Static Versus Dynamic Evaluation of Cushioning Properties of Plastic Foams

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Synopsis

The protective properties of several plastic foams, represented by cushioning curves calculated from static stress–strain curves, were compared to those obtained in shock tests. It was found that the amount of energy absorbed in the two types of tests is almost the same, while the force applied to the product is about 30–50% higher in the dynamic test. Accordingly, the relatively simple static test may be used for choosing the most suitable foam for protection of a fragile product.

INTRODUCTION

In recent years significant expansion has taken place in use of plastic foams as protective packaging materials and they have successfully replaced rubberized hair, peanut hulls, and paper chips for the protection of fragile products. Much work, effort, and resources have been invested in characterization of the cushioning properties of these foams. The complete picture, however, should include shock and vibration transmissibility and compressive stress–strain curves, which necessitate highly sophisticated and costly equipment (apart from the volume of experimental work involved). In these circumstances only a limited number of materials have been evaluated and described, and in fact most of the available relevant literature is confined to polyurethanes (PUR)[1,2] and polyethylene (PE).[3] To remedy this shortage, attempts were made to predict the protective properties from relatively simple tests. For example, Meinecke and Schwaber[4,5] compared the energy-absorption characteristics of PUR and nitrile rubber foams as determined from compressive and pendulum-impact measurements; Rusch[6,7] studied the compressive behavior of several flexible and brittle foams; DeGisi and Neet[8] suggested equations for predicting the compressive strength and modulus of rigid PUR foams as a function of density and temperature.

The present authors, in earlier publications[9,10] proposed a method for evaluating the cushioning properties of plastic foams from compressive measurements. This method was applied to characterize PUR and urea–formaldehyde (UFA) foams, respectively. In this context, two parameters were defined:

(a) Energy absorption efficiency E, defined as the ratio of the energy absorbed by a real foam compressed to a maximum strain ϵ_m, and that absorbed by an ideal one which transmits the same maximum (but constant) stress σ_m to the product when fully compressed (see Fig. 1):

$$E = \frac{Ah \int_0^{\epsilon_m} \sigma \, d\epsilon}{Ah\sigma_m \times 1} = \frac{\int_0^{\epsilon_m} \sigma \, d\epsilon}{\sigma_m} \tag{1}$$

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Journal of Applied Polymer Science, Vol. 28, 135–143 (1983)
 CCC 0021-8995/83/010135-09$01.90

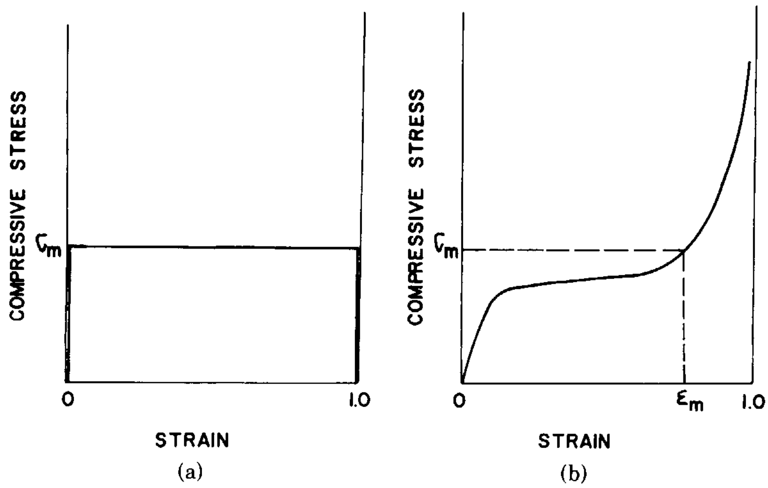

Fig. 1. Schematic stress–strain curves for (a) an ideal foam and (b) a real foam.

σ, ϵ, A, and h being stress, strain, cushion area, and thickness, respectively. Using eq. (1), E is obtainable from static (low strain-rate compressive testing) measurements.

(b) Ideality I, defined as the ratio of the energy absorbed by a real and an ideal cushion compressed to the same strain:

$$I = \frac{Ah \int_0^{\epsilon_m} \sigma \, d\epsilon}{Ah \sigma_m \epsilon_m} = \frac{\int_0^{\epsilon_m} \sigma \, d\epsilon}{\sigma_m \epsilon_m} \tag{2}$$

The parameters are seen to be related as follows:

$$I = E/\epsilon_m \tag{3}$$

The cushioning curves, usually representing dimensionless maximum deceleration (number of gs) G_m, vs. static stress are obtainable from the stress–strain curves as follows:

Assume that a body of weight W is dropped onto a foam cushion of the same area A from a height H. The cushion restrains the body while undergoing compression to a maximum strain ϵ_m under a maximum stress σ_m, and the kinetic energy absorbed in the process equals the initial potential energy of the body E_p. Disregarding the additional potential energy due to the compression of the cushion, we have

$$E_p = WH = Ah \int_0^{\epsilon_m} \sigma \, d\epsilon \tag{4}$$

The static stress generated in the cushion being W/A, we have

$$W/A = (h/H) \int_0^{\epsilon_m} \sigma \, d\epsilon \tag{5}$$

The dimensionless maximum deceleration G_m is given by

$$G_m = \frac{\sigma_m A}{mg} = \frac{\sigma_m A}{W} = \frac{\sigma_m A}{(Ah/H) \int_0^{\epsilon_m} \sigma \, d\epsilon} \tag{6}$$

or

$$G_m = \frac{\sigma_m}{\int_0^{\epsilon_m} \sigma \, d\epsilon} \frac{H}{h} \tag{7}$$

For a foam with a given stress–strain curve, the value of ϵ_m for any static stress, cushion thickness, and drop height is obtainable with the aid of eq. (5) and a simple computer program. Since ϵ_m determines σ_m for a specific foam, G_m can be calculated from eq. (7), and thus the cushioning curve is obtained.

Combining eqs. (1) and (7), we have

$$E = \frac{1}{G_m} \frac{H}{h} \tag{8}$$

which is the dynamic counterpart of (1), yielding E by means of shock testing. The dynamic stress is obtainable as

$$\sigma_m = (W/A) G_m \tag{9}$$

The experimental part consisted in evaluating the cushioning properties of several plastic foams by the two modes of testing and comparing the results.

EXPERIMENTAL

Materials

A total of five locally manufactured foam brands (for properties, see Table I) were studied: One flexible polyurethane foam (designated PUWN) and two semirigid bonded polyurethane chipfoams (designated PUBP and PUOP)—all of them polyether-based and supplied by courtesy of Caesarea Polymers Ltd.—and two urea–formaldehyde foams (designated UFA-1 and UFA-2) supplied by courtesy of Carmel Insulation Ltd. 10 × 10 cm specimens of varying thickness (see once again Table I) were used.

TABLE I
Properties of Studied Foams

FOAM[a]	Density (g/cm^3)	Cell diameter (cm)	Chip size (cm)	Modulus (kg/cm^2)
PUWN[(1)]	0.026	0.03	—	1.27
PUBP[(2)]	0.135	0.04	0.5 × 0.3	1.02
PUOP[(3)]	0.235	0.03	0.3 × 0.1	5.88
UFA-1[(4)]	0.017	0.005	—	10.60
UFA-2[(4)]	0.021	0.005	—	10.60

[a] Foam thicknesses (cm): (1) 2.5, 5.1, and 10.1; (2) 1.2, 1.9, 3.1, and 4.3; (3) 1.3, 2.3, 3.3, and 4.3; (4) 2.9, 4.9, and 6.8.

Methods

Static testing was carried out in the compression cage of a J.J. Lloyds (U.K.) apparatus at a strain rate of 2%/s. No difference in results was found in tests carried out at strain rates, in the range of 0.5–4%/s.

Dynamic testing was carried on an MTS (Model 36) shock tester, with the desired static stress in the specimen produced by means of combinations of modular cylindrical weights equal in diameter to the diagonal of the former. The loaded tester table was dropped from different heights (verticality ensured by a special device) onto a 2-ms semisinusoidal programmer, and the deceleration was measured by means of an accelerometer (mounted on the top of the weight stack) and recorded on an oscilloscope. At least 5-min relaxation was allowed between consecutive drops of the same specimen, and a new specimen was used for the final drop height of the series to obliviate a possible history effect. Each stress level and drop height was tested in at least two replicates, and the values reported are averages.

RESULTS AND DISCUSSION

Polyurethane Foams

Representative cushioning curves for the three brands are shown in Figures 2–7, the solid lines referring to data calculated from static measurements by means of eqs. (5) and (7), and the dashed lines to recordings from the dynamic tests.

It is seen that the pairs of curves are in good agreement at small drop heights, especially for the larger thicknesses. Moreover, the minima in each pair—at which G_m is lowest i.e., the efficiency as per eq. (1) is maximum—correspond almost to the same static stress level. This result supports the authors' earlier conclusion[9,10] that the static stress–strain curves permit choice of the most efficient foam for a specific product. At larger drop heights the measured curves lie higher (i.e., correspond to a higher G_m level) but the similarity of the pair

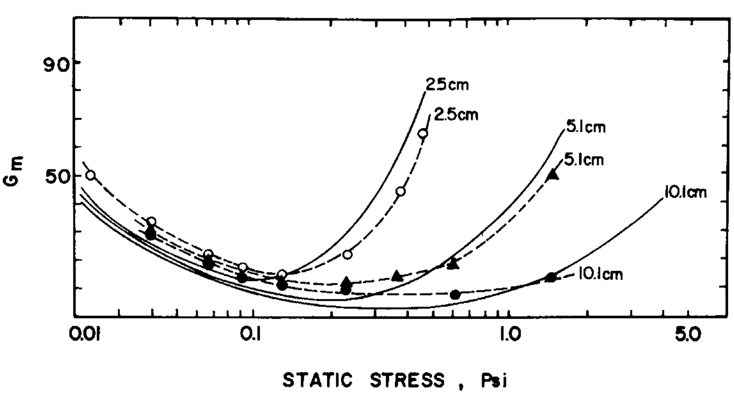

Fig. 2. Effect of static stress on peak deceleration; comparison of dynamic (measured) (---) and static (calculated) (—) results for foam PUWN. H = 15 cm.

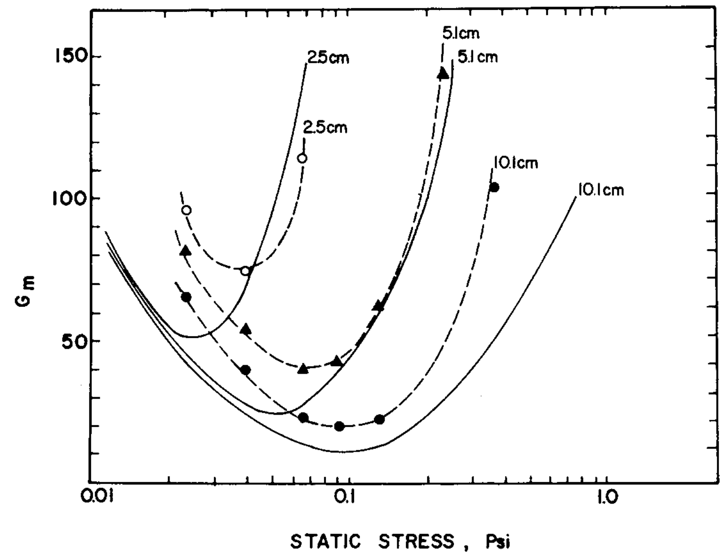

Fig. 3. Effect of static stress on peak deceleration; comparison of dynamic (measured) (---) and static (calculated) (—) results for foam PUWN. H = 61 cm.

relative to the stress axis is preserved. In these circumstances, the stress–strain curve may be used to yield, as well, the amount of energy absorbed by the foam under dynamic loading, since this energy is proportional to the static stress. (This will be also shown later in a different way.)

The relatively higher stress levels under dynamic loading (maximum difference

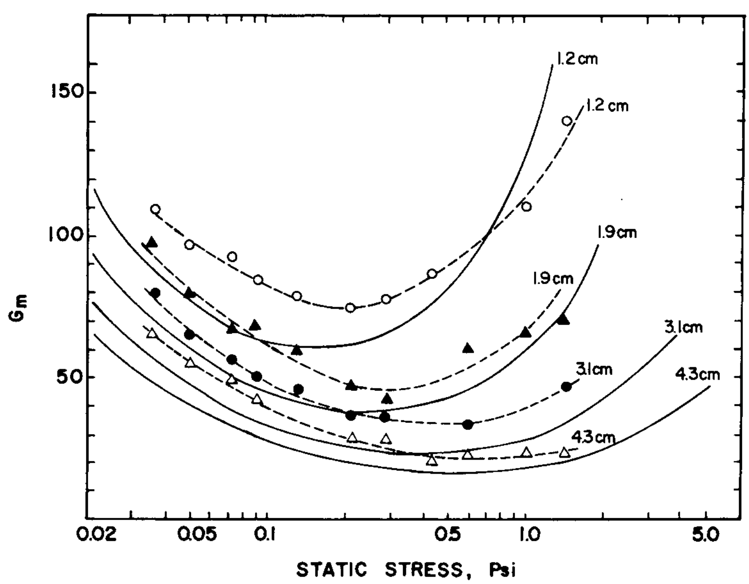

Fig. 4. Effect of static stress on peak deceleration; comparison of dynamic (measured) (---) and static (calculated) (—) results for foam PUBP. H = 15 cm.

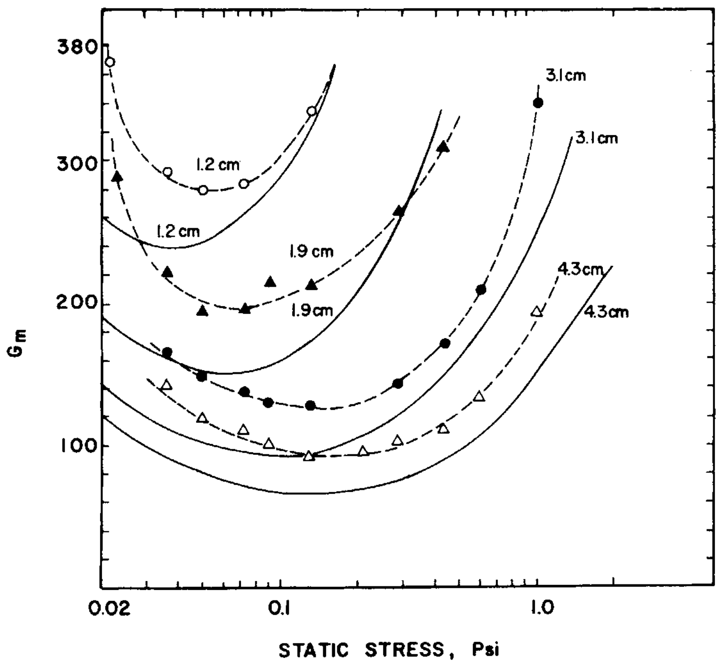

Fig. 5. Effect of static stress on peak deceleration, comparison of dynamic (measured) (---) and static (calculated) (—) results for foam PUBP. H = 61 cm.

observed, 30–50%) are attributable to differences in the air-flow pattern in the two types of experiments, and perhaps to some dependence on the strain rates. Although no such dependence was observed within each narrow range of rates (0.5–4%/s in the static measurements and 500–3000%/s in the dynamic ones) used in the present study, yet the difference in order of magnitude may be reflected

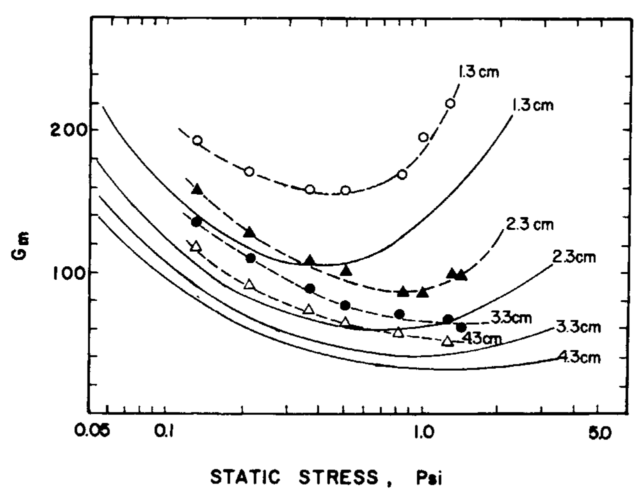

Fig. 6. Effect of static stress on peak deceleration; comparison of dynamic (measured) (---) and static (calculated) (—) results for foam PUOP. H = 30 cm.

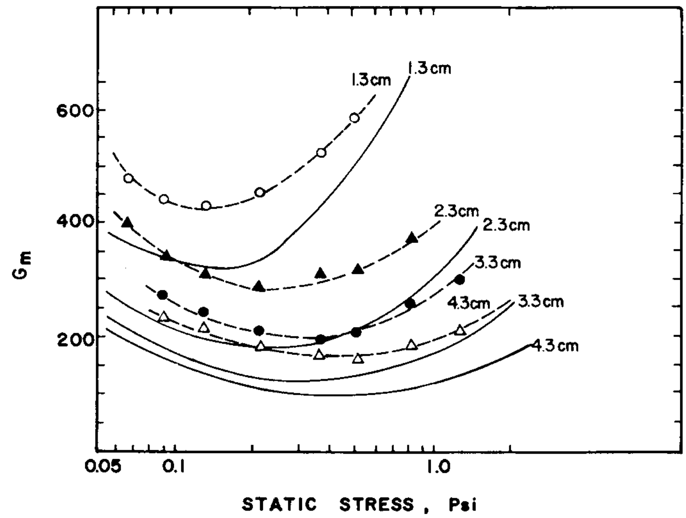

Fig. 7. Effect of static stress on peak deceleration, comparison of dynamic (measured) (- - -) and static (calculated) (—) results for foam PUOP. $H = 91$ cm.

in the results; moreover, whereas in the static measurements the strain rate is constant, in the dynamic ones it varies from very high at the onset of the shock to zero at its termination. This will be the subject of a separate publication.

The discrepancy between the calculated and experimental curves widens as thickness decreases. For a combination of very small thickness and very large drop height (not reported here), the correspondence along the stress axis is also disrupted, apparently due to bottoming of the foam during the shock tests.

An alternative mode to compare the static and dynamic experiment is by

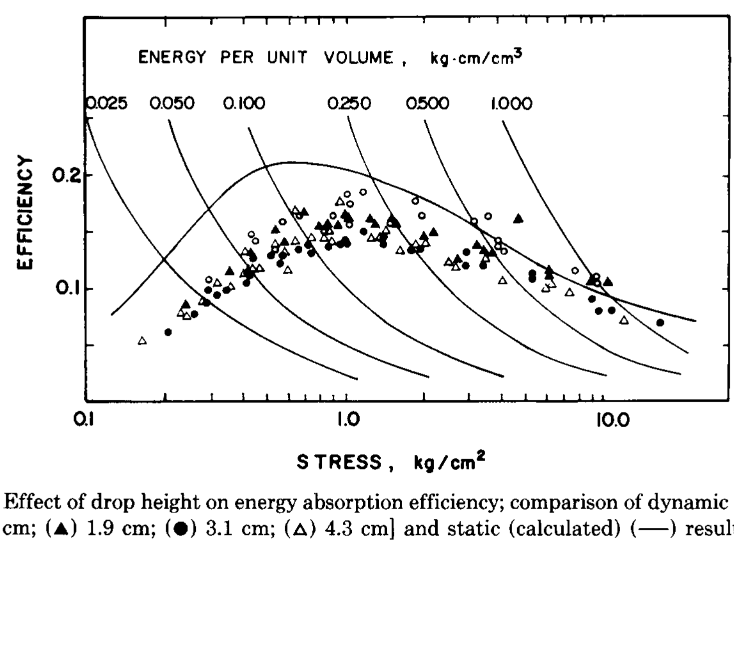

Fig. 8. Effect of drop height on energy absorption efficiency; comparison of dynamic (measured) [(○) 1–2 cm; (▲) 1.9 cm; (●) 3.1 cm; (△) 4.3 cm] and static (calculated) (—) results for foam PUBP.

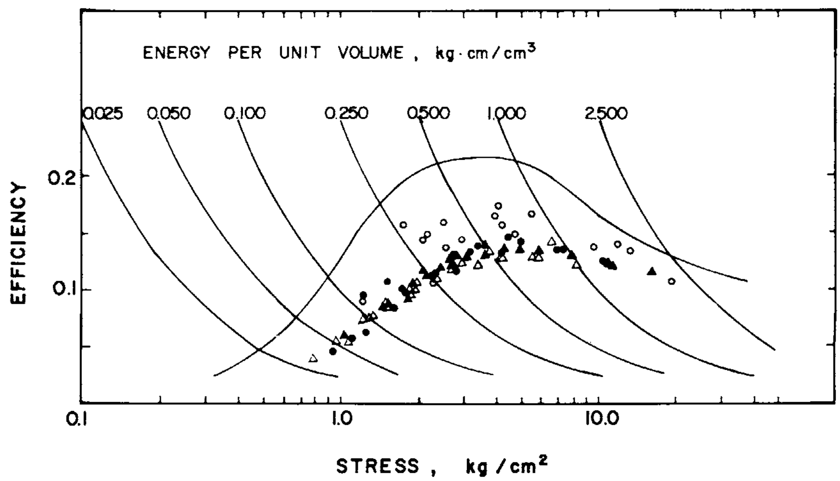

Fig. 9. Effect of drop height on energy absorption efficiency; comparison of dynamic (measured) [(○) 1.3 cm; (▲) 2.3 cm; (●) 3.3 cm; (△) 4.3 cm] and static (calculated) (——) results for foam PUOP.

plotting E versus the dynamic stress as suggested earlier.[9,10] This mode of comparison is illustrated in Figures 8 and 9 for PUBP and PUOP, respectively, and the diagrams contain also constant energy contours as per Ref. 9. It is seen that in this case the calculated curves from compressive measurements predict higher efficiencies while the correspondence relative to the stress axis is again preserved. The energy absorption at maximum efficiency is also similar in both types of experiments.

Urea–Formaldehyde Foams

In principle, the results obtained for the UFA foams were similar to those of

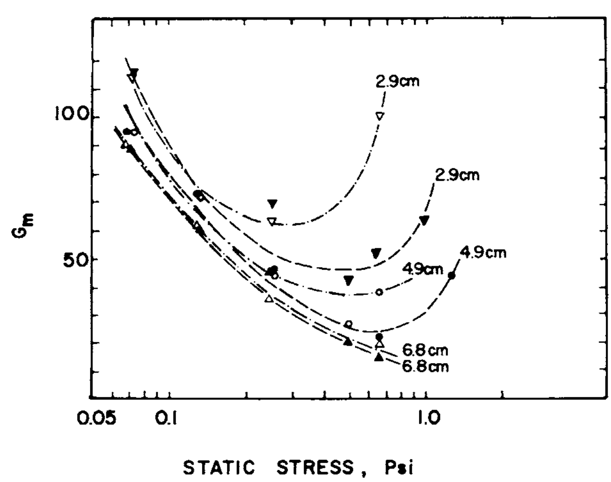

Fig. 10. Comparison of peak deceleration transmitted by urea–formaldehyde in first (- - -) (▼, ●, ▲) and second (-·-·-·) (▽, ○, △) consecutive drops. H = 30 cm.

their PUR counterparts. However, whereas the PUR foams return to their original size and properties after each shock if a sufficient relaxation period is allowed, the UFA foams show an irreversible deformation (permanent set) after each shock experiment.

Representative cushioning curves for two consecutive drops of the UFA foams are shown in Figure 10. It can be seen that the force transmitted in the second drop is larger than in the first, the difference increasing as thickness decreases. This result stems from the fact that UFA is a brittle foam, and in each shock experiment a part of its cells are ruptured, resulting in a gradual change in properties.

In conclusion, the present study shows that plastic foams absorb almost the same amount of energy in a static and a dynamic test, the force that the foam applies to a packaged product in the latter (as a result of free fall) being 30–50% higher than the one predicted from static measurements. Accordingly, the relatively simple static test may be used for choosing the most suitable foam for protection of a fragile product.

The financial support of this project by the Israeli National Council for Research and Development is greatly appreciated.

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Received November 12, 1981
Accepted July 19, 1982