Behavior of Elastomeric Bearing Pads Under Simultaneous Compression and Shear Loads

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A study of elastomeric bearing pad performance was conducted on laboratory-size test pieces but under conditions which approached as nearly as feasible the cyclic shear conditions found on actual structures rather than the initial shear conditions of currently published investigations. It is shown that the current definition of shear modulus is not applicable to elastomeric materials. A simple formula is developed and the constants are determined by which a satisfactorily close approximation of the stress/strain curve can be reconstituted mathematically. The parameters that affect such curves were found to be testing rate, degree of strain, and previous deformation history of the sample. Other parameters such as grain direction and shape factors of less than unity are suspected of affecting these curves but present study was not conclusive. With a knowledge of the effects of these parameters and a stress/strain curve established by a standard procedure, it is possible to compute pier shear forces as the engineering problem dictates.

•PRACTICAL KNOWLEDGE of shear/strain curves, their composition, derivation, and interpretation with a knowledge of the factors which influence deviations from these curves and the extent of such deviations is essential to intelligent elastomeric bridge pad design. The response of elastomers to external force is not the same as the response of other construction materials. This difference can lead to erroneous and costly conclusions unless the difference is recognized by the engineer and the pad is designed accordingly.

OBJECTIVE

The objective of the current investigation was to determine the shear strain characteristics of molded neoprene slabs on laboratory-size test pieces and as far as possible to interpret such results in terms of design performance. The properties primarily investigated were the characters of the compressive and shear stress/strain curves (hereinafter referred to as the compression and shear curves, respectively). Other properties investigated were the effect of shape factor, hardness, grain direction, variable cyclic loading and loading rate.

METHOD

The method of investigation consisted of cutting laboratory test samples from sheet stock submitted by various suppliers and subjecting these samples to the tests indicated. The maximum size of sample that could be accommodated in the current test equipment was 3 by 3 in. All compression and shear deformation rates were 0.05 in./min unless otherwise stated.

In general, the method employed was to cycle the samples in compressive deformation to reproducibility at 500-psi compressive stress and then, while maintaining this

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compressive load, to cycle the samples in shear deformation, alternately in both a positive and a negative direction from this initially compressed position to a numerical distance equal to one-half, or other stated factor, of the original uncompressed thickness. A standard method of test was developed and is included as Appendix B.

EQUIPMENT

The equipment consisted of a shear modulus device similar in design to the Maguire machine (1) with 4- by 4-in. steel compression heads and a steel drawplate. The compression heads and drawplate were machined, ground, and polished in the earlier investigations, but knurled (40 lines to the inch) heads and plate were substituted in the later work. Four dial gages were used to determine pad compressed thickness, one dial on each side of each pad. The average of the readings of the two dials on the opposite sides of each pad was taken as pad compressed thickness. Vertical deformations were produced by mounting the shear modulus device in a twin-screw Tinius Olsen universal testing machine of 20,000-lb capacity.

One dial gage, centered on the draw axis, was used to determine shear deformation, accomplished with a double-acting hydraulic cylinder. Rate of shear loading was controlled by a needle valve which controlled the rate of fluid feed to the hydraulic cylinder. Shear forces in the positive shear direction were measured with a tension ring. Compression rings were not available; therefore, shear forces in the negative shear direction were not measured.

COMPRESSION CHARACTERISTICS

Figure 1 is a typical compression curve. Line abc represents the initial cycle. It originates at the origin, a, and proceeds to the maximum, b, along line ab. The unloading portion is represented by line bc. The curve of the second cycle originates at point c, proceeds to d at maximum load, and returns to e when unloaded. Succeeding cycles follow a similar pattern. The increment of increase in both the maximum compressive strain and the compressive strain at zero load decreases with each succeeding cycle until eventually the cycles reproduce. For the purpose of this study, all

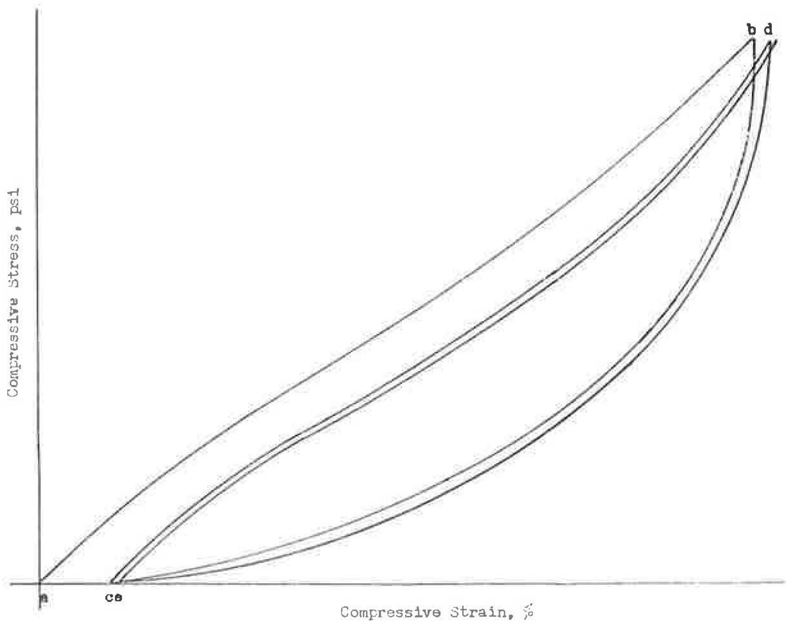

Figure 1. Typical compression curve.

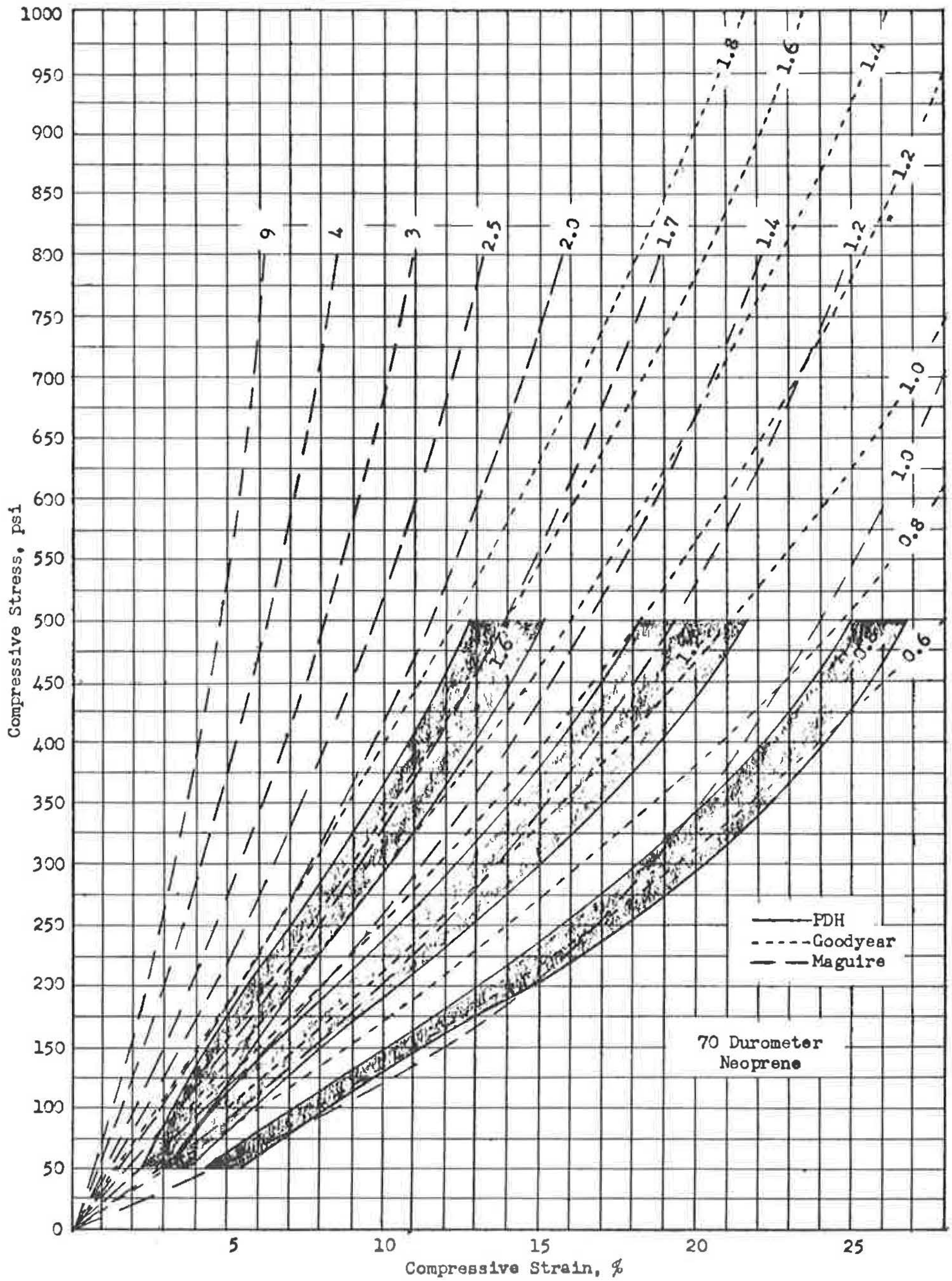

Figure 2. Composite compression curves.

samples were cycled in compressive loading to reproducibility before shear loading to minimize the effects of stress relaxation and creep.

Figure 2 is a composite of the loading portions of the reproducible compression curves of 74 durometer neoprene compressed to 500-psi stress each cycle. The solid line on either side of each shape factor designation represents the high and low value obtained at that shape factor. Values from the literature (1, 2) are plotted for comparison. Compressive deformation values are in some measure dependent on the condition of the compressing surfaces (2): the smoother the surface, the higher the deformation values. The Goodyear values were based on bonded samples presumably compressed to 1,000 psi. The Maguire values (1) were obtained on concrete and steel surfaces and were compressed to 2,000 psi.

In general, it was found that the area of the compression diagrams increased with percent compressive strain; i.e., lower shape factor or softer materials gave greater hysteresis curves (Figs. 3 and 4). It was also found that ff', the relative energy loss between the input and recovery portions of the hysteresis curves, was independent of the shape factor and hardness per se but dependent on the testing rate if the testing rate exceeded the recovery rate. Recovery rates were exceedingly low; consequently, practical testing rates were always greater than the recovery rates. Therefore, the value of ff' was dependent on the difference between these two rates and increased as the difference increased. In addition, ff' was dependent on surface condition; the smoother the compressive surfaces, the greater the freedom of compressive expansion and corresponding increase in the hysteresis curve.

The effect of increasing the maximum value of the cyclic load is illustrated in Figure 5. Line ab represents the loading portion of the initial cycle to 250-psi compressive stress; line bc represents the unloading portion. Line $\overline{cd}$ represents the loading portion of the reproducible cycle to 250-psi compressive stress, and line $\underline{dc}$ represents the unloading portion. Line cde represents the loading portion of the initial cycle to 500-psi compressive stress, as well as the loading portion $\overline{cd}$ of the reproducible cycle to 250-psi compressive stress plus its extension de. Such a cycle whose maximum compressive stress is different from the maximum compressive stress of the previous cycle is referred to as a transition cycle. Line ef represents the unloading portion of the transition cycle to 500-psi compressive stress. Line $\overline{fg}$ represents the loading portion of the reproducible cycle to 500-psi compressive stress, and line $\underline{gf}$ is the unloading portion. Each successively increasing increment of compressive stress follows a similar pattern with the additional loading portion of the curve of the transition cycle being an extension of the reproducible loading portion of the previous loading and with

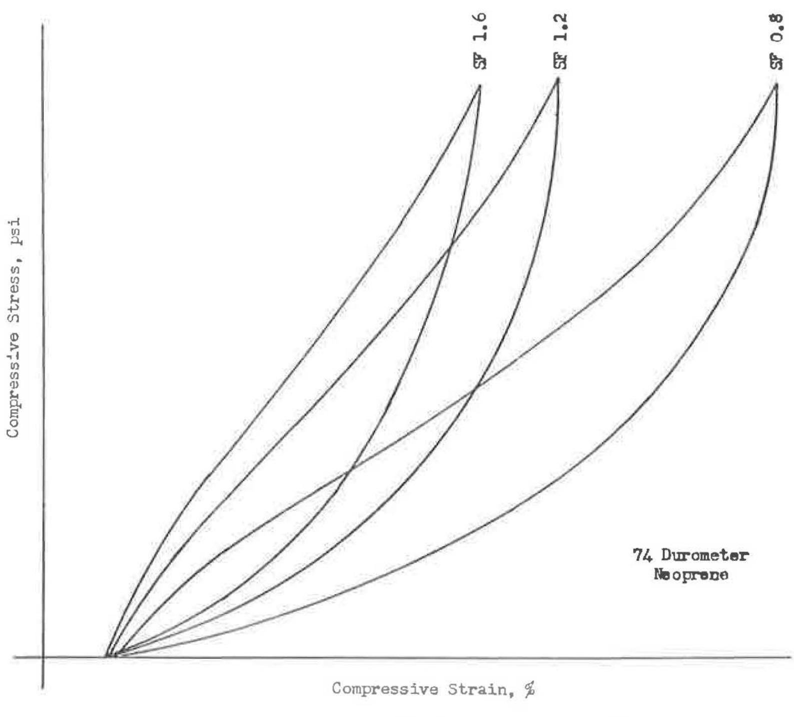

Figure 3. Effect of shape factor on compression curves.

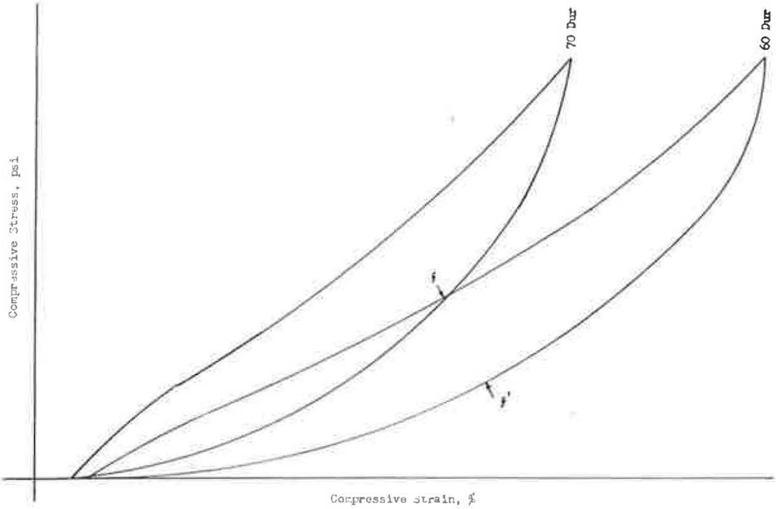

Figure 4. Effect of hardness on compression curves.

the reproducible curve falling below the transition curve. From this it can be seen that cyclic compression curves are dependent on the maximum load at which cycled; therefore, the maximum stress values must be stated when such curves are presented.

The effect of decreasing cyclic load is illustrated in Figure 6. Line $\overline{aba}$ represents the loading portion of the reproducible cycle of the maximum compressive stress at which cycled (in this case, 1,750 psi). Line $\overline{aca}$ represents both the transition and the reproducible loading portions of the cycle at the next succeeding decreasing increment of load (1,500-psi compressive stress), line $\overline{ada}$ at the next increment, etc. In all cases, the loading portion of the curve follows the curve of the maximum cyclic load to which the sample was compressed and does not return to the loading portion of the corresponding reproducible curve for increasing loads from Figure 5. From this it follows that compression curves are dependent on the previous compressive history of the sample (3).

The effect of loading amplitude is illustrated in Figure 7. By loading amplitude is meant the difference between the minimum and maximum compressive stress of any one cycle. A sample may be loaded in a single increment from the minimum to the maximum compressive stress on each cycle as illustrated in Figures 1, 3 and 4, or it may be loaded in successively changing increments as illustrated in Figure 5. The first type of loading is referred to as a single increment cycle and the second type of loading is a multiple increment cycle. The dotted line ab is a plot of the maximum values obtained from the transition curves of a uniformly increasing incremental compression similar to that illustrated in Figure 5 and as determined by points a, b, e, etc. The dotted line cd represents the maximum incremental reproducible values as determined by points c, d, g, etc. The solid line ae represents the loading portion of the actual initial cycle of a duplicate sample of the same material loaded from zero to maximum in a single increment. The solid line fg represents the loading portion of the actual single increment reproducible cycle and is identical with the loading portion of the final increment of the multiple increment reproducible cycle as represented by xy (Fig. 5).

It is apparent from Figure 7 that small, uniformly increasing loading has a stiffening effect on elastomers. Line ae should initially follow line ab and then deviate to the left. This deviation is proportional to the time differential required by the two testing methods to reach the same point being compared because elastomers take a permanent set under load and this set increases with loading time. Line ae is initially less than ab and remains so for a substantial length of the curve. The low rate of testing was

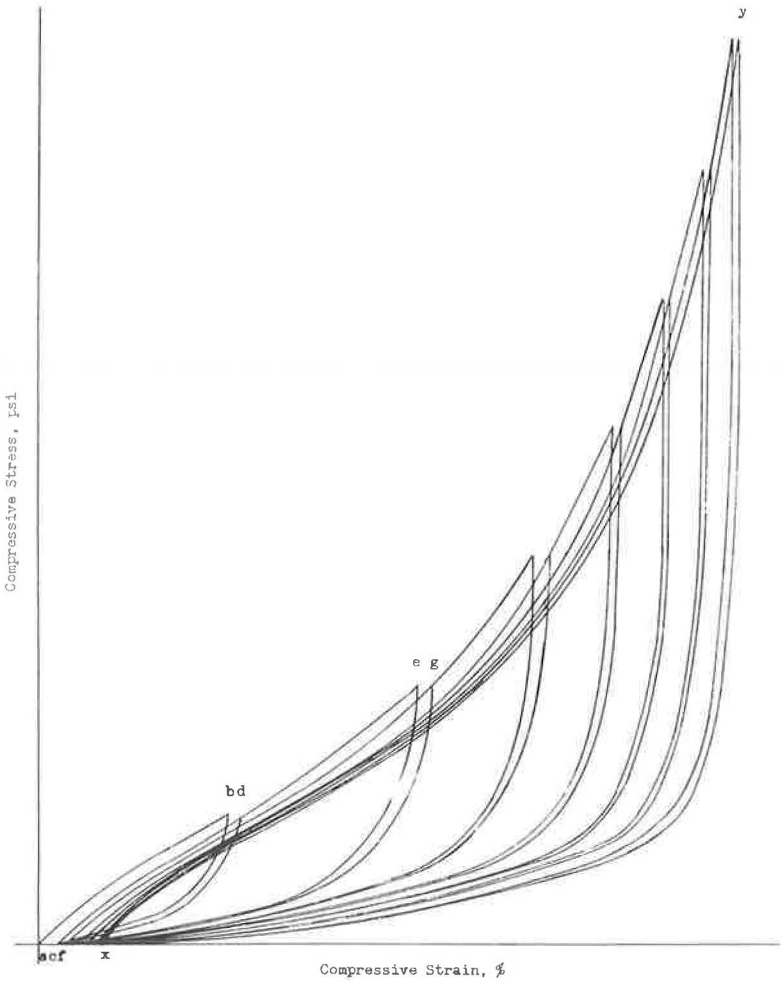

Figure 5. Effect of increasing compressive loads.

insufficient to produce any heat buildup in the samples; thus, this stiffening cannot be accounted for by the Joule effect. This increase or stiffening in ab can only be explained by some other phenomenon associated with the mechanical working of the sample.

The fact that the loading portion of the single increment reproducible curve is identical with that of the final multiple increment reproducible curve is encouraging. In fact, not only were the loading portions of the curves identical, but the entire hysteresis loops were also identical; this means that although compression curves are dependent on previous compressive history of the sample, they are dependent only on the previous maximum values and not on the sequence in which the maximums are obtained.

Successive determinations of percent compression on the same sample often give progressively smaller values for percent compression with each determination (all calculations based on original uncompressed thickness). This may be another manifestation of the same stiffening due to mechanical working previously indicated.

It must be pointed out that this study was made entirely under compressive loads. A true study of the compressive character of an elastomer should be made on a tension/compression diagram wherein the sample is stretched as much in one direction as it is compressed in the other. However, the study herein presented is valid for the

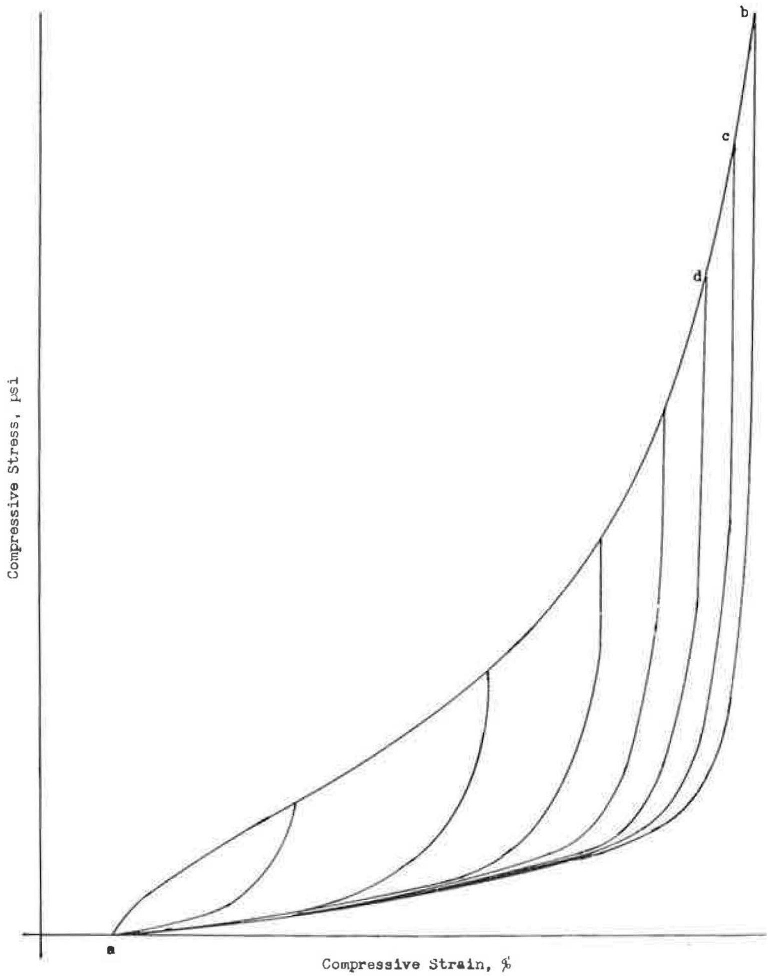

Figure 6. Effect of decreasing compressive loads.

intended application because only compressive loads varying from zero to maximum will be encountered and it is the cumulative effects of this continual compression that must be evaluated.

SHEAR CHARACTERISTICS

Typical shear curves were of two types. Figure 8 is typical of the first type. The portion above the horizontal axis is under positive shear load and the portion below the horizontal axis is under negative shear load. Line abcde represents the initial cycle. It originates at the origin, a, and increases to b along the line ab which represents the positive loading portion of the first cycle. The unloading portion is represented by line bc. At point c, the positive shear load becomes zero and the negative shear load is applied. The negative loading portion of the cycle is represented by line cd. The negative unloading portion is represented by de which completes the initial cycle.

The stress values of the negative loading could not be determined with present equipment, but the value of D/T at maximum negative load was determinable since D is deformation and T is compressed thickness at D deformation (Appendix A), both of which can be measured; therefore, the dotted lines were plotted to indicate the extent to which samples were cycled.

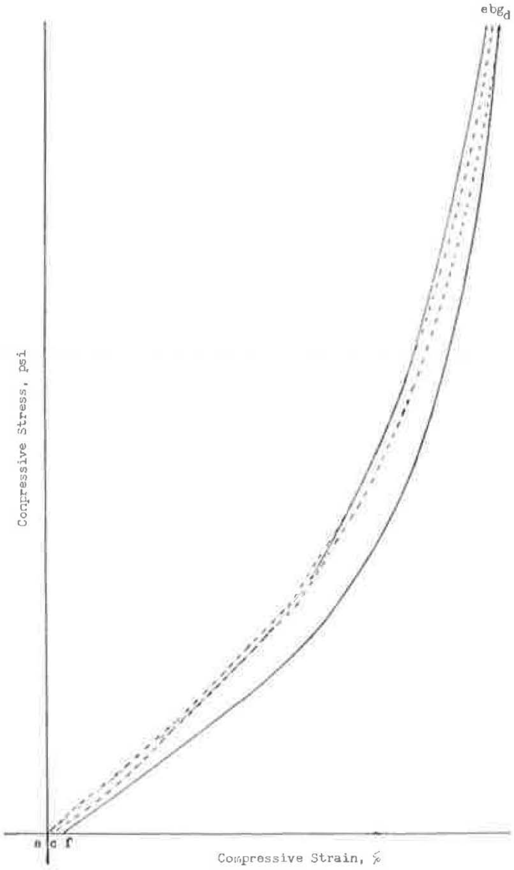

Figure 7. Effect of loading amplitude.

The second cycle is represented by the curve efghi. Succeeding cycles approach the curve ijklm with the following characteristic trends: (a) point f becomes increasingly greater along both axes; (b) a portion of ef approaches linearity and this linear portion increases with each cycle; and (c) the incremental increase in the values of f as well as the increase in the linear portion of ef becomes less with each cycle until eventually succeeding cycles reproduce. The curve ijklm represents the reproducible cycle. Unless otherwise stated, all shear computations are made from values taken from these reproducible cycles.

The characteristics of Type 1 shear curves are as follows:

1. The curve of the initial cycle is not linear over any portion of its path.
2. The horizontal (shear) force transmitted to the piers at any given deformation is greater for the same deformation on the second and succeeding cycles than on the initial cycle.
3. If the bearing pad is once deformed, there always remains a residual shear force on the pier at zero horizontal deformation.
4. The reproducible shear curves approach linearity over that portion of the curve from D/T = 0 to a point at which the sample starts to slip (within the limits herein investigated) but do not pass through the origin. With equipment capable of obtaining negative as well as positive loading values from maximum negative position to maximum positive position, and vice versa, on continuously loaded cycles at uniform loading rate, it is expected that the linear portion would begin well into the negative portion of the curve and continue to the positive maximum.
5. As with compression deformations, the hysteresis curves for shear deformations and the values computed from these curves are dependent on testing rate, if rate of shear exceeds recovery rate.
6. The slope of the curve, and again the values computed therefrom, are dependent on the degree of deformation at which cycled and on the previous deformation history of the sample.
7. Deformations in direction of the grain give more uniform values than those computed from cross-grain deformations.

This type of curve is in agreement with the work of Wilkinson and Gehman (4).

The second type of shear curve is represented in Figure 9. In this type, the curves of the second and succeeding cycles lie very near the curve of the initial cycle and may quite often undercut the curve of the initial cycle. The curve of the initial loading cycle may even approach linearity over a portion of its length. This type of curve is in agreement with the Maguire report (1). The curves from the Maguire report are essentially linear after the first 10 to 20 percent deformation. In this type of curve, the curve of the second cycle will approach linearity, but normally the slope will be less than that of the curve of the initial cycle. With each succeeding cycle, the slope of the

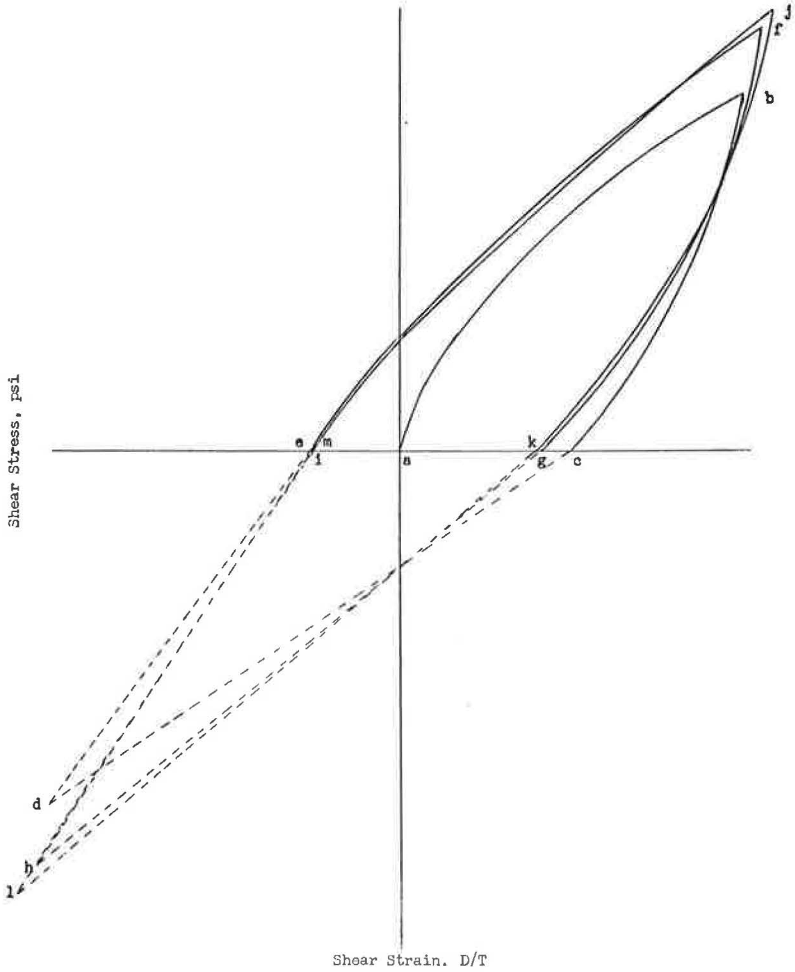

Figure 8. Typical shear curve, Type 1.

curve decreases, but the amount of decrease becomes less and less until the cycles eventually reproduce. The shear force transmitted to the piers is greatest on the first cycle, except for those small deformations of the initial cycle in the vicinity of zero deformation. Other curve characteristics are similar to the first type of curve.

The effect of increasing the cyclic load is illustrated in Figures 10 and 11. Figure 10 represents a sample that conforms to a typical curve of the first type of material and Figure 11 represents a sample that conforms to a curve of the second type. In both types, as with compressive strains, the transition curves are extensions of the previous reproducible curves. The differences between the two are as follows:

1. In the first type the extensions are curved lines, and in the second type the extensions approach straight lines, providing the increments of load increase are moderate. With large load increments, the extensions for the second type of material are not entirely linear.

2. In both types, the slopes decrease with increased strain and the stress axis intercepts at D/T = 0 increase. The effect of the change in slope is that in the first type of material, the deviation is greater at strain D/T = 0; in the second type of material, the deviation is greater at strain D/T maximum.

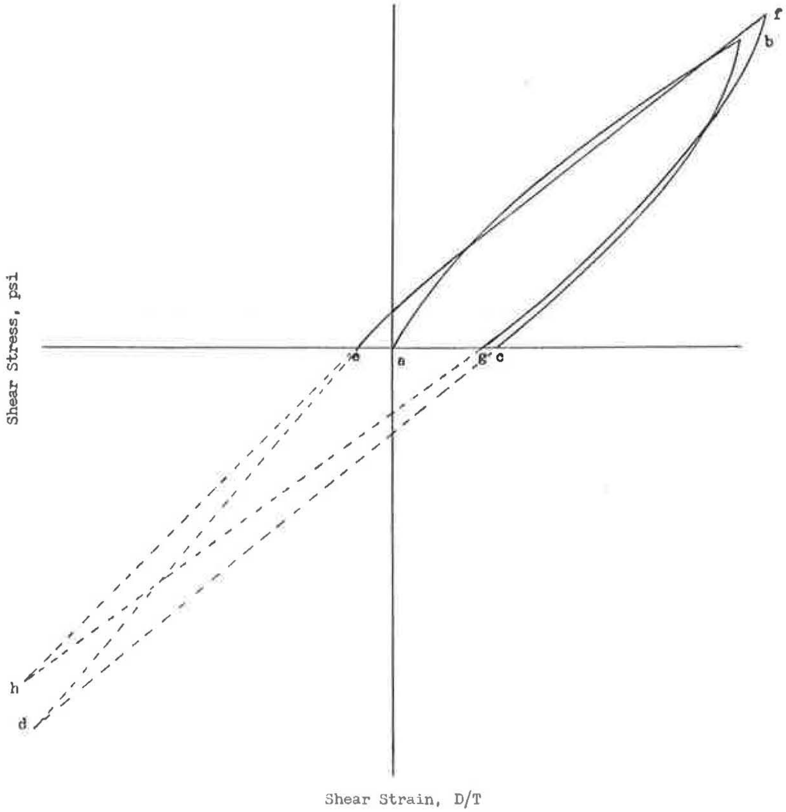

Figure 9. Typical shear curve, Type 2.

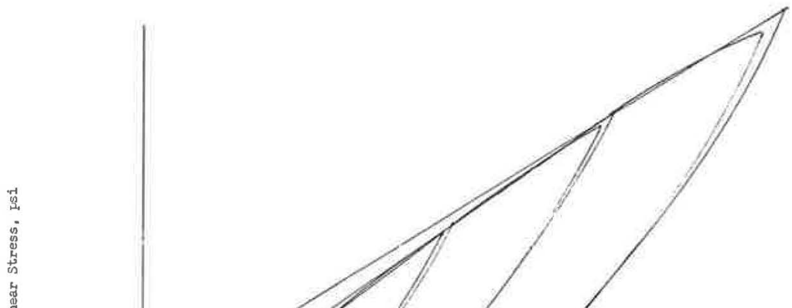

Figure 10. Effect of increasing shear loads.

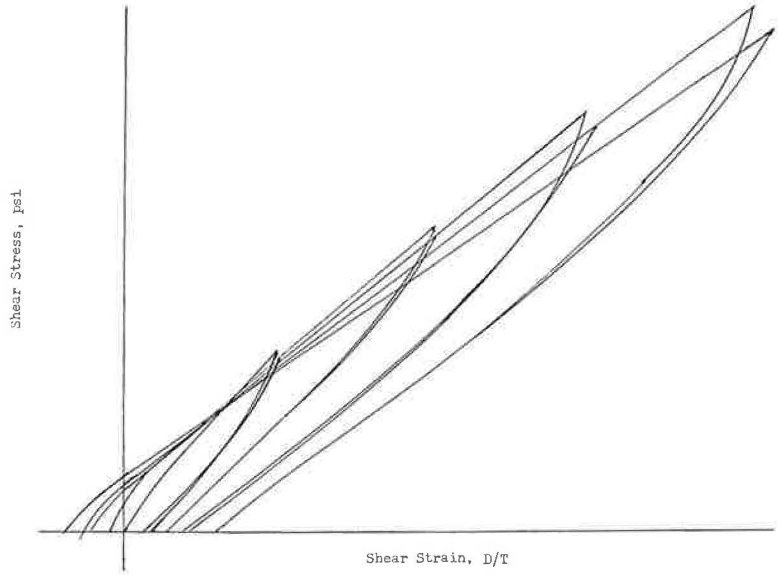

Figure 11. Effect of increasing shear loads.

The effect of decreasing cyclic loads in both types of curves is similar to that obtained with compression curves in that the curves do not return to the corresponding reproducible curves for increasing loads from Figures 10 and 11, nor do they follow the cyclic load curve for maximum stress. The curves lie between these two values. This is probably due to the completely reversible cycling (both positive and negative) and not to a higher recovery rate in shear as compared to compression. Once again the values obtained are dependent on the previous history of the sample, but with complete reversibility technique this difference is reduced.

The effects of shear loading rate, hardness, shape factor, and grain direction can be estimated from Table 1. The effect of shear loading rate is immediately apparent and is one of the most critical parameters of the method of test. Many of the variations in Table 1 are directly attributable to fluctuations in shear loading rate. This is especially true on small samples (SF less than 1.0). The numerical data given in Table 1 also illustrate the apparent stiffening of the sample under stepwise increases in stress.

In general, at the same strain, samples with higher durometer hardness have higher stress values, but the deviations at any one hardness are greater than the average differences between samples at two separate hardnesses (60-70 durometer). Therefore, stress cannot be estimated from durometer values.

There are indications that grain direction has an influence on stress values. At least the variations in stress values with shape factor are not as pronounced in one direction as in the other. Where grain direction has been identified, the "with grain" has been the more stable. However, this may be an indirect result of loading rate control because "with grain" deformations and the larger samples were found to be the easier to control.

The effect of testing temperature was not evaluated. These tests were made during a time span of more than one year and were made at the prevailing room temperatures.

DEFINITION OF SHEAR MODULUS FOR ELASTOMERS

Modulus in general is defined as unit stress per unit strain:

$$\text{Modulus} = \frac{\text{Stress}}{\text{Strain}} \qquad (1)$$

TABLE 1

Sample	Size (in.)	SF	Direction of Shear	Run	Head	(%) Shear	f	k	λ	M_r	M_i
					(a) BH-36509, Type 1, 74 Durometer						
3/4	3 × 3	1.57	w/g	1	M	50	-	-	-	-	-
				2	M	50	80.6	21.6	118.0	161.2	-
				3	M	25	53.0	12.0	164.0	212.0	-
						50	84.0	22.2	123.6	168.0	-
						25	51.5	12.6	155.6	206.2	-
13/14	3 × 1	0.77	w/g	1	M	50	-	-	-	-	-
				2	M	50	90.9	32.7	116.4	181.8	-
1/2	3 × 3	1.57	c/g	1	M	50	-	-	-	-	-
				2	M	50	79.0	24.4	109.2	158.0	-
				3	M	25	55.0	11.7	173.2	220.0	
						50	81.2	20.0	122.4	162.4	-
						25	48.9	7.6	165.2	195.6	-
						50	93.8	18.1	151.4	187.6	-[a]
						50	76.8	15.9	121.8	153.6	-[b]
				4	M	12.5	28.8	2.4	211.2	230.4	-
						25	49.0	8.8	160.8	196.0	-
						50	79.4	20.7	117.4	158.8	-
						100	136.8	58.4	78.4	136.8	-
						50	87.0	34.6	104.8	174.0	-
5/6	3 × 3	1.54	c/g	1	M	50	83.4	29.0	108.8	166.8	148.1
				2	M	50	77.9	24.8	106.2	155.8	-
						25	-	-	-	-	-[c]
				3	M	50	81.6	24.9	113.4	163.2	-
7/8	3 × 2	1.23	c/g	1	M	50	-	-	-	-	-
				2	M	50	87.0	27.6	118.8	174.0	-
11/12	3 × 1	0.78	c/g	1	M	50	-	-	-	-	-
				2	M	50	97.7	35.7	124.0	195.4	-
					(b) BJ-29109, Type 2, 62 Durometer						
1/2	3 × 3	1.51	w/a	1	M	50	55.4	7.9	95.0	110.8	117.4
5/6	3 × 3	1.56	w/a	1	K	50	58.6	8.1	101.0	117.2	119.2
						100	94.8	19.5	75.3	94.8	-
				2	K	50	59.1	5.9	106.4	118.2	-
						100	98.4	12.4	86.0	98.4	-
7/8	3 × 3	1.54	w/a	1	K	25	34.6	2.8	127.2	138.4	-
						50	60.8	6.7	108.2	121.6	-
						75	80.6	10.0	94.1	107.5	-
						100	97.9	13.2	84.7	97.9	-
						75	77.0	10.8	88.3	102.7	-
						50	55.3	7.9	94.8	110.6	-
						25	31.3	5.2	104.4	125.2	-
9.1/10.1	2 × 2	1.06	w/a	1	K	50	53.8	8.9	89.8	107.6	111.4
9.2/10.2	3 × 1	0.79	w/a	1	K	50	61.6	10.8	101.6	123.2	129.4
3/4	3 × 3	1.52	c/a	1	M	50	53.7	6.6	94.2	107.4	113.3
9.3/10.3	2 × 1	0.71	c/a	1	K	50	53.9	11.3	85.2	107.8	110.4
					(c) BJ-29110, Type 1, 75 Durometer						
1/2	3 × 3	1.55	w/a	1	M	50	118.7	27.4	182.6	237.4	226.6
				2	M	50	120.1	30.3	179.6	240.2	-
						100	-	-	-	-	-[d]
3/4	3 × 3	1.53	c/a	1	M	50	117.8	31.7	172.2	235.6	211.9
					(d) BJ-29108, Type 1, 74 Durometer						
5/6	3 × 3	1.36	w/a	1	K	6.25	28.8	4.7	385.6	460.8	-
						12.5	44.6	7.2	299.2	356.8	-
						18.75	56.9	10.8	245.9	303.5	-
						25	69.2	12.2	228.0	276.8	-
						31.25	79.8	14.4	209.3	255.4	-
						37.5	87.3	16.6	188.5	232.8	-
						43.75	100.3	15.8	193.2	229.3	-
				2	K	6.25	23.0	2.0	336.0	368.0	-
						12.5	37.6	5.6	256.0	300.8	-
						18.75	50.4	8.1	225.6	268.8	-
						25	62.5	11.2	205.2	250.0	-
						31.25	74.5	13.1	196.5	238.4	-
						37.5	85.2	15.0	187.2	227.2	-
						43.75	95.9	18.1	177.9	219.2	-
						50	107.2	21.1	172.2	214.4	-
						62.5	124.5	26.6	156.6	199.2	-
						75	140.3	34.0	141.7	187.1	-
						100	176.8	33.2	143.6	176.8	-
7/8	3 × 3	1.38	w/a	1	K	50	110.4	35.4	150.0	220.8	203.4
13.1/14.1	2 × 2	0.92	w/a	1	K	50	101.2	35.7	131.0	202.4	192.6
13.2/14.2	3 × 1	0.70	w/a	1	K	50	120.5	48.0	145.0	241.0	189.4
9/10	3 × 3	1.37	c/a	1	K	50	108.0	37.4	141.2	216.0	195.2
						100	-	-	-	-	-[d]
				2	K	50	102.3	28.1	148.4	204.6	-
11/12	3 × 3	1.39	c/a	1	K	50	111.8	39.1	145.4	223.6	200.2
13.3/14.3	2 × 1	0.62	c/a	1	K	50	108.8	41.7	134.2	217.6	194.8

[a] Fast rate. [b] Slow rate. [c] Initial cycle only. [d] Sample slipped.

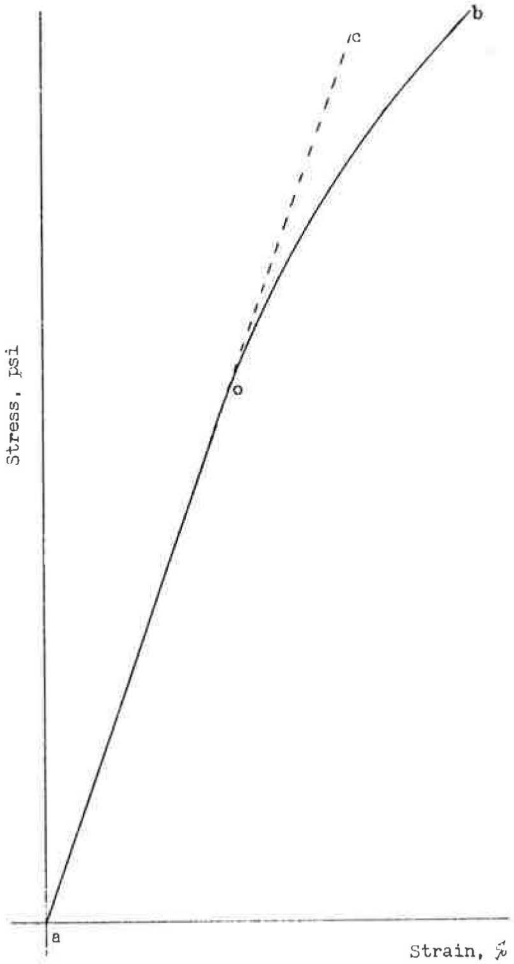

Figure 12. Stress/strain curve—elastic material.

Because for elastomers the unit stress is equal to the shearing force divided by the bearing area and the unit strain is the shear deformation divided by the pad thickness, Eq. 1 becomes:

$$\text{Modulus} = \frac{\dfrac{\text{Shearing Force}}{\text{Bearing Area}}}{\dfrac{\text{Shear Deformation}}{\text{Pad Thickness}}} \quad (2)$$

This is the definition of shear modulus for elastomers (5).

If the stress is plotted vs strain for a perfectly elastic material, the plot would be as indicated in line aob of Figure 12. The portion of the plot within the elastic limit of the material in linear as represented by the straight line, ao, whose value is indicated by the tangent aoc.

Elastomers under strain always have some permanent set, regardless of how small the strain, and the plot of stress vs strain is not linear. The characteristic curve for rubber and rubber-like materials is not a straight line but an S curve (2), similar to line ab of Figure 13. This is a typical tensile curve. Line ab of Figure 14 is a typical compression curve from the literature (1, 2). Our experience has been that all elastomeric deformations (tensile, compression, and shear) exhibit the typical S character, some more than others; tensiles are the most pronounced, compressions the least. Furthermore, because these deformations are not straight-line functions, it is customary to identify the stated modulus by the degree of strain at which the modulus was determined (2), i.e., 300 percent modulus. This modulus value does not identify the stress/strain curve for elastomers as it does for an elastic material but actually identifies only the chord of the curve from the origin to a point on the curve at the degree of strain stated (straight lines aA, Figs. 13 and 14). For small strains, this cord is a reasonable and adequate approximation. Other values often quoted in the literature are the slope static moduli and the tangential modulus (lines c, Figures 13 and 14) which is the tangent to the curve at the point of strain designated.

For large strains, the modulus value identifies the chord only of an arc of appreciable curvature and has limited application. Data are comparable only at identical points on the curve. Elaborate calculations or an actual physical test must be resorted to in order to obtain the stress at any other desired point as dictated by the engineering problem.

RECOMMENDATIONS

We have shown that shear cycling produces curves that are reproducible and that a substantial length of the loading portion of these curves approach a straight line. Therefore, in lieu of the present practice of computing shear forces from the "chord shear

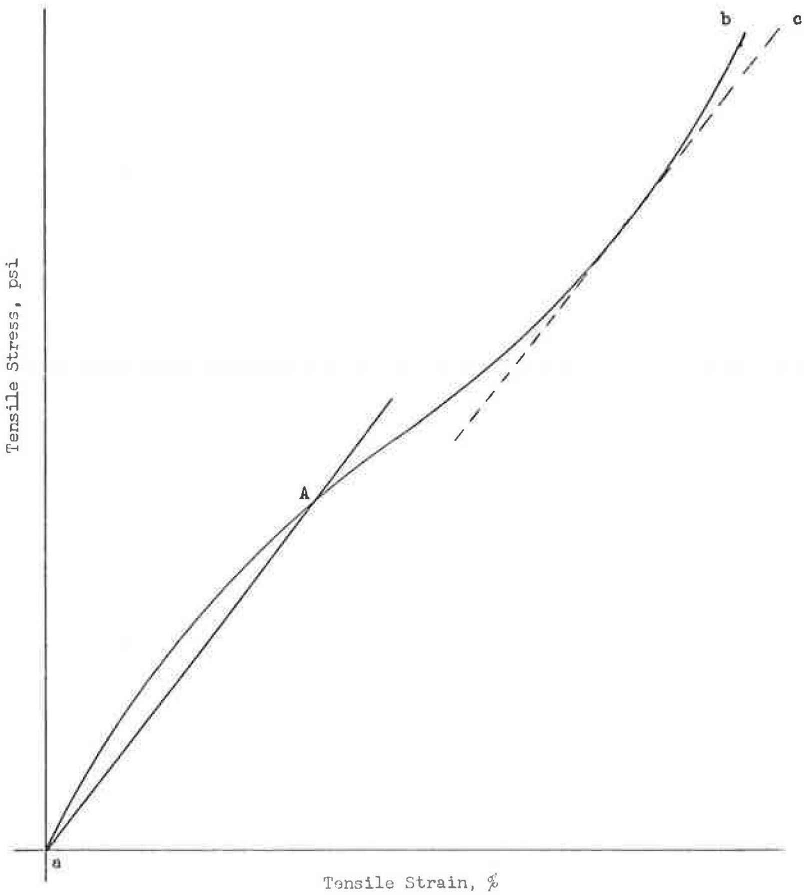

Figure 13. Tensile stress/strain curve—elastomeric material.

modulus," which are approximations only, it is proposed that standard curves be established from which the shear forces can be computed according to the following formula:

$$f = k + x\lambda \tag{3}$$

where f is the shear stress at shear strain D/T = x; k is a constant from the standard curve, which represents the stress axis intercept or residual pier stress at zero horizontal deformation; x is the ratio of the shear deformation to the pad compressed thickness at the same deformation at which f is being computed; and λ is the tangent to the loading portion of the standard curve at the point on the standard curve where the strain D/T based on the pad compressed thickness is equal to the decimal equivalent of the percent of shear based on the uncompressed pad thickness. Because the standard curves approach linearity from the stress intercept at the point where D/T = 0 to that at the point where D/T is equal to the decimal equivalent of the percent of shear, for practical purposes this tangent, λ, is equal to the slope of the chord between these two points. The values of λ in Table 1 are computed from this chord.

For a standard curve at 50 percent shear strain based on the uncompressed pad thickness (which is our test strain; 100 percent or any other desirable strain could be designated), the value of k is determined by the stress axis intercept, the value of f is determined at D/T = 0.500 (designated as the standard strain for 50 percent shear strain), and λ is computed from the slope of the chord according to:

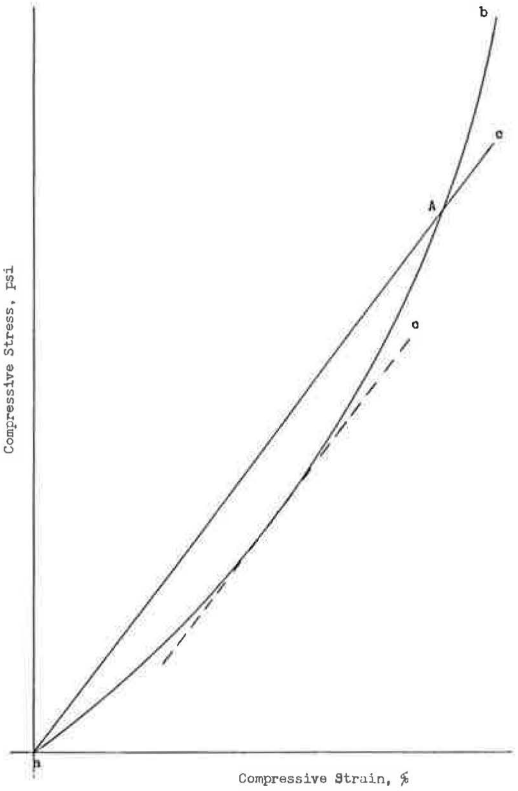

Figure 14. Compressive stress/strain curve—elastomeric material.

$$\lambda = \frac{f - k}{x} \quad (4)$$

With the values of k and λ known for a 50 percent shear strain, it is possible to reconstruct the loading portion of the shear curve and to compute the shear stress at any desired deformation within the limits to which the curve is applicable.

COMPILATIONS

Table 1 gives the values for the samples indicated of f, k and λ from standard curves at the percent of strain indicated and as computed by Eq. 3. It also gives the values of M_r, the reproducible chord shear modulus, as computed from the standard curve by:

$$M_r = \frac{f}{x} \quad (5)$$

where f is the shear stress from the reproducible cyclic curve at the standard strain x. Also given are the values of M_i, the initial chord shear modulus, as computed by:

$$M_i = \frac{f_i}{x} \quad (6)$$

where f_i is the shear stress from the initial cycle at the standard strain x. Appendix A gives a comparison of computations based on each of these three formulas.

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Appendix A

COMPARISON OF COMPUTATIONS

Figure 15 illustrates a comparison of computations of the shear stress according to current practice and according to the recommendations proposed in the basic presentation. Figure 15 is a representation of the shear cycles of pads 7/8, Sample BJ-29108, from Table 1.

The arc abc represents the positive loading portion of the initial cycle of the pads cycled at 50 percent shear deformation as based on the uncompressed thickness of the pads. The arc ab represents the segment of this curve from D/T = 0 to D/T = 0.500. The stress coordinate of point b is f_i, 101.7 psi. The initial chord shear modulus, as represented by the chord ab and defined by Eq. 6, then becomes 203.4.

The arc khg represents the positive loading portion of the reproducible shear cycle of the same sample. The line kh is the chord of this curve from D/T = 0 to D/T = 0.500. The stress coordinates of k and h are k and f, respectively. Since k = 35.4

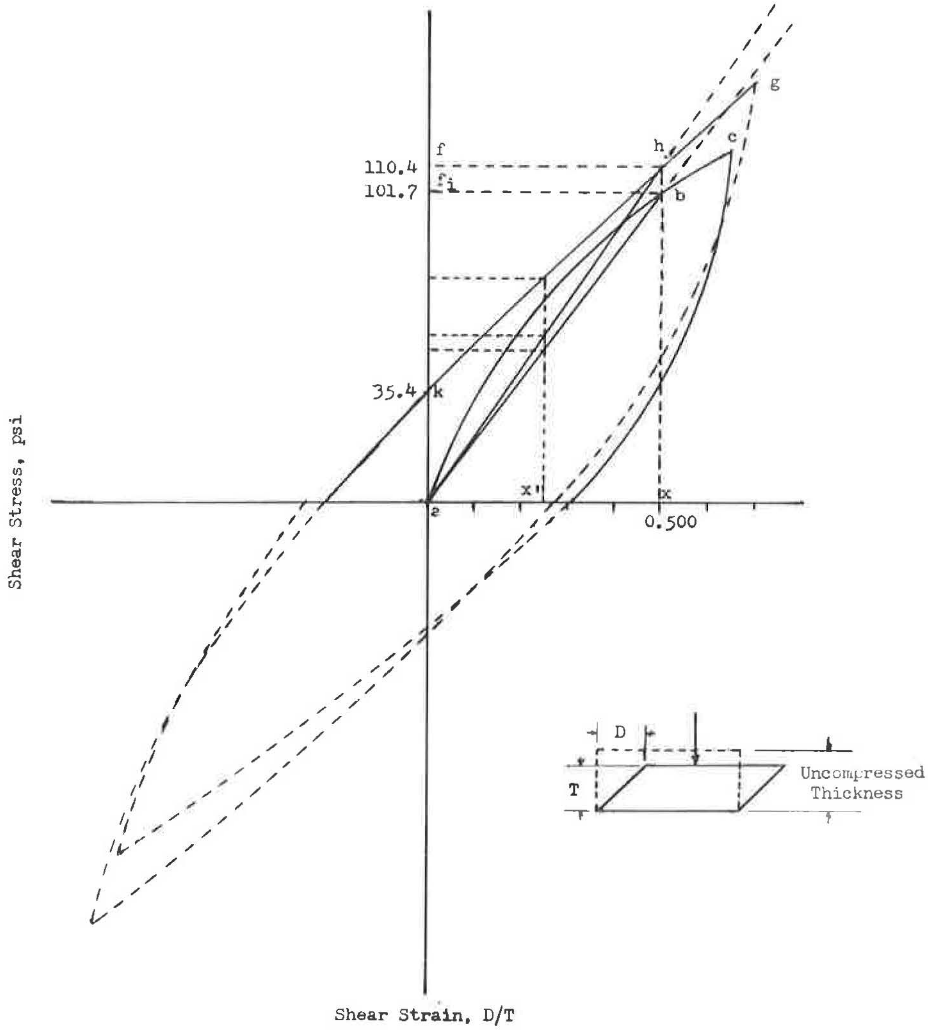

Figure 15. Comparison of shear stress computations.

and f = 110.4, the value of λ, as indicated in the basic presentation and as computed from Eq. 4, is as follows: $\lambda = \frac{110.4 - 35.4}{0.500} = 150.0$

The line ah represents the cyclic chord shear modulus as defined by Eq. 5 and, in this instance, has the value of 220.8.

These and similarly determined values for other samples and/or degrees of shear will be found in Table 1 of the basic presentation. Assuming we wish to compute the shear stress at some point, x', and we choose $x' = 0.250$, then from Eq. 3 which for the value x' becomes $f' = k + x'\lambda$, and with the substitution of the values of $k = 35.4$ and $\lambda = 150.0$, from the standard curve, $f' = 35.4 + (0.250 \times 150.0) = 35.4 + 37.5 = 72.9$, which is the computed shear stress by the method proposed in the basic presentation.

The computed shear stress based on the present practice of computing the shear stress from the chord shear modulus would be as follows:

1. For the cyclic chord shear modulus as defined by Eq. 5, with $M_r = 220.8$ as computed previously and x' chosen as 0.250, $f' = x' M_r = 0.250 \times 220.8 = 55.2$.
2. For the initial chord shear modulus as defined by Eq. 6, with $M_i = 203.4$ as computed previously and again with x' chosen as 0.250, $f_i' = x' M_i = 0.250 \times 203.4 = 50.8$.

The actual stress as determined experimentally at the strain $x' = 0.250$ was found to be 73.0 psi.

Appendix B

SHEAR DEFORMATION STANDARD METHOD OF TEST

Equipment

The equipment consists of a universal testing machine modified with two steel compression heads of 4 by 4 in. and a steel drawplate of approximately ½ by 8 by 12 in. The compression heads and sample areas of the drawplate are knurled at 40 lines to the inch. The heads are positioned so that they are matched and parallel at contact. Four gages are used to determine pad compressed thickness, one dial on each side of each pad. The universal testing machine must be capable of rapid adjustment, either manual or automatic, to maintain the specified compressive load within ±0.5 percent of actual load. Compressive loading rate must be 0.05 in./min. Total compressive load must exceed 15 percent and be less than 85 percent of the calibrated capacity of the universal testing machine.

Shear displacement must be accomplished at 0.050 ± 0.002 in./min. Mechanical control of shear loading rate is the most reliable. Shear displacement shall be measured by one gage centered on the draw axis. Shear load is determined by load cell, load rings or some other method and must be measurable to within 0.5 percent of actual load. The load measuring device shall be so selected that determined shear load exceeds 15 percent and is less than 85 percent of the calibrated capacity of the device.

Standard Conditions

The following conditions are considered standard, and any deviations must be noted:

1. Testing temperature—68 ± 5 F;
2. Compressive stress—500 psi;
3. Loading rate, both compressive and shear—0.050 ± 0.002 in./min;
4. Degree of shear deformation—50 and 100 percent, respectively, of the uncompressed thickness; and
5. Standard sample—two samples, each ½ by 3 by 3 in., for each grain direction.

Method

1. Two samples, both of the same grain direction, are centered between the compression heads with the grain of both samples oriented in the same direction. The two samples are placed exactly one above the other with the drawplate between. The compression heads are brought together to zero load. The average thickness of each sample is calculated and compared with the original premeasured thickness. Deviation should not be more than ± 0.001 in.

2. The samples are loaded in compression at the rate of 0.050 ± 0.002 in./min to testing compressive load and then unloaded to zero load. The cycles are repeated until percent compressive strain at maximum load remains constant. The plane of the drawplate is maintained parallel with the plane of the compression heads during cycling. Percent compressive strain is assumed to be constant when, after three consecutive cycles, the compressive deformation has not changed more than ± 0.001 in.

3. After the percent compressive strain becomes constant, the compressive load and load in shear are maintained at the rate of 0.050 ± 0.002 in./min until the drawplate has been displaced a distance equal to one-half (± 0.005 in.) of the original uncompressed (premeasured) average thickness of the two samples under test. The drawplate is reserved and returned through the original position to a like negative distance. Then it is reversed again and displaced to the original positive position. These cycles are repeated until they reproduce. Samples are considered to have reproduced when the variations in shear load at zero shear deformation and the variations in slope at D/T = 0.500 (or 1.000 as appropriate) are less than 5 percent. The shear load, the shear deformation (D), and the thickness at shear (T) are recorded at sufficient intervals to plot the shear stress/strain curve.

4. After the shear stress values reproduce at 50 percent shear deformation, the samples are cycled at 100 percent shear deformation without change in the compressive load.

Calculations

The shear stress is plotted in psi against the shear strain, D/T, where D is the shear deformation in inches and T is the compressed thickness in inches at that deformation. The shear stress at the point D/T = 0 is then designated as k for the percent of shear deformation at which cycled. The slope of the chord of the shear stress/strain curve is determined from the point where D/T = 0 to the point where D/T is equal to the decimal equivalent of the percent of shear deformation at which cycled (0.500 or 1.000 as appropriate). This slope is designated as λ.

Appendix C

DESIGN COMPUTATIONS

The general formula as established is $f = k + x\lambda$ (Eq. 3). For 50 percent deflections and at the value D/T = 0.500, the specific formula for the standard curve becomes $F_{0.500} = k + 0.500\ \lambda$. It must be borne in mind that the constants of this specific formula are valid only under the conditions of test. Any deviations of actual conditions from standard test conditions must be compensated for by correction factors. Also, these constants are based on compressed thicknesses. Therefore, an estimate of the compressed thickness under service conditions must be made and such thickness is used in computations.

For example, to calculate various shear stresses on pads 5/6, Sample BJ-29190, from Table 1, we must first know the cyclic degree of strain at which the bearing is flexing to choose the proper values of k and λ. If the bearing is undergoing random cycling, values for k and λ appropriate to the immediately previous cycle are used as a close approximation. If previous cycle is unknown, the next approximation is the design cycling value.

We may assume that it is desired to know the stress at deflection D/T = 0.250 at some future date. Because the sample will in all probability be undergoing random cycling in which the immediately previous cycle is unknown, we will use the values of k and λ appropriate to the design which we will assume to be 50 percent deflection. Then $f_{0:500}^{0:250}$, which is the stress at deflection D/T = 0.250 based on previous deflection (or standard curve) of 50 percent deflection, will be equal to the value of k at 50 percent deflection plus 0.250 multiplied by the value of λ at 50 percent deflection: $f_{0:500}^{0:250} = k + 0.250\ \lambda = 8.1 + 0.250 \times 101.0 = 8.1 + 25.2 = 33.3$ (actual value = 34.3).

If we assume we wish to know the stress at some future date at 25 percent deflection and it is assumed that at 25 percent deflection D/T = 0.343: $f_{0:500}^{0:343} = k + 0.343\ \lambda = 8.1 + 34.6 = 42.7$ (actual value = 43.3).

If we assume we now wish to know the stress at D/T = 0.250 after a maximum cycle at 100 percent deflections: $f_{1:000}^{0:250} = k + 0.250\ \lambda = 19.5 + 0.250 \times 75.3 = 38.3$ (actual value = 39.6).

If we assume we wish to know the stress at 50 percent deflection and it is assumed that at 50 percent deflection D/T = 0.700: $f_{0:500}^{0:700} = k + 0.700\ \lambda = 8.1 + 70.7 = 78.8$ (actual value = 77.5).

Under the standard conditions of test the 50 percent deflection curve is valid over values of D/T = 0.250 to 0.750 and 100 percent deflection curve is valid from D/T = 0.500 to approximately 1.300.