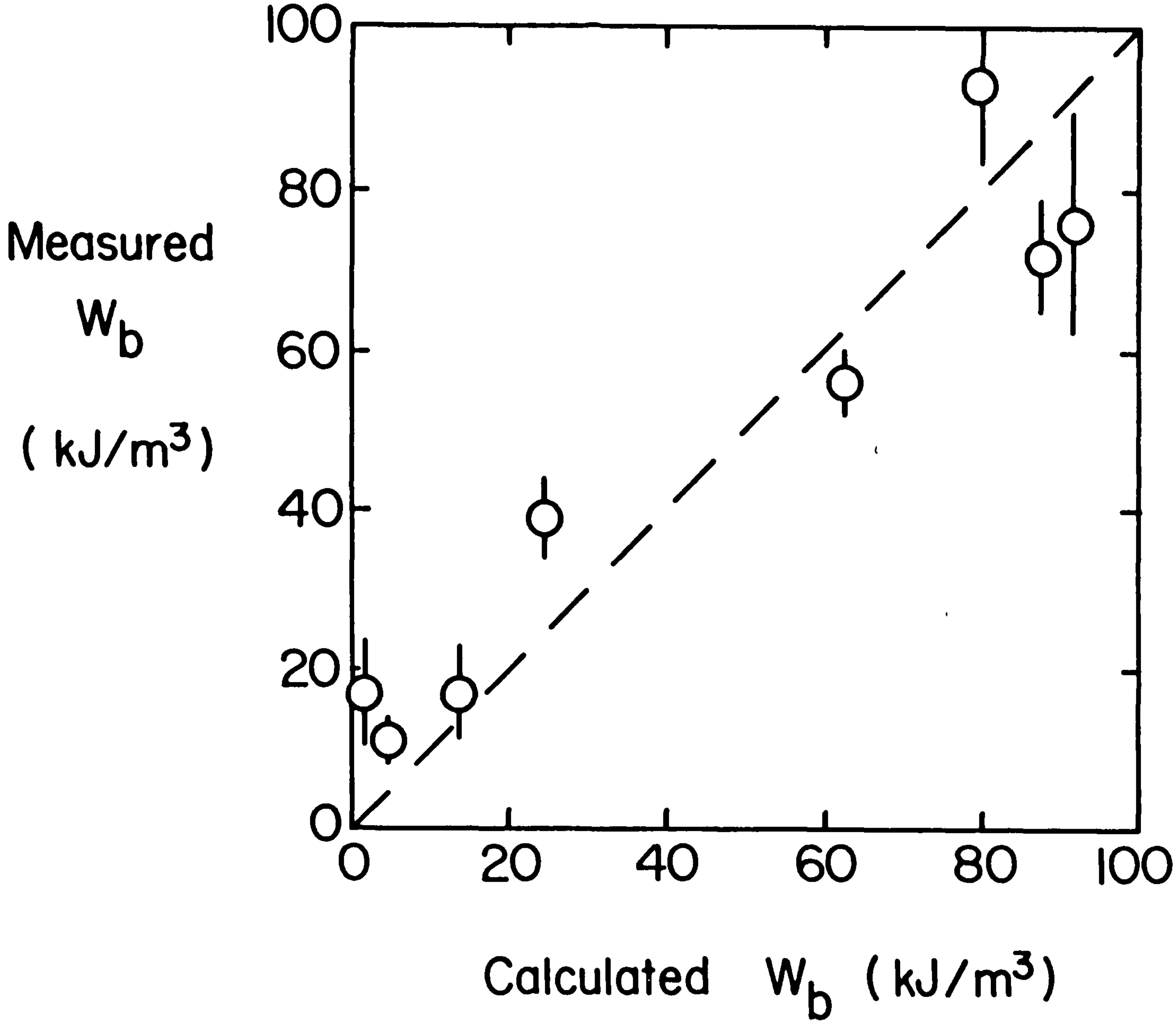
Measured
W_b
(kJ/m^3)
100
80
60
40
20
0
0
20
40
60
80
100
Calculated W_b (kJ/m^3)

Figure 5

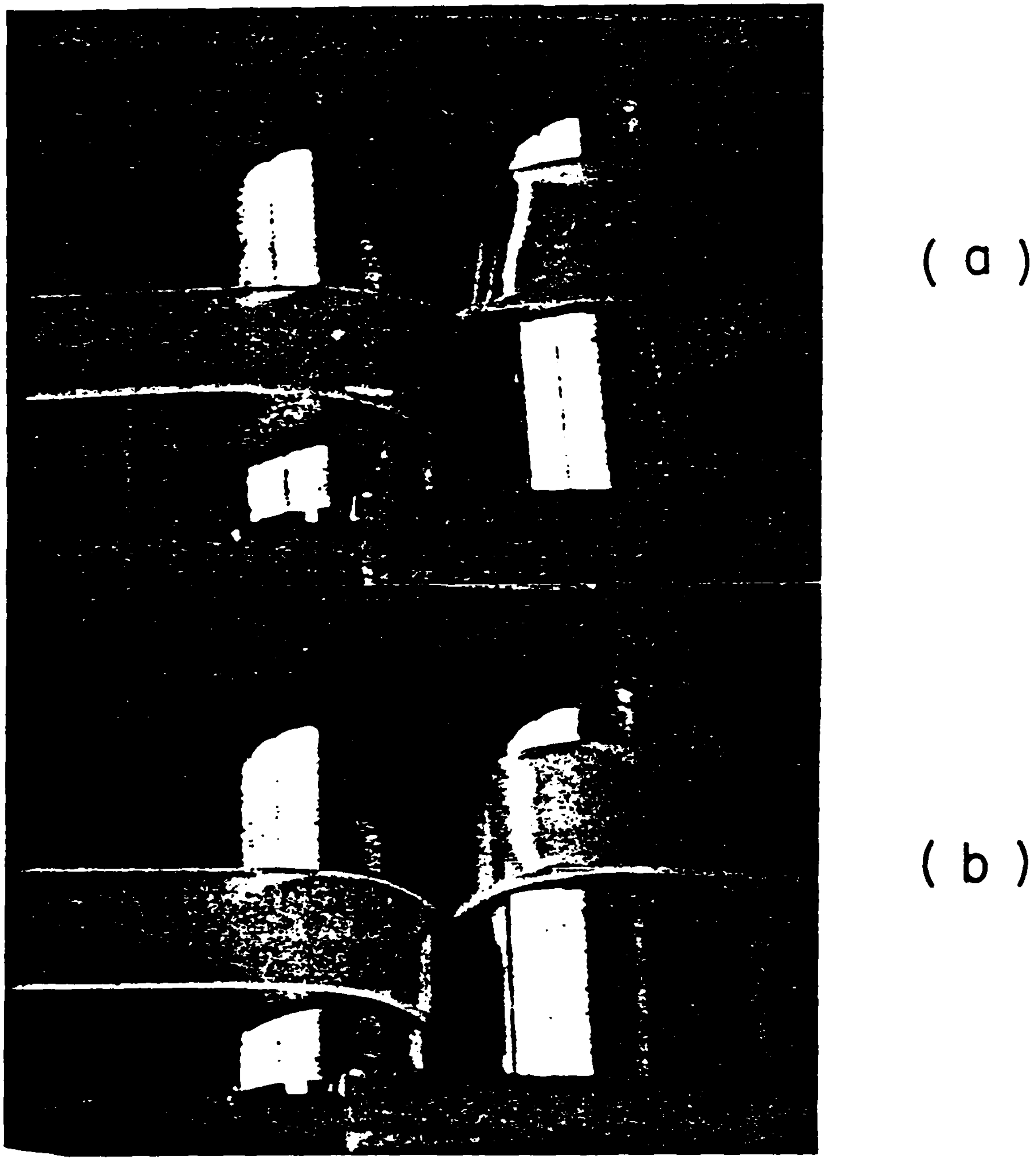

Figure 6

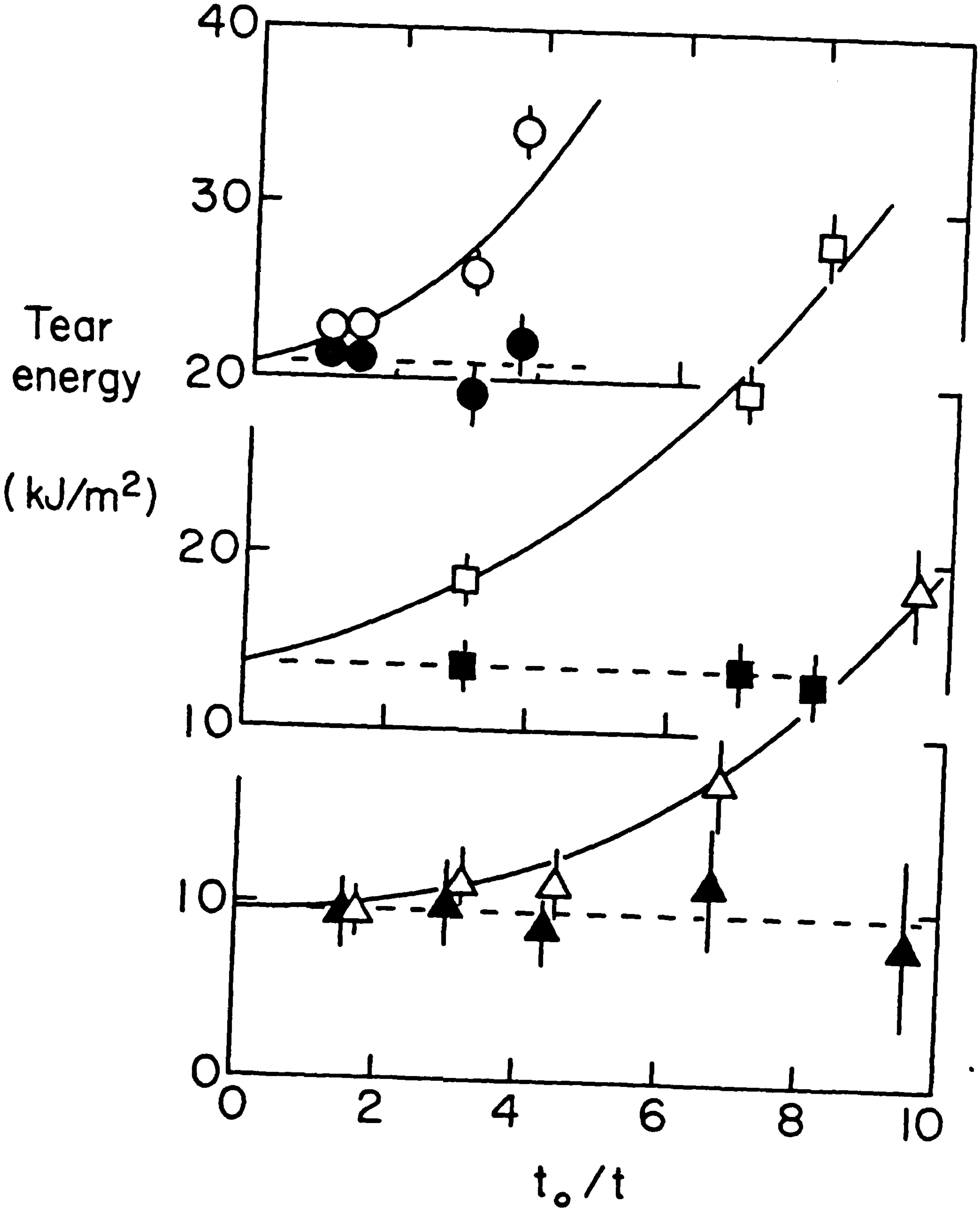

Figure 7

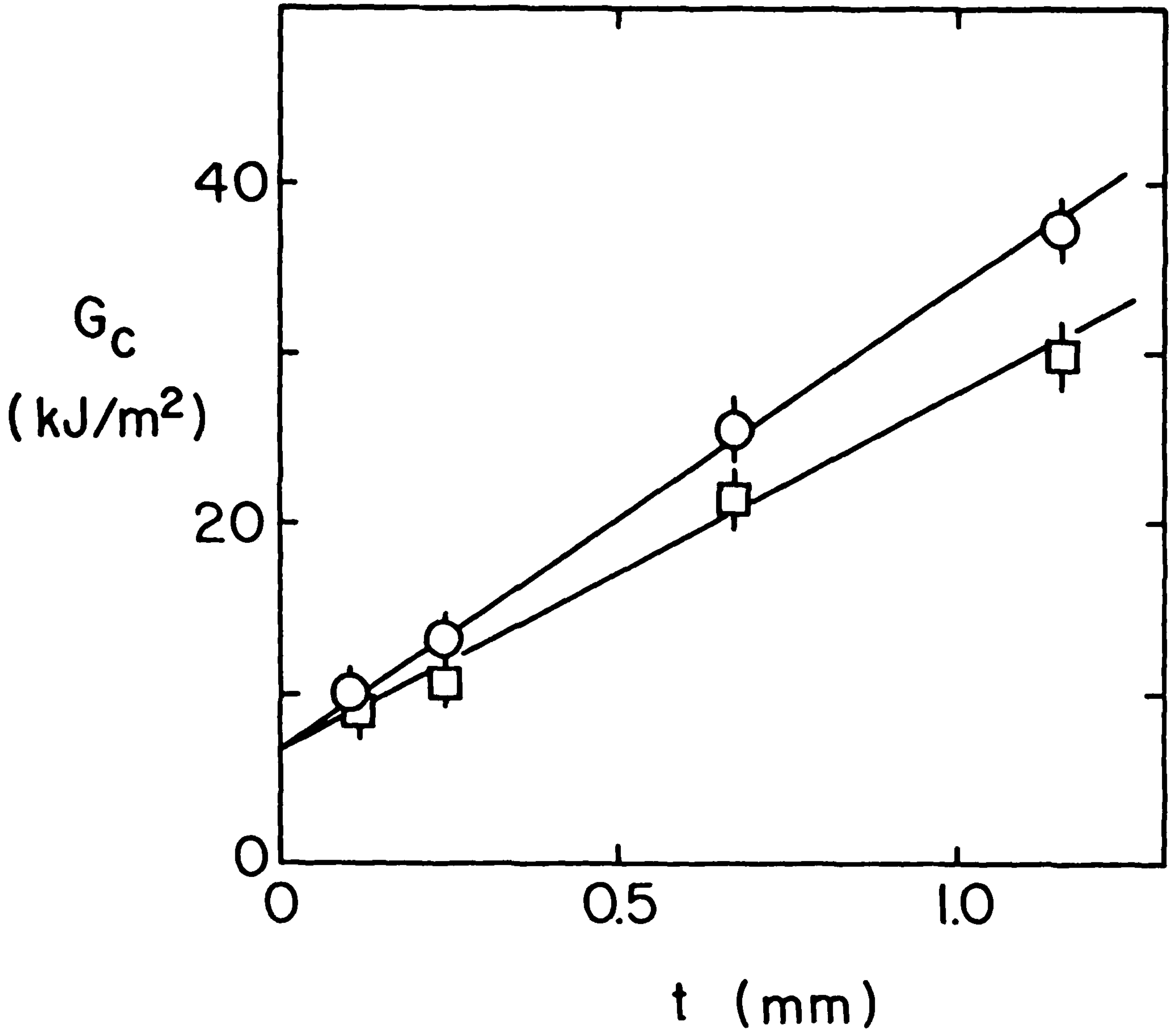

Figure 8

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