Pull-Off Forces for Adhesive Tapes

A. N. GENT and S. KAANG*, *Institute of Polymer Science,*
University of Akron, Akron, Ohio 44325

Synopsis

An analysis is given of the force F required to pull an adhesive tape of unit width away from a rigid substrate in terms of the strength G_a of adhesion, the tensile modulus E of the tape, and its thickness t. Measurements are reported for several commercial adhesive tapes and compared with the predictions of the theory. Excellent agreement is obtained, suggesting that the theory is basically correct. Attention is drawn to the unusual form of the dependence of the failure force F upon the work G_a of detachment and the resistance Et of the tape to stretching in this case: $F^4 \propto EtG_a^3$. Even though the tape is assumed to be linearly elastic, the markedly nonlinear (cubic) relation between force F and displacement δ of the tape away from the substrate leads to this unusual result. Differences observed in G_a from pull-off and from 90° peeling experiments are tentatively attributed to additional energy losses in the latter case due to the severe bending deformations imposed on the tape as it is peeled away.

INTRODUCTION

When adhesive tapes are pulled away from a rigid substrate, as shown schematically in Figure 1, the force required depends upon both the strength of adhesion and the resistance of the tape to stretching. Although these two factors are obviously significant, no previous analysis of their relative importance is known to the present authors. A simple theoretical treatment is therefore given relating the pull-off force F to the strength of adhesion, characterized by the work G_a required to detach unit area of adhering tape from the substrate, and the effective tensile (Young's) modulus E of the tape, assumed for simplicity to be linearly elastic. Measurements with various commercial tapes are then reported, and compared with the theoretical predictions.

Because of the simplicity of this experiment, and the ready way in which values of G_a and E can be deduced from it, it may have potential value as a routine test method for adhesive tapes. This is particularly the case for tapes that are commonly used to secure items to a rigid base, when the pull-off force F represents an important service parameter.

Quite apart from any potential practical value, the analysis of the pull-off force F has some scientific interest, for two reasons. It demonstrates once again the power of simple energy considerations in fracture mechanics, using a characteristic value of the detachment energy G_a as the criterion for debonding.[1-6] And the pull-off force F is found to be neither proportional to G_a, as might at first be expected and is, indeed, observed in simple peeling experiments,[7-9] nor is it proportional to $(EG_a)^{1/2}$ as is found in many linearly elastic

---

*On leave of absence from Kumho & Co., Inc., R & D Center, Korea.

Journal of Applied Polymer Science, Vol. 32, 4689–4700 (1986)
CCC 0021-8995/86/044689-12$04.00

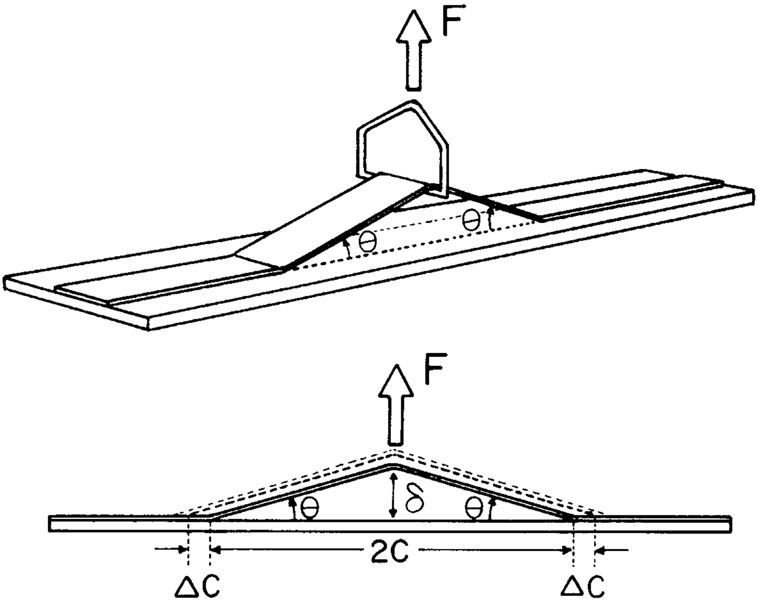

Fig. 1. Sketch of the pull-off experiment.

("Griffith") systems where energy is expended in deforming layers after debonding them.[10-13] Instead, it is found to be proportional to $(EG_a^3)^{1/4}$, a result which emerges directly from the analysis as a consequence of the particular relation which holds between the force F and the corresponding elastic displacement δ of the tape when no further debonding occurs; $F \propto \delta^3$; even though the components are assumed to be linearly elastic.[14] This is the first time to the authors' knowledge that other possible types of dependence of the failure force F upon E and G_a have been pointed out.

THEORETICAL CONSIDERATIONS

Elastic Behavior

A sketch of an adhesive tape being pulled away from a rigid substrate is shown in Figure 1. The tensile strain e in the tape is obtained in terms of the angle θ between the detached part of the tape and the substrate surface from geometrical considerations:

$$e = \sec\theta - 1 \tag{1}$$

Thus, when θ is small,

$$e \simeq \theta^2/2 \tag{2}$$

The tensile force F^1 in the detached part of the tape is related to the applied pull-off force F,

$$F = 2F^1 \sin\theta \tag{3}$$

Assuming that the tape is linearly elastic, with an effective value of tensile (Young's) modulus E, the force F^1 is given by $Eewt$, where w and t are the width and thickness of the tape. Thus,

$$F = 2Ewt\sin\theta(\sec\theta - 1) \tag{4}$$

When θ is small, this simplifies to yield:[14]

$$F = Ewt\theta^3. \tag{5}$$

Conditions for Detachment

We now consider the energy changes that take place for further detachment by a distance $2\Delta c$ (Fig. 1). Work supplied by the pull-off force F is $F\tan\theta\Delta c$. Work expended in detachment is $2G_a w\Delta c$, and work expended in stretching the newly detached parts of the tape is $Ee^2wt\Delta c = Ewt(\sec\theta - 1)^2\Delta c$. By equating the work supplied to the total work expended we obtain

$$F\tan\theta = 2G_a w + Ewt(\sec\theta - 1)^2 \tag{6}$$

On substituting for F from Eq. (4) and rearranging:

$$G_a/Et = \tfrac{1}{2}\tan^2\theta + \cos\theta - 1 \tag{7}$$

When θ is small this becomes

$$G_a/Et = 3\theta^4/8 \tag{8}$$

Equations (7) and (8) give the work G_a of detachment in terms of the angle θ between the detached tape and the substrate. In terms of the pull-off force F and angle θ from Eq. (5),

$$G_a = (3/8)F\theta/w, \tag{9}$$

and in terms of F and the tape modulus E,

$$F/w = (8G_a/3)^{3/4}(Et)^{1/4} \tag{10}$$

These results are valid only at small values of θ, because they depend upon the approximations leading to Eqs. (5) and (8). The exact result for F is given in parametric form by Eqs. (4) and (7). However, even for values of the angle θ as large as 45° the error is less than 10% when G_a is calculated from Eq. (10) because of compensating errors in Eqs. (5) and (8). On the other hand, if G_a is calculated from measurements of θ by means of Eq. (8) or (9), then the error is about 10% when θ is 25° and becomes rapidly greater for larger angles.

In the following parts of the paper experimental measurements of the pull-off force F and angle θ are described for some pressure-sensitive adhesive tapes and compared with the theoretical relations given above.

EXPERIMENTAL DETAILS

Materials

Several commercial pressure-sensitive adhesive tapes were employed in the experiments:

A, a vinyl plastic electrical tape, 19 mm wide and about 0.235 mm thick (3M Company, denoted 88)
B, a window film mounting tape, 12.7 mm wide and about 0.105 mm thick (3M Company, Catalog No. 2145)
C, a relatively thick, soft, extensible mounting tape, 12.7 mm wide and about 1.34 mm thick (3M Company, Catalog No. 110)
D, a clear tape, 25.4 mm wide and about 0.14 mm thick (Manco Tape Inc., denoted All-Weather Clear Tape)
E, a paper-based masking tape, 25.4 mm wide and about 0.145 mm thick (Tuck Tape)

Tensile Stress–Strain Relations

Measurements were made of the relations between tensile force per unit width and extension for the first three tapes, using strips about 300 mm long, stretched at 5 mm/min. They were approximately linear for tapes *A* and *C* over the range 0–20% extension [Fig. 2(a)], but highly nonlinear for tape *B*, which underwent plastic yielding at about 3% extension [Fig. 2(b)]. Values of the average tensile strains set up during pull-off experiments from glass were deduced from the measured pull-off angles θ by means of Eq. (2); they were 5.0% for tape *A*, 2.3% for tape *B*, and 13.3% for tape *C*. Effective values of Et were calculated from the corresponding tensile stresses of 3.50 kN/m, 85.5 kN/m, and 1.25 kN/m, respectively. (Using the measured tape thicknesses t, these results correspond to effective values of tensile modulus E of 15 MPa, 820 MPa, and 0.92 MPa for tapes *A*, *B*, and *C*, respectively.)

Because the detachment forces with a Teflon substrate were significantly smaller for tapes *B* and *C*, the average tensile strains were also smaller, about 0.8% and about 3.8%, respectively, and the effective values of Et were correspondingly somewhat larger than before, about 105 kN/m and about 1.5 kN/m, due to the nonlinear stress–strain relations.

Measurement of Pull-Off Forces

Samples of tape about 350 mm long were applied to a rigid horizontal substrate, a polished glass plate or a smooth Teflon plate, previously cleaned with acetone. A stiff wire loop, trapped between the center of the strip of tape and the substrate, was then used to pull the tape away. Pull-off forces F and angles θ were measured as shown schematically in Figure 1, with a tensile testing machine. To prevent the tape from slipping along the substrate during pull-off, the ends were wrapped around the ends of the substrate plate and in some instances secured there by tape clamps. In order to vary the effective stiffness Et without changing the detachment energy G_a up to ten layers of tape were applied, one on top of another. On the other hand, by using the

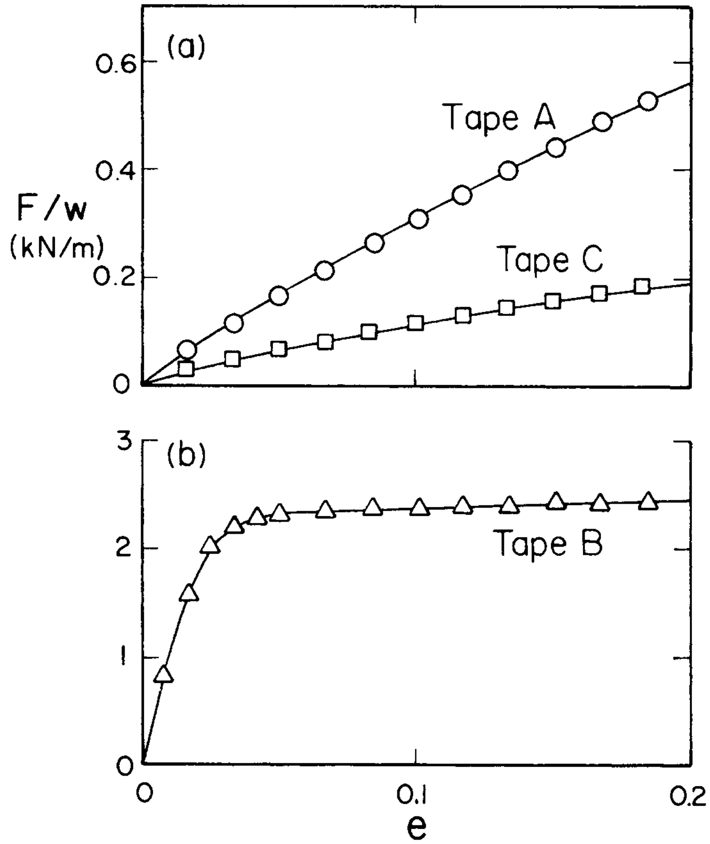

Fig. 2. Experimental relations between tensile load per unit width F/w and extension e for selected tapes. (a) Tapes A and C; (b) Tape B.

same tapes on two different substrates, glass and Teflon, it was hoped to vary G_a substantially without changing the effective stiffness of the tape.

As the tape began to pull away from the substrate the applied force F rose to a relatively large starting value and then fell to a value about 30% lower and remained at this level as detachment continued over long distances. Steady-state values of F and the pull-off angle θ have been taken here as representative of pull-off at a constant rate of detachment. The initial surge is ascribed to higher start-up velocities.

All experiments were carried out at ambient temperature, about 24°C, and with a crosshead speed of 83 μm/s.

Independent Measurements of G_a

Measurements were made of the force F required to peel tapes away from the substrates at an angle of 90° (Fig. 3), and at various speeds v in the range 0.1–1 mm/s. Values of detachment energy G_a were then calculated:

$$G_a = F/w \tag{11}$$

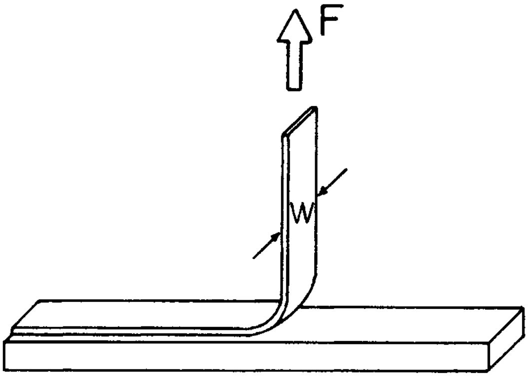

Fig. 3. Peel experiment.

By interpolation, values were obtained appropriate to the speed dc/dt at which debonding took place in the pull-off experiments, where $dc/dt = v/\tan\theta$ (Fig. 1).

EXPERIMENTAL RESULTS AND DISCUSSION

Pull-Off Forces and Angles

Measured values of pull-off force F and angle θ are given in Tables I and II. Values of detachment energy G_a calculated from them by means of Eq. (9) are given in the fourth column of Tables I and II and values calculated from the pull-off force F alone, with the separately determined value of the effective tensile stiffness Et for each tape 1, using Eq. (10), are given in the fifth column of Tables I and II. These two estimates of G_a are in reasonable agreement with each other in all cases, suggesting that the essential features of the mechanics of pulling away an extensible tape from a rigid substrate are contained in the theoretical treatment. However, they are not generally in good agreement with direct measurements of G_a by peeling away the tape at an angle of 90°, given in the final columns of Tables I and II for peel velocities equal to the computed rates of advance of the separation front in the pull-off experiments. The discrepancies are significant, and rather different in magnitude for the different tapes. For tapes A and D, for example, the peel energies are about 2–3 times the pull-off energy, whereas for tapes C and E and for tape B adhering to Teflon, the peel energy is closer to the pull-off energy. Possible reasons for these differences are discussed later. We note here only that values of detachment energy G_a obtained from pull-off experiments are internally consistent and generally lower than those obtained from peeling experiments.

A striking feature of the present theoretical treatment is the form of the predicted dependence of pull-off force F upon the effective thickness of the adhering tape t; $F \propto t^{1/4}$, [Eq. (10)]. Experimental values of F are plotted in Figures 4 and 5 against $N^{1/4}$, where N is the number of layers of tape applied one on top of another and pulled away together. Clearly, the effective tape thickness t is proportional to N in these experiments. As can be seen in

TABLE I
Detachment from Glass

Number of layers N	Pull-off force F/w (N/m)	Pull-off angle θ (rad)		G_a (N/m)	
			From Eq. (9)	From Eq. (10)	From Eq. (11)
Tape *A*					
1	217 ± 5	0.42	34	32	95
2	268 ± 10	0.34	34	33.5	100
3	320 ± 10	0.31	37	37	102
4	360 ± 20	0.30	40.5	39.5	104
5	445 ± 20	0.29	48.5	48.5	105
6	455 ± 20	0.27	46	47	107
7	475 ± 20	0.26	46.5	47.5	108
8	545 ± 20	0.255	52	54.5	109
9	550 ± 20	0.245	50.5	53	110
10	558 ± 20	0.235	49	52	112
Tape *B*					
1	1585 ± 15	0.36	214	157	290
2	2110 ± 20	0.255	202	183	305
3	2400 ± 155	0.225	202	190	315
4	2665 ± 155	0.20	201	198	320
5	2550 ± 230	0.175	167	174	330
6	2705 ± 230	0.165	167	176	335
7	3170 ± 310	0.165	197	208	335
8	3245 ± 310	0.165	201	205	335
9	3630 ± 310	0.165	225	228	335
10	3475 ± 310	0.165	216	208	335
Tape *C*					
1	340 ± 25	0.70	89	83	172
2	400 ± 25	0.59	88.5	82	173
3	480 ± 25	0.56	101	91.5	174
4	585 ± 25	0.56	123	108	174
5	735 ± 25	0.54	149	136	174
6	635 ± 25	0.47	112	105	176
7	740 ± 25	0.445	123	122	176
8	710 ± 25	0.43	114	111	177
9	710 ± 25	0.395	105	107	178
10	790 ± 25	0.375	111	118	179
Tape *D*					
1	485 ± 40	0.365	67	59	199
2	580 ± 40	0.28	62	60	207
Tape *E*					
1	570 ± 40	0.225	48	42.5	63
2	735 ± 40	0.20	55	47.5	65

Figures 4 and 5, approximately linear relations were obtained between F and $N^{1/4}$ in all cases, in good accord with the theoretical prediction.

A further prediction of the theory is that the product $F\theta$ will be independent of the stiffness of the tape, and hence of the thickness t or number N of layers pulled off together (except insofar as the speed of separation is altered, so that changes are brought about in the detachment energy G_a on this

TABLE II
Detachment from Teflon

Number of layers N	Pull-off force F/w (N/m)	Pull-off angle θ (rad)	G_a (N/m) From Eq. (9)	G_a (N/m) From Eq. (10)	G_a (N/m) From Eq. (11)
			Tape *A*		
1	238 ± 10	0.40	36	37	80
2	297 ± 10	0.34	38	39.5	83
3	325 ± 10	0.295	36	38.5	86
4	382 ± 15	0.27	39	43.5	88
5	435 ± 15	0.26	42	48	89
6	435 ± 20	0.25	41	45	90
7	470 ± 20	0.24	42.5	48	91
8	510 ± 20	0.24	46	51	91
9	530 ± 20	0.24	48	52	91
10	555 ± 20	0.23	47.5	52.5	92
			Tape *B*		
1	525 ± 25	0.175	34.5	34	49
2	725 ± 30	0.155	42	41	49
3	850 ± 30	0.14	44.5	44	49
4	1005 ± 30	0.12	45	50	49
5	1080 ± 30	0.12	48.5	51.5	49
6	1145 ± 40	0.115	49.5	52	49
7	1195 ± 40	0.105	47	52.5	49
8	1275 ± 75	0.105	50	54.5	49
9	1275 ± 75	0.105	50	52.5	49
10	1315 ± 75	0.095	47	53	49
			Tape *C*		
1	89 ± 4	0.42	14.0	13.0	24
2	116 ± 8	0.35	15.2	14.7	24
3	124 ± 8	0.305	14.2	14.1	24
4	151 ± 8	0.28	15.9	16.6	24
5	170 ± 8	0.26	16.6	18.1	24
6	182 ± 8	0.245	16.7	18.6	24
7	185 ± 8	0.22	15.3	18.1	24
8	193 ± 8	0.21	15.2	18.3	24
9	208 ± 8	0.19	14.8	19.6	24
10	228 ± 8	0.185	15.8	21.2	24

account). Values of $F\theta$ are plotted in Figures 6, 7, and 8 against the number N of adhering layers. They are seen to be substantially constant, independent of N, even though F and θ vary separately with N to a significant extent (Tables I and II).

It is interesting to note that the apparent detachment energy G_a, given by $3F\theta/8w$, was approximately the same for tape A pulled away from a glass or a Teflon surface. In contrast, for tapes B and C the detachment energies for a Teflon surface were only about 25% and 15%, respectively, of those for a glass surface, in accord with the lower wettability expected for Teflon. The adhesion of tape A must be attributed largely to its rheological features rather than to selective wettability.

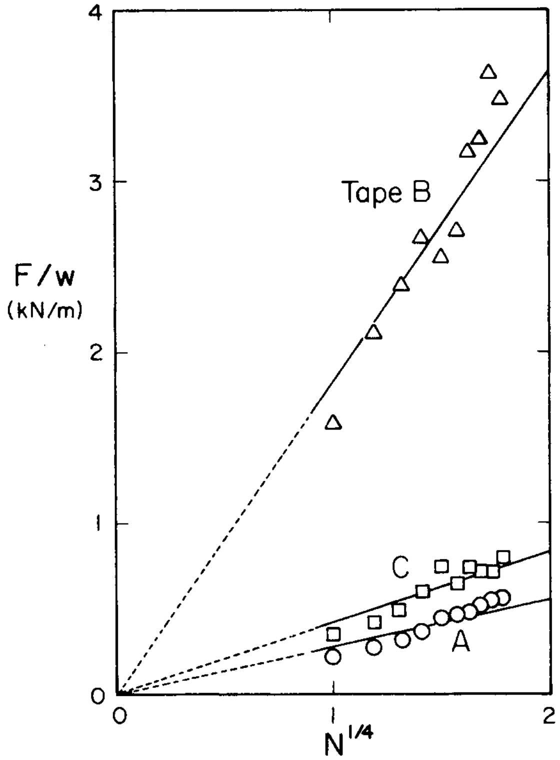

Fig. 4. Plot of the pull-off force per unit width F/w vs. $N^{1/4}$ where N is the number of layers of tape applied one on top of another to a glass substrate and pulled away together.

Discrepancies in G_a

Several possible reasons may be adduced for the observed discrepancies in the detachment energy G_a from pull-off and from peeling experiments. In the first place, Eqs. (9) and (10) are based on the assumption that the pull-off angle θ is small. This is not always a valid assumption, especially for strongly adhering, easily stretched tapes (Tables I and II). However, the values obtained from Eqs. (9) and (10) are in good agreement, even though the assumption of small θ is more stringent in the first case. Also, the discrepancy is not markedly reduced when many layers of tape are detached together and the angle θ is much smaller. Finally, the size of the discrepancy does not correlate well with the magnitude of θ. We conclude that the simplifying assumption that θ is small is not responsible for the observed discrepancies.

A second possible cause is nonlinear elastic behavior of the tapes in tension. In contrast to the assumed linear elastic response, the tapes followed a nonlinear relation between tensile force and elongation to various degrees (Fig. 2) so that the effective stiffness Et at small strains and pull-off angles was greater than at large ones. It seems probable that the use of an average value of Et in calculating G_a from pull-off experiments is responsible for a small but systematic change in the values obtained as the number of layers was increased and the imposed tensile strain was correspondingly reduced. This

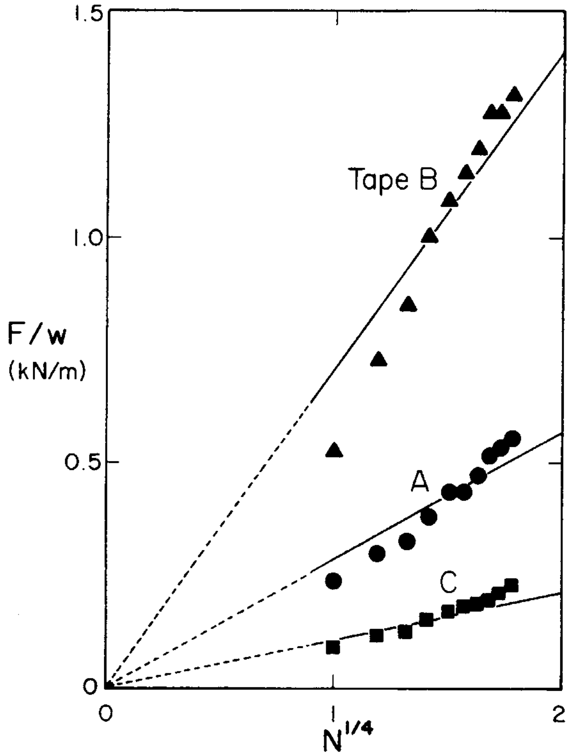

Fig. 5. Plot of the pull-off force per unit width F/w vs. $N^{1/4}$ where N is the number of layers of tape applied one on top of another to a Teflon substrate and pulled away together.

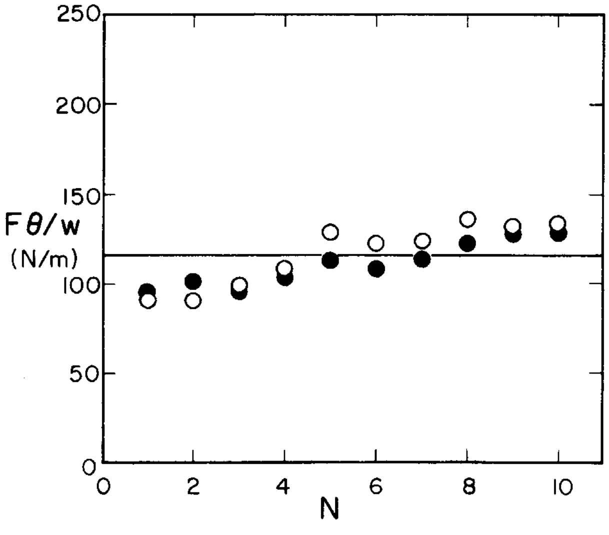

Fig. 6. Plot of $F\theta/w$ vs. N for tape A adhering to glass (open circles) and to Teflon (filled-in circles).

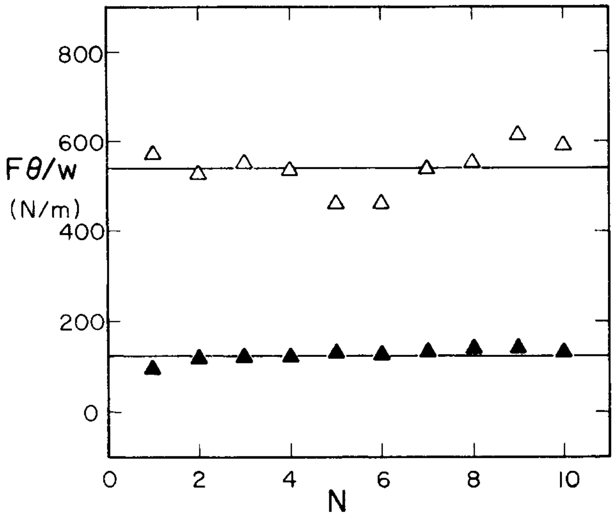

Fig. 7. Plot of $F\theta/w$ vs. N for tape *B* adhering to glass (open triangles) and to Teflon (filled-in triangles).

feature should be most pronounced for tapes which yield in tension, tapes *B* and *D*, and at large values of θ, i.e., for pull-off of single layers. But these results do not seem to be particularly anomalous (Tables I and II). It must therefore be concluded that the simplifying assumption of linearly elastic behavior, although quite inadequate for tapes which undergo plastic yielding, was a reasonably satisfactory approximation in most of the experiments reported here.

A third assumption implicit in the theoretical treatment is that work expended in bending the tape away from the substrate is negligible, or at least is the same in both the pull-off and the peeling experiments so that it

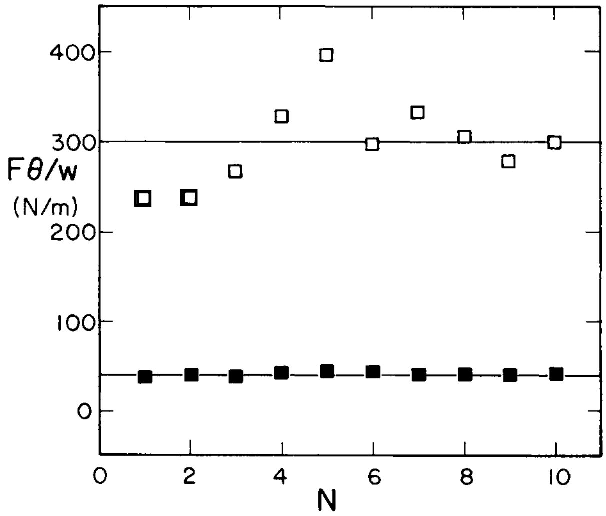

Fig. 8. Plot of $F\theta/w$ vs. N for tape *C* adhering to glass (open squares) and to Teflon (filled-in squares).

contributes equally to the values obtained for G_a. In some circumstances this contribution can be both large and strongly dependent upon the magnitude of the peel angles.[15] It would also be expected to depend upon the structure of the tape and hence to vary from one tape to another. Thus, it may be the primary factor responsible for the observed discrepancies in G_a from pull-off at small angles and from peeling at 90°, even though the mode of failure appears to be so similar in the two cases. Further work is needed to clarify this point.

CONCLUSIONS

The predicted dependence of the pull-off force upon the effective stiffness Et of the tape, the number N of layers applied, and the type of substrate used were found to hold reasonably well. In particular, the unusual forms of the predicted dependence upon $(Et)^{1/4}$ and upon $G_a^{3/4}$ appear to be correct. Thus, the pull-off experiment appears to be a simple way of characterizing both the energy G_a required for detaching an adhesive tape at small angles and the effective tensile stiffness of the tape. Moreover, it resembles many service applications of pressure-sensitive tapes. If a tape stretches too much, so that the angle θ becomes unreasonably large (greater than about 30°, say) then two or more layers of tape can be applied and pulled off together. In some instances it was found that the layers did not adhere to each other as well as they adhered to the substrate; the multilayer method is then not a feasible way of reducing θ to sufficiently small values and the parametric solutions for F must be employed.

This work forms part of a program of adhesion research at The University of Akron supported by the Adhesive and Sealants Council. Additional support by the Office of Naval Research (Contract N00014-85-K-0222) is gratefully acknowledged. The authors are also indebted to Professor Roger Fosdick, Department of Aerospace Engineering and Mechanics, University of Minnesota, for helpful discussions on nonlinear elastic behavior.

References

1. R. S. Rivlin, *Paint Technol.*, **9**, 215 (1944).
2. E. J. Ripling, S. Mostovoy, and R. L. Patrick, *Materials Res. Stand.*, **4**, 129 (1963).
3. B. M. Malyshev and R. L. Salganik, *Int. J. Fracture Mech.*, **1**, 114 (1965).
4. M. L. Williams, Proc. 5th U.S. Natl. Congress on Applied Mechanics, Minneapolis, June, 1966, ASME, New York, 1966, p. 451.
5. A. N. Gent and A. J. Kinloch, *J. Polym. Sci., Part A-2* **9**, 659 (1971).
6. K. Kendall, *Proc. Roy. Soc. Lond.*, **A344**, 287 (1975).
7. A. Ahagon and A. N. Gent, *J. Polym. Sci.: Polym. Phys. Ed.*, **13**, 1285 (1975).
8. K. Kendall, *J. Phys. D: Appl. Phys.*, **8**, 512 (1975).
9. R. J. Chang and A. N. Gent, *J. Polym. Sci.: Polym. Phys. Ed.*, **19**, 1619 (1981).
10. M. L. Williams, *J. Appl. Polym. Sci.*, **13**, 29 (1969).
11. K. Kendall, *J. Materials Sci.*, **11**, 638 (1976).
12. G. P. Anderson, S. J. Bennett, and K. L. DeVries, *Analysis and Testing of Adhesive Bonds*, Academic Press, New York, 1977.
13. A. N. Gent, G. S. Fielding-Russell, D. I. Livingston, and D. W. Nicholson, *J. Materials Sci.*, **16**, 949 (1981).
14. R. V. Southwell, *An Introduction to the Theory of Elasticity*, 2nd ed., Oxford University Press, London, 1941, p. 19.
15. A. N. Gent and G. R. Hamed, *J. Appl. Polym. Sci.*, **21**, 2817 (1977).

Received January 14, 1986
Accepted February 14, 1986