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FRACTURE MECHANICS APPLIED TO ELASTOMERIC COMPOSITES
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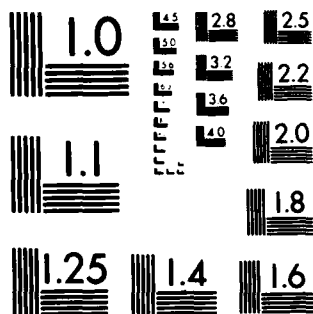
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FRACTURE MECHANICS APPLIED TO ELASTOMERIC COMPOSITES

by

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April, 1983

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Fracture Mechanics Applied to
Elastomeric Composites

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Abstract

Griffith introduced a general fracture criterion in 1920: a crack will grow only when enough energy is available in the system to cause further fracture. This simple concept has been applied to various tear processes in elastomeric materials by Rivlin and Thomas and to a variety of adhesive failures by Kendall. Their results are reviewed, with particular reference to the fracture and debonding of elastomeric composites. Two further cases are then considered: the detachment of an elastic matrix from a rigid spherical inclusion and the pull-out of inextensible cords from an elastic block in which they are embedded.

Introduction

In general, the strength of an adhesively-bonded joint is a function of the mode of loading and the dimensions and elastic properties of the bonded components, as well as of the intrinsic strength of the interface. The objective of fracture mechanics is to relate the breaking load to these diverse factors. One method of analysis uses a simple energy criterion for fracture, in terms of a characteristic energy for breaking apart the interface. Originally proposed by Griffith (1) for the brittle fracture of elastic solids, an energy criterion for fracture has been success-

fully applied to materials which become locally dissipative by Irwin (2) and Orowan (3), to highly-elastic materials by Rivlin and Thomas (4), and to the separation of two adhering solids by a number of authors (for example (5-17)).

An alternative method consists of evaluating the stresses set up at the site of fracture, and then invoking a characteristic fracture stress as the criterion for rupture (18). These two methods are fundamentally equivalent, but energy calculations are often easier to perform. The energy method is used here exclusively, for this reason.

In applying an energy criterion to adhesive failure, it is first necessary to identify an initial zone of separation, usually a flaw or region of high stress concentration at the interface between the two adhering solids. Then, failure is assumed to take place by growth of this initial debond until the joint is completely broken. An energy balance is formulated for a small growth of the debond--changes in the strain energy of the joint and the potential energy of the loading device are equated to the characteristic energy needed for debonding. This energy balance provides the required relation between the breaking load, the properties of the two adhering solids and the dimensions of the joint.

The fracture strength of a number of simple adhesive joints is now discussed, using these concepts of fracture mechanics. In all cases it is assumed, for simplicity, that one of the adherends is linearly elastic and uniformly stressed and that the other is rigid and inextensible. Strain

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energy is supplied by a loading device and stored in the deformable material. It is expended at failure in two ways: in supplying the work of fracture or detachment and in deforming material which was previously undeformed. By identifying the energy available to that required to propagate a fracture or detached zone, the magnitude of the stored strain energy at the moment of fracture is deduced, and hence the applied stress σ_b at break.

Relations obtained in this way for the failure load contain no adjustable parameters. Successful prediction of failure loads is therefore strong evidence for the validity of the proposed failure criterion and of the simplifying assumptions made in the analysis, viz., linearly elastic behavior of the adherends and substantially homogeneous deformation of parts of each adherend. Moreover, the predicted failure loads may be used as the basis for rational design of bonded components, once the basic assumptions of the theory have been shown to hold. Also, simple test methods can be developed for determining the characteristic strength of bonded interfaces from the measured failure loads of suitable model joints. The analysis of the pull-out force of cords embedded in rubber blocks (16) has been employed in this way to measure the adhesion of tire cords to rubber (19).

Modes of Failure

Peeling separation.

The peel test is particularly simple to analyze because the elastic energy of deformation of the adherends changes very little as peeling proceeds. This is because most adhering layers are sufficiently stiff that they

do not stretch significantly under the force of peeling, and the amount of material subjected to bending does not alter. Thus, for flexible but inextensible adherends the work of detachment is provided directly by the loading device. Hence, for peeling at 90° (Figure 1a) the peel force $\underline{P}$ per unit width is given by

$$P = G_a \quad (1)$$

where $\underline{G}_a$ denotes the work of detachment per unit area of interface. For peeling at 180° (Figure 1b)

$$P = G_a/2 \quad (2)$$

The factor of 2 arises in this case because the point of loading moves through twice the displacement of the detachment front.

Lap shear

When a deformable adhering layer is subjected to a force applied parallel to the interface, Figure 2, then the layer becomes stretched after detachment. For an increase Δc in the length of the detached portion, the detached layer becomes stretched by an amount $\underline{e}\Delta c$ where $\underline{e}$ is the tensile strain in the already-detached layer. If the layer is assumed to be linearly-elastic, with a tensile (Young's) modulus $\underline{E}$, then $\underline{e} = \underline{P}/\underline{E}t$, where $\underline{P}$ is the applied tensile force per unit width of the layer and $\underline{t}$ is the layer thickness. The loading device thus supplies energy given by $\underline{P}\underline{e}\Delta c (= \underline{P}^2 \underline{w} \Delta c / \underline{E}t)$. Some of this energy, $\underline{P}^2 \underline{w} \Delta c / 2 \underline{E}t$, is expended in stretching the newly-detached length Δc to the tensile strain $\underline{e}$. The remainder, $\underline{P}^2 \underline{w} \Delta c / 2 \underline{E}t$, is expended in the detachment process itself and is thus equal to the work required for detachment, $\underline{G}_a \underline{w} \Delta c$ (2).

Hence,

$$P^2 = 2 t E G_a \quad (3)$$

or, since $\sigma_b = P/t$,

$$\sigma_b^2 = 2EG_a/t \quad (4)$$

The above relation resembles Griffith's solution (1) for the tensile breaking stress of a bar containing a small circular cavity of radius r ,

$$\sigma_b^2 = \pi EG_c/3r \quad (5)$$

where G_c denotes the work required to propagate a fracture plane. However, in Griffith's solution, as the flaw grows and its radius increases, the stress required for fracture is predicted to decrease. Thus, if the applied stress is large enough to cause the (small) initial flaw to grow, it will then be more than sufficient to make the process continue, so that tensile fracture is catastrophic. On the other hand, equation 4 does not contain the size of the debonded zone. Shearing detachment is therefore predicted to take place continuously at a constant tensile stress in the deformable layer, related inversely to its thickness. These features of shearing detachment have been verified experimentally for adhering elastomeric layers (12) and the theory has been extended to deal with short overlaps (when bending deformations become important) (12), with unequal adherends (12), and with prestressed layers (20). In all cases, the success of a simple energy criterion for detachment confirms its general validity.

Tensile detachment from a rigid plane

For a circular debonded patch at the interface between a half-space of an elastic material and a rigid substrate, Figure 3, the relation corresponding to equation 5 for the applied stress σ_b sufficient to cause growth of the debond is (21)

$$\sigma_b^2 = 2\pi E G_a / 3r \quad (6)$$

The same result is obtained for a pressurized debond (a "blister") of radius r at the interface between an elastic half-space and a rigid plane (22). If the adhering material is incompressible in bulk, as is assumed here, then a tensile stress σ_b applied at infinity is mechanically equivalent to a pressure σ_b applied to the inner surfaces of the debonded region.

Detachment from a spherical inclusion

A relation analogous to equation 6 has been deduced for the applied stress required to cause detachment of an elastic matrix from a rigid spherical inclusion, Figure 4. The relation obtained then is (15)

$$\sigma_b^2 = 4\pi E G_a / 3r \sin 2\theta, \quad (7)$$

where r now denotes the radius of the inclusion and 2θ denotes the angle subtended by an initially-debonded patch located in the most favorable position for growth, i.e., in the direction of the applied tensile stress, Figure 4.

It is clear that σ_b will be extremely large for inclusions of small radius r , even if the level of adhesion, represented by G_a , is relatively

small, only of the order of magnitude of Van der Waal's attractions. For example, when $\underline{E}$ is assumed to be 2 MPa, representative of soft elastomers, and $\underline{G}_a$ is given the relatively low value of 10 J/m^2 , then the critical applied stress for detachment is predicted to reach a magnitude similar to $\underline{E}$ when the radius of the inclusion is about $20 \text{ }\mu\text{m}$, even if the initially-debonded zone is as large as is feasible, $\theta = 45^\circ$.

Now, a triaxial tension or negative hydrostatic pressure of magnitude 2σ is set up in the immediate vicinity of a rigid spherical inclusion, at the two poles in the direction of applied tensile stress σ . Any small voids present within the adhesive in these regions will grow in a catastrophic way by rupture of the adhesive when the material around them is subjected to a triaxial tension exceeding a critical level, given approximately by $\underline{E} + (2 \underline{S}/a)$ where $\underline{S}$ is the surface energy of the adhesive and $\underline{a}$ is the initial radius of the void (23). The condition for catastrophic growth of pre-existing voids is, therefore:

$$\sigma = \frac{1}{2}\underline{E} + (\underline{S}/a). \quad (8)$$

Thus, instead of detaching from the inclusion the adhesive itself will fail by cavitation when the inclusion is small in size because the critical stress for growth of cavities, given by equation 8, will be reached before the critical stress for debonding, given by equation 7. The smallest inclusion for which detachment will take place is given by

$$r = 16\pi \underline{G}_a / 3\underline{E}$$

on putting $\theta = 45^\circ$ in equation 7 and $\underline{S} = 0$ in equation 8.

The second term in equation 8 cannot be ignored, however, when the inclusion is extremely small, because voids located within the immediate vicinity of an inclusion must be small in size in comparison with the inclusion itself. Thus, when the inclusion radius $\underline{r}$ is reduced, the radius $\underline{a}$ of a suitably located void is necessarily smaller, and growth of it by tearing will require an increasingly-large applied stress. When reasonable values are assigned to $\underline{E}$ and $\underline{S}$, it may be concluded that growth of local voids by tearing will become increasingly difficult as the particle diameter is reduced below about 50 μm and when it is less than about 1 μm then tearing failures in the vicinity become virtually impossible also. The matrix will then be effectively bonded to the inclusion under all circumstances. These considerations appear to account for the general features of reinforcement of elastomers by particulate fillers (15).

Pull-out of inextensible fibers

By applying the same principle of energy conservation during detachment, it can be shown that the pull-out force $\underline{P}$ for an inextensible fiber of radius $\underline{r}$ embedded in a cylindrical elastic block of radius $\underline{R}$ is given by (16):

$$P^2 = 4\pi^2 R^2 r E G_a. \quad (9)$$

A sketch of this experimental arrangement is given in Figure 5a. When a bonded elastic cylinder of radius $\underline{r}$ is pulled out from a cylindrical cavity of the same radius, Figure 5b, then the pull-out force is also given by equation 9 in the special form (17):

$$P^2 = 4\pi^2 r^3 E G_a. \quad (10)$$

Experimental results with rubber cylinders have confirmed the general validity of equations 9 and 10, and measurements of failure loads in compression and torsion have also been successfully analyzed in the same way (17). Thus, again, energy considerations account for the principal features of the strength of simple joints.

It is noteworthy that equations 9 and 10 predict increasing pull-out forces as the radius of the inclusion (fiber) is increased. This trend is in striking contrast to the result for a single spherical inclusion, equations 7 and 8, where the detachment stress is predicted to decrease as the radius of the inclusion is increased. Both trends are direct consequences of the theoretical analysis, and both are confirmed by experiment (16,24). The surface area to be debonded and the energy required to do so are both greater for fibers of larger diameter and, as a result, the pull-out force is increased. For spherical inclusions, on the other hand, the amount of highly-stressed material in the vicinity of the debond, which provides the energy needed for propagating the debond in this case, also increases as the size of the inclusion is increased. Indeed, the highly-stressed volume grows in proportion to r^3 whereas the area to be debonded only grows in proportion to r^2 . In consequence, it is easier to propagate a debond on a larger inclusion than it is on a smaller one.

All highly-elastic materials tend to contract on stretching. When an embedded fiber is pulled out, the surrounding material contracts on to it when the pull-out force is applied, and it becomes gripped by friction as well as by adhesion. When the work of frictional sliding

is added to the work of debonding the pull-out force is obtained as (17).

$$P^2 = 4\pi^2 R^2 r E G_a / [1 - 4\mu x / 3R^2] \quad (11)$$

in place of equation 9, where μ denotes the coefficient of friction and x denotes the length of fiber embedded in the block of elastomer. In both equation 9 and 11, it has been assumed that the radius R of the elastic block is much larger than the radius r of the fiber.

It is clear from equation 11 that the pull-out force P will rise to extremely high values when the fiber is embedded deeply enough so that the second term in the denominator approaches unity. Although the theoretical treatment leading to equation 11 is rather approximate, it accounts for the general nature of the experimental observations and, in particular, for the greater influence of friction for fibers or embedded cylinders of larger diameter (17).

When a number n of fibers are embedded in a single block of elastomer and they are all pulled out together, then the work required for detachment is obviously larger than for a single fiber by a factor of n . The strain energy stored within the block must therefore be larger than before, by a factor of n , and the total force applied for pull-out must be increased by a factor of $n^{\frac{1}{2}}$. Thus, energy considerations lead immediately to the surprising conclusion that the total force required to pull out n fibers simultaneously from a single elastic block will increase in proportion to $n^{\frac{1}{2}}$. This prediction has been verified experimentally for 1-10 cords embedded in a rubber block, Figure 6 (16). It provides a striking example of the success of simple energy calculations in accounting for important features of the strength of joints and structures.

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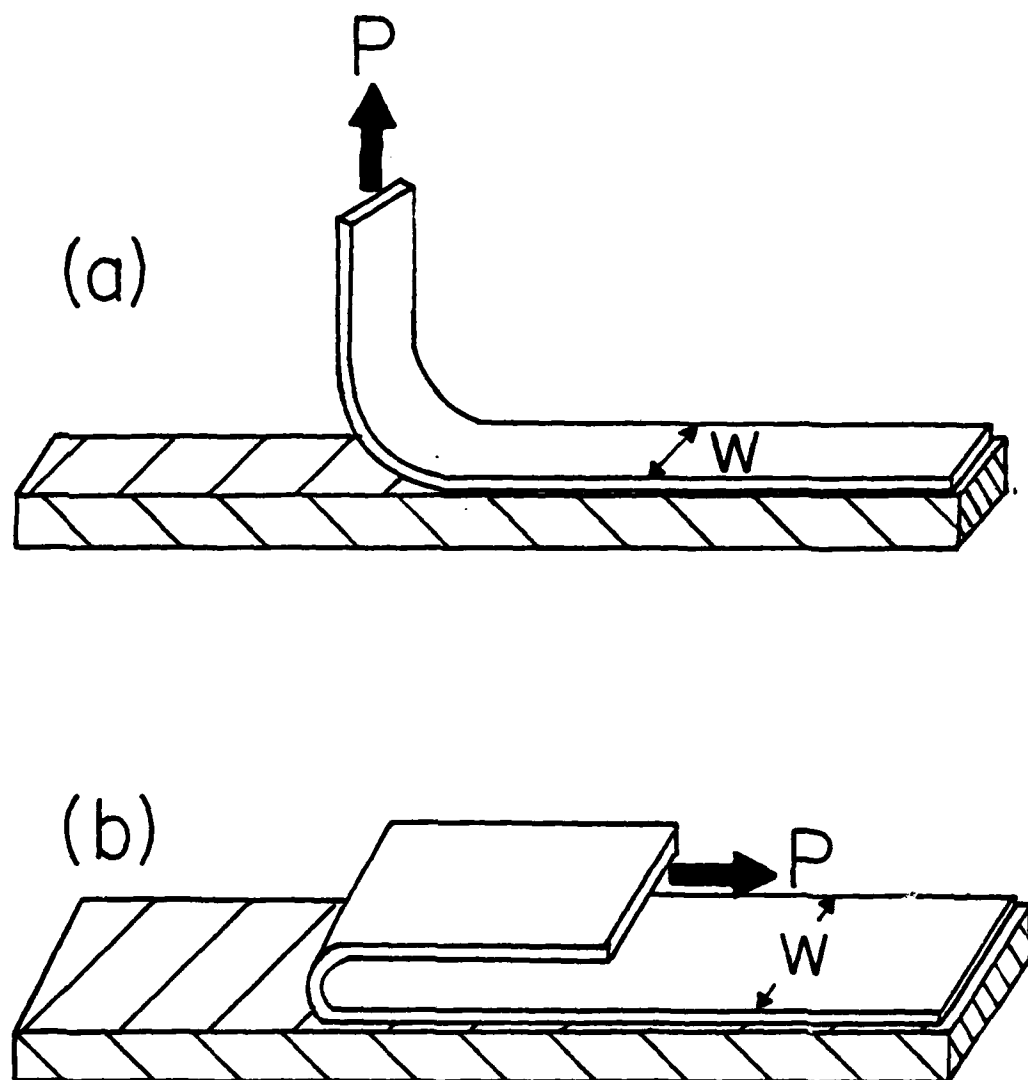


Figure 1. Peel Tests

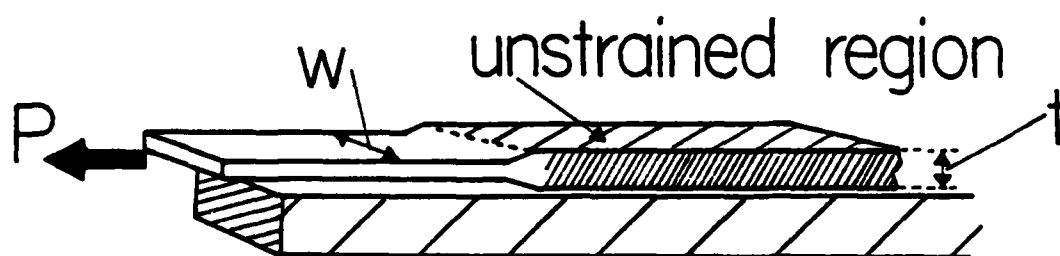


Figure 2. Detachment by a Force Parallel to the Interface

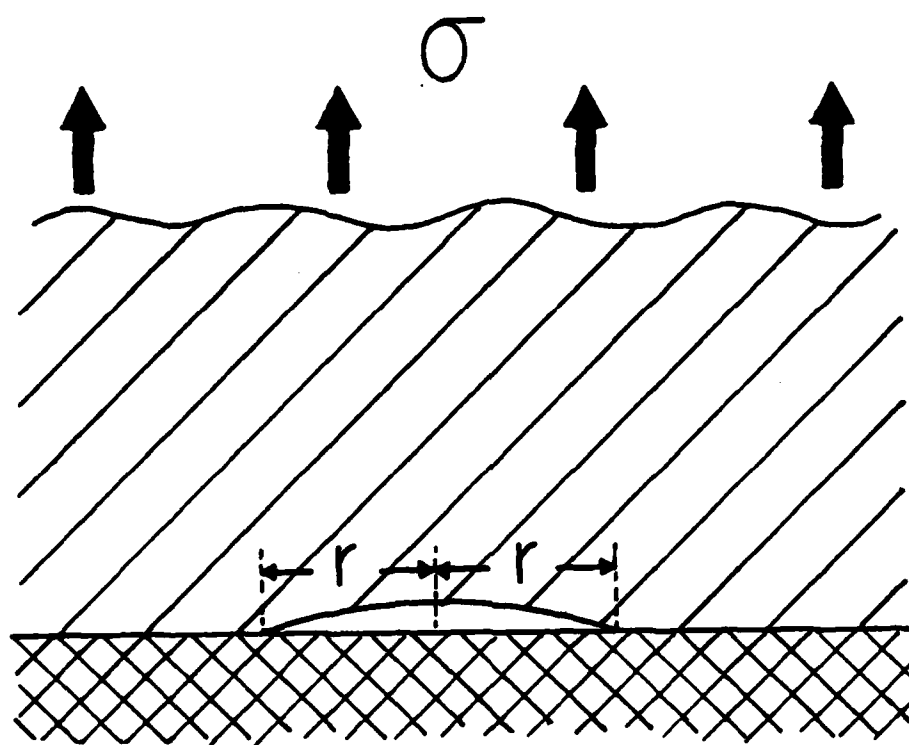


Figure 3. Detachment by a Tensile Stress

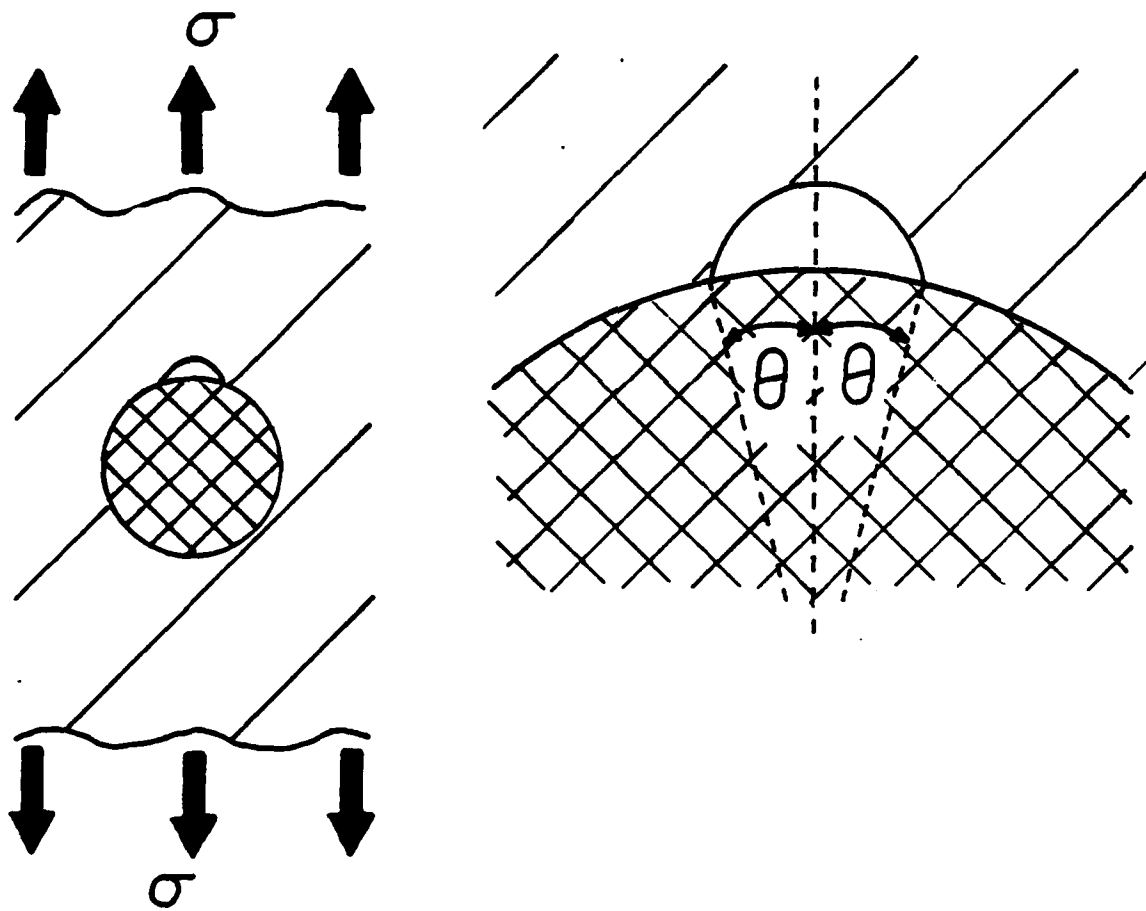


Figure 4. Detachment from a Rigid Spherical Inclusion

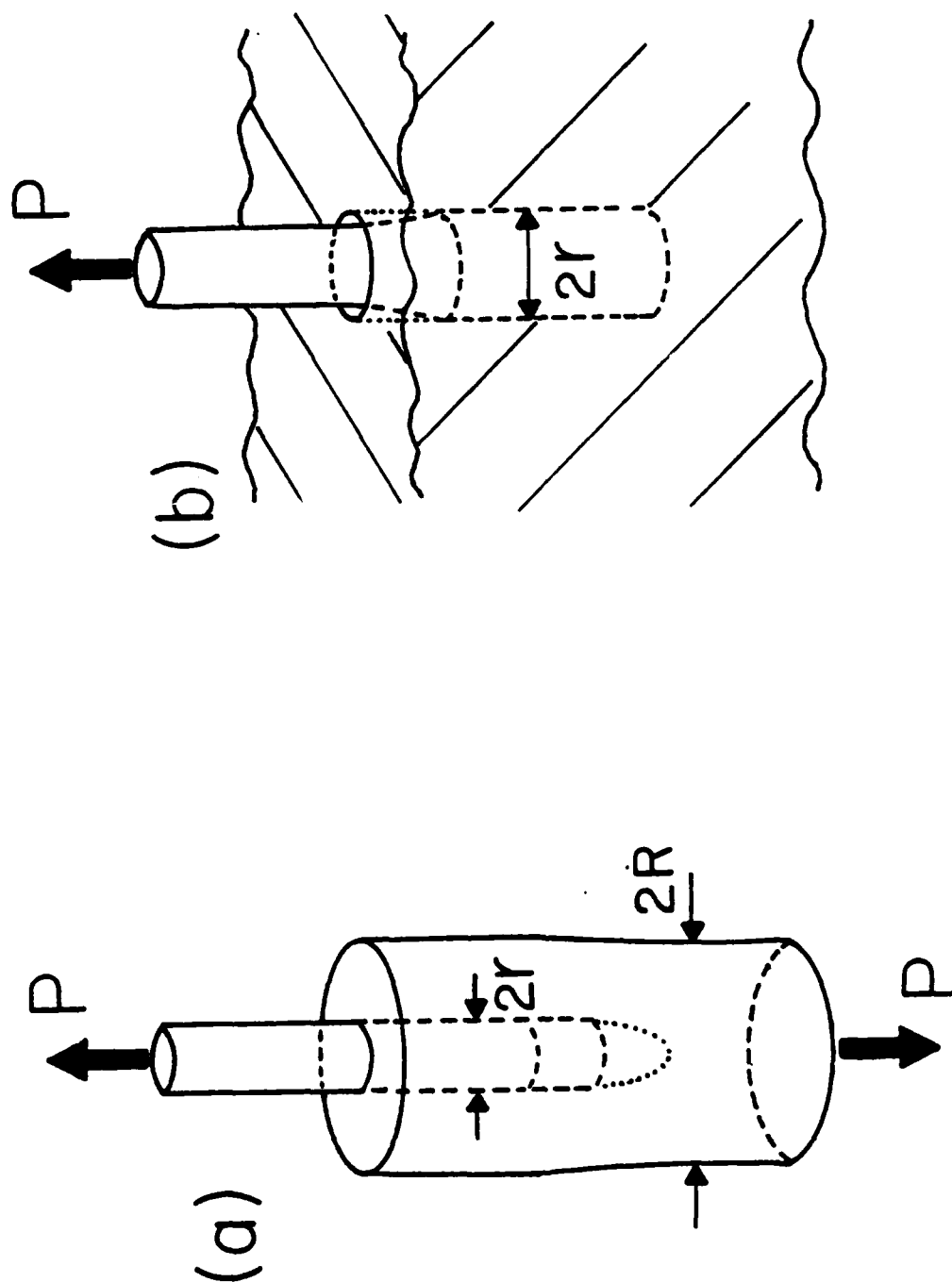


Figure 5. Pull-out of (a) an Inextensible Rod from an Elastic Cylinder
(b) an Elastic Rod from an Inextensible Block

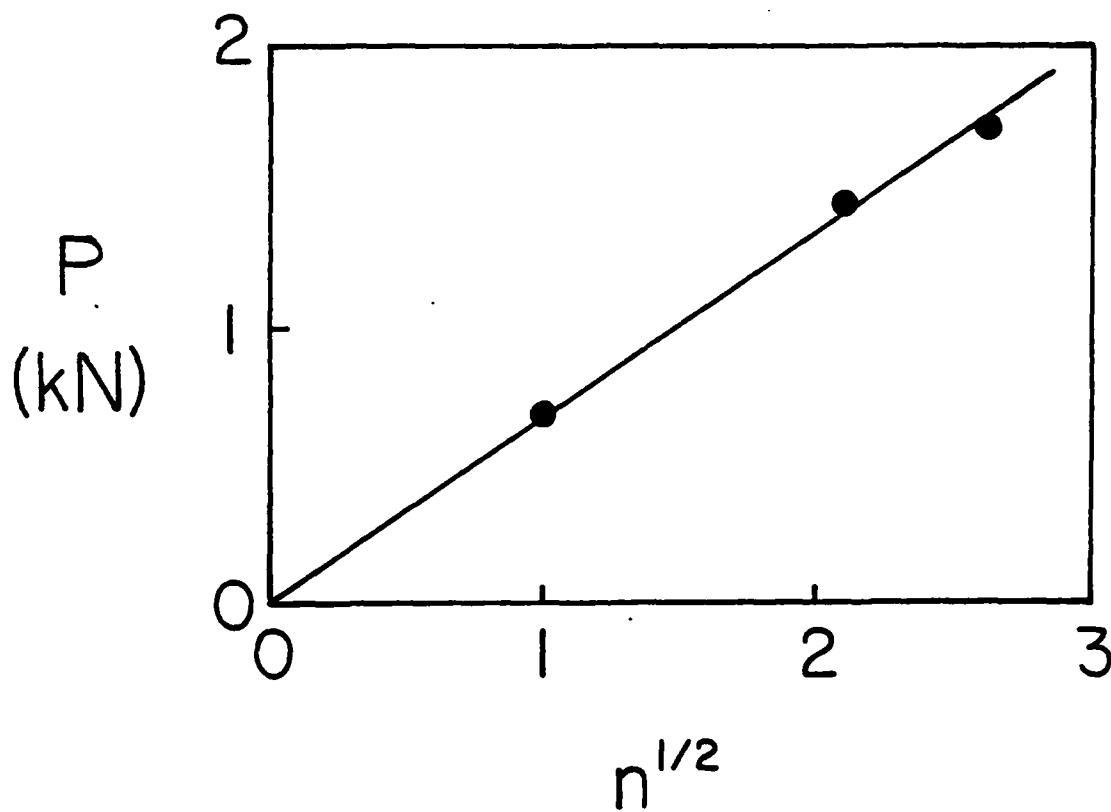


Figure 6. Total Pull-out Force for $\underline{n}$ fibers Embedded in a Single Rubber Block, Plotted Against $\underline{n}^{1/2}$ (16)

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