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THE EFFECT OF RIBBING ON SHOCK TRANSMISSION THROUGH

EXPANDED POLYSTYRENE CUSHION MATERIAL

presented by

George Kuo-Hsin Chen

has been accepted towards fulfillment
of the requirements for

MS degree in Packaging

Julian Lee
Major professor

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THE EFFECT OF RIBBING ON SHOCK TRANSMISSION THROUGH EXPANDED POLYSTYRENE CUSHION MATERIAL

By

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A THESIS

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ABSTRACT

THE EFFECT OF RIBBING ON SHOCK TRANSMISSION THROUGH EXPANDED POLYSTYRENE CUSHION MATERIAL

By

George Kuo-Hsin Chen

This study evaluates the effect of ribs on shock transmission through Expanded Polystyrene (EPS). Since the shape of a cushion influences its cushioning behavior, the cushion curves developed on Flat EPS are inadequate to describe the cushioning characteristics of Ribbed EPS packages used in industry.

The effects of ribs on shock transmission were examined for two different densities (1.25 pcf and 1.35 pcf) EPS cushion. The experimental results showed that at low drop heights (24 inch and lower) or under low static stress levels (0.6 psi and lower), both Ribbed EPS and Flat EPS produced similar peak acceleration levels. At greater drop heights (24 inch and higher) or under high static stress levels (1.0 psi and higher), Ribbed EPS yielded greater peak acceleration levels than Flat EPS. Therefore, when designing an EPS cushioning package for a fragile product involving high static stress levels and drop heights, the effect of EPS ribbing on shock transmission must be taken into consideration.

To my wife, mother and sons

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First, Dr. Julian Lee, my major professor, for his considerable amount of time, advice, and encouragement devoted to my study. I would also like to express my appreciation to the members on my thesis committee, Dr. Richard K. Brandenburg and Dr. Gary J. Burgess, for their support during the research.

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Finally, my gratitude and appreciation to Mr. David E. Henderson, President of International Packaging Systems Inc. and Mr. Y. M. Yang for their kind encouragement and financial support during the study.

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LIST OF SYMBOLS AND ABBREVIATIONS

A*	Effective bearing Area
ANOVA	Analysis of Variance
E	Young's Modulus of Elasticity
EFFDH	Equivalent Free Fall Drop Height
EPS	Expanded Polystyrene cushion
F	Loading Force
FFDH	Free Fall Drop Height
g	Acceleration of Gravity
g's	Shock transmission (Peak acceleration) level
h	Drop Height
k	Spring constant
ns	Statistically not significant
pcf	Pounds per Cubic Foot
t	Thickness of cushion
V	Impact Velocity
X	Total deflection of cushion
dx	Compression of slice dy of cushion
dy	Elemental thickness of cushion
σ	Static stress
ϵ	Strain
$\int$	Integration
*	Significant at 5% level of probability
**	Significant at 1% level of probability

INTRODUCTION

"Damage to a product occurs when it receives an excessive shock encountered during distribution and handling" (6). In order to prevent the product from damage, a cushion material must be used to buffer the impact by reducing the shock transmitted to the product. Ribbed cushions have been commonly used in industries for reasons of economy and ease of fabrication.

The easiest way for a packaging engineer to determine the optimum amount of cushion material required for a fragile product is to use cushion curves. The cushion characteristics of buffering materials are described by cushion curves with peak acceleration level (g's) plotted on the ordinate and static stress level plotted on the abscissa. Cushion curves are generally developed following the procedures described in ASTM D 1596-78a, Shock Absorbing Characteristics of Packaging Cushioning Materials (1). It states that "The Test Method is applicable to materials exhibiting a high degree of compressibility and recovery in bulk, sheet or laminated forms used for cushioning packaged articles" (1).

The ASTM Test Method D 1596-78a does not take into account the effect of shape of test specimen on shock transmision. Therefore, all cushion curves generated and reported by manufacturers are based on flat planks. Yet physical properties (compression, spring constant, and deflection) of the material are affected by the shape of the test specimen (7). It follows then that the cushion curves developed on flat planks may not be adequate for describing the ribbed cushion's behavior.

In general, not much research was found to have been done on the influence of the shape of EPS (Expanded Polystyrene) on its physical properties. Yet EPS is a widely used cushion material. Therefore, the influence of geometric shape of EPS on the cushioning characteristics is the basis for this study.

In practice, an EPS cushion is molded with Ribs either on the exterior contact surface or the interior contact surface. The commonly used Rib shape is the trapezoid or the modified trapezoid. A comparison between the trapezoid Ribbed EPS which consists of 3-piece rib on a one inch thick base and the Flat EPS of the same material was performed, and the difference in shock transmission between these two samples was observed.

Further, the cushioning deterioration of EPS cushion has to be considered when designing an EPS cushion package. "In normal distribution environments, a cushioned article usually encounters several shocks of varying magnitude" (3). Cushions subjected to an increasing number of loading and unloading stress cycles exhibit a decreasing hysteresis effect (7).

EPS cushions produced higher shock levels as the number of successive drops increased due to cushion deterioration. Figure 1 shows that a greater shock is transmitted through the cushion with each successive drop. Therefore, it is reasonable to develop the first drop and the multiple drop cushion curves separately for the evaluation of cushioning properties of Ribbed EPS and Flat EPS cushions.

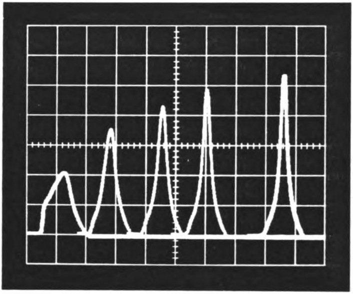
The purpose of this study is to investigate the cushion curves of Ribbed EPS and Flat EPS cushions in relationship to shock transmission. The experiment of this study attempts to answer the following questions:

1) Do the cushion curves of Ribbed EPS and Flat EPS of the same material reveal any difference on shock transmission? If so,

2) How do the first drop and the multiple drops on shock transmission through Ribbed EPS differ from those of Flat EPS?

FIRST DROP THROUGH FIFTH DROP

Peak acceleration (20 g's/div)



Duration (20 ms/div)

Figure 1. REPRESENTATIVE SHOCK PULSES RECORDED ON AN OSCILLOSCOPE INDICATING A SUCCESSIVE INCREASE IN g's DUE TO MULTIPLE DROPS (Photograph of a 3 in. 1.25 pcf Ribbed EPS at 36 in. free fall drop height under a static stress of 1.4 psi)

MATERIALS AND METHODS

TEST APPARATUS

The generation of cushion curves was performed according to ASTM Test Method D 1596-78a using a Lansmont Model 23 Cushion Tester.

DETERMINATION OF GATE TIME & EQUIVALENT FREE FALL DROP HEIGHT

The impact velocity corresponding to a specific free fall drop height (FFDH) was determined by the time required for a trigger blade (a 0.5 in. wide metal plate firmly mounted to the back side of the platen) to pass through a photoelectric sensor located just above the impact surface of the test specimen. The impact velocity was calculated by using Equation (1) on page 5.

The gate time was measured (in milliseconds) by a GHI VS 200 Velocity Sensor. The impact velocity was used to determine the platen's equivalent free fall drop height (EFFDH) by using Equations (2) and (3) on page 5. The EFFDH is the height from which the platen is dropped to produce an impact velocity identical to the velocity that occurs from a free fall drop (2).

Friction between the platen and the guide rods makes the platen velocity slightly lower than it would be in a free fall drop. Consequently, actual platen drop height is slightly greater than the free fall drop height to compensate for friction.

The following equation developed by Lansmont Corp. (2) was used to calculate the impact velocity,

$$V = \frac{d}{t} + 0.5gt \qquad \text{Equation (1)}$$

where: V = impact velocity

d = width of trigger blade

t = time readout on velocity sensor

g = acceleration of gravity

Since the impact velocity in a free fall can be calculated by $V = \sqrt{2gh}$, the EFFDH is

$$h = \frac{V^2}{2g} \qquad \text{Equation (2)}$$

Substituting Equation (1) into Equation (2), the EFFDH is

$$h = \frac{(\frac{d}{t} + 0.5gt)^2}{2g} \qquad \text{Equation (3)}$$

The output shock pulse from each drop was recorded using a Kikusui COS 5020 ST Oscilloscope and a Kistler 8602A500 Accelerometer with a Kistler 5116 Piezotron Coupler. Shock pulses were also photographed using the Shackman 7000 Camera with Polaroid Type 667 film.

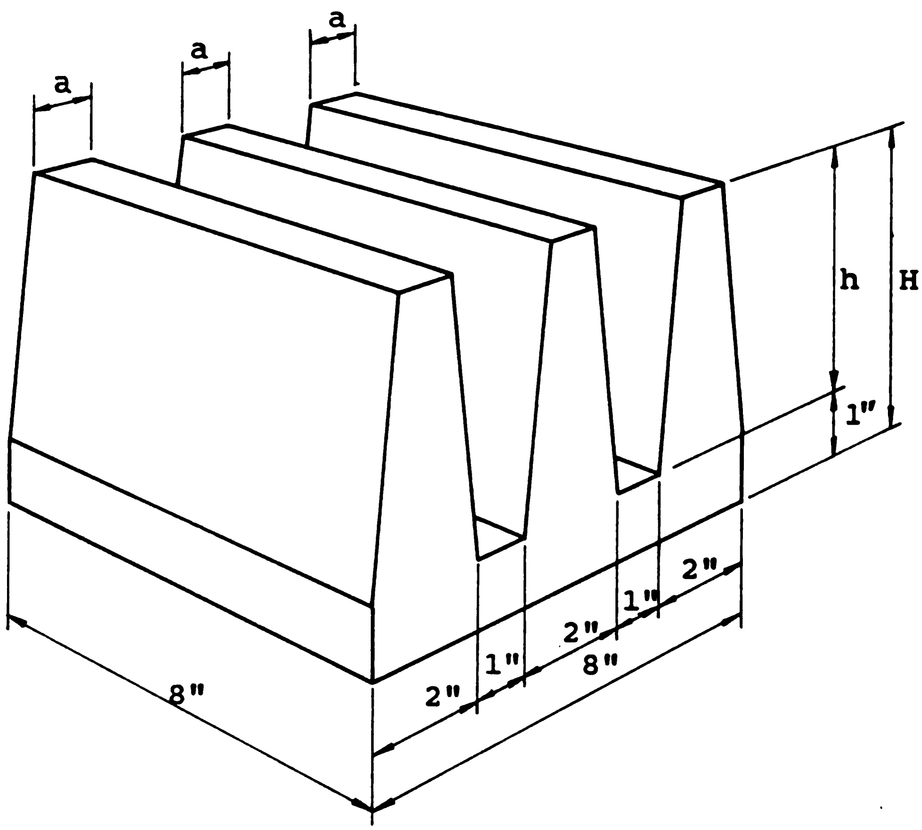
Table 1, below, shows the gate time and impact velocity for each free fall drop height as calculated by using Equation (3).

Table 1. GATE TIME, IMPACT VELOCITY & FREE FALL DROP HEIGHT

GATE TIME (m sec)	IMPACT VELOCITY (inch / sec)	FREE FALL DROP HEIGHT (inch)
5.25±0.02	96.3±0.36	12±0.09
4.27±0.02	117.9±0.57	18±0.17
3.69±0.02	136.2±0.74	24±0.26
3.30±0.02	152.3±0.91	30±0.36
3.01±0.02	166.8±1.10	36±0.49
2.78±0.02	180.2±1.30	42±0.61

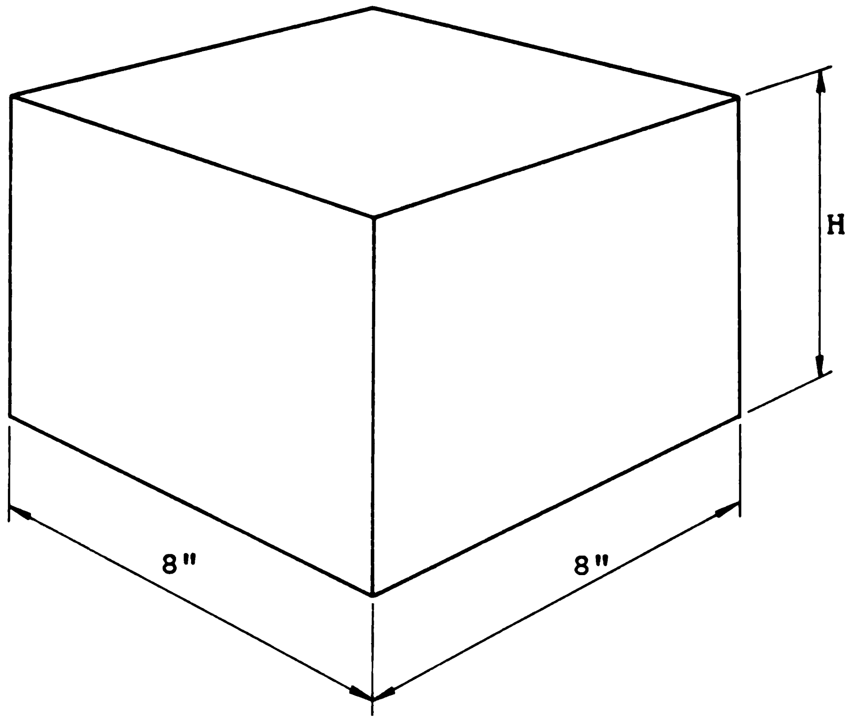
DETERMINATION OF EFFECTIVE BEARING AREA

Configurations and dimensions of Ribbed EPS and Flat EPS test samples are shown in Figures 4 and 5 respectively. Effective bearing areas for Ribbed EPS test samples were determined by applying Hooke's Law to each crossectional



SAMPLE NUMBER	DIMENSION (inch)			EFFECTIVE BEARING AREA (sq in)
	H	h	a	
1	5	4	1	38.12
2	4	3	1 1 /4	42.57
3	3	2	1 1/2	47.19
4	2	1	1 3/4	52.80

Figure 2. CONFIGURATIONS AND DIMENSIONS OF RIBBED EPS TEST SAMPLES



SAMPLE NUMBER	DIMENSION H (inch)	BEARING AREA (sq in)
5	5	64
6	4	64
7	3	64
8	2	64

Figure 3. CONFIGURATIONS AND DIMENSIONS OF FLAT EPS TEST SAMPLES

slice and integrating to arrive at a total force-deformation relationship that accounts for variation in crossectional area from top to bottom. Details of the determination of the effective bearing areas for Ribbed EPS test samples are described in Appendix A.

TEST SPECIMENS

Expanded polystyrene slabs of 2 in., 3 in., 4 in., and 5 in. thick were molded by Tuscarora Plastics Inc. The slabs were cut into 8 in. x 8 in. pieces and then randomly packaged in corrugated boxes for shipment to the School of Packaging.

In order to maintain consistency in Rib size, a hot wire cutter and a set of Ribbed aluminum guide plates mounted on a pair of wood clamps were employed to do the rib cutting. Figure 2 shows the Rib cutting device and Figure 3 illustrates the operation.

The initial thickness of a test specimen was determined by averaging the four measurements obtained from the four corners of each test specimen prior to testing. Final thicknesses of the test samples were determined in the same way with measurements conducted at least one minute after the fifth drop was completed.

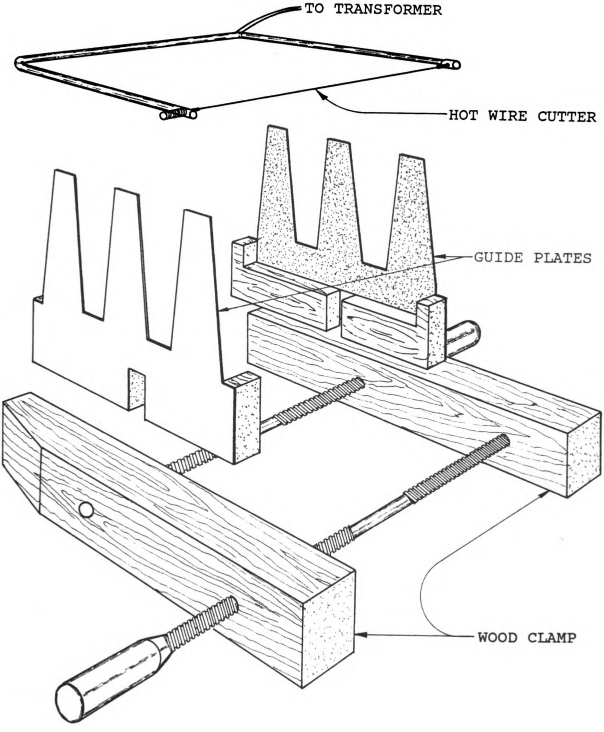


Figure 4. EPS RIB CUTTING DEVICE

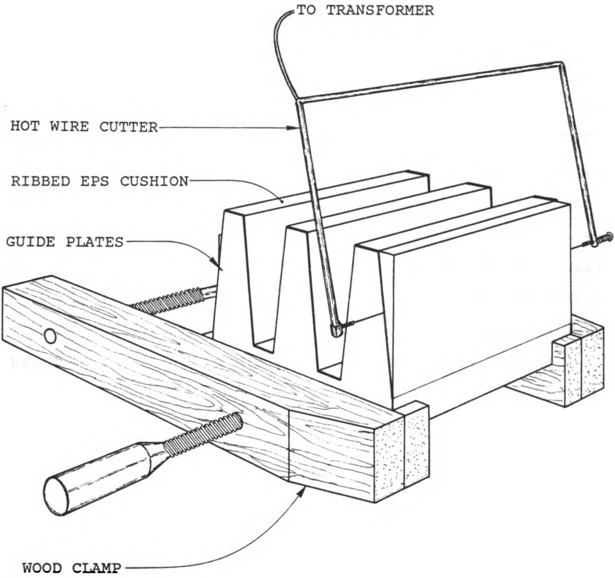


Figure 5. EPS RIB CUTTING DEVICE IN OPERATION

Test samples were conditioned at a temperature of 72 ± 1 °F and a relative humidity of 50 ± 2% for 24 hours or more prior to testing, in conformance to ASTM Test Method D 1596-78a (1).

TEST PROCEDURES

This experiment was carried out in triplicate. The samples studied consisted of 1.25 pcf EPS and 1.35 pcf EPS. The 1.25 pcf EPS samples were tested at drop heights of 12 inches through 42 inches with an increment of 6 inches under each of five static stress levels (0.2, 0.6, 1.0, 1.4, and 2.0 psi). The 1.35 pcf EPS samples were investigated only at 36 inches drop height under each of five static stress levels. The static stress levels in all samples were based on effective bearing areas illustrated in Appendix A.

DATA ANALYSIS AND RESULTS

DATA ANALYSIS

Determination of Peak Acceleration Level (g's)

The shock responses of the triplicated specimens were averaged for each of the test combinations (i.e., 6 drop heights x 5 static stress levels x 4 thicknesses) and are reported as acceleration levels (g's). Tables 2 through 7 (Appendix B) show the averaged peak acceleration levels (g's) obtained from 1.25 pcf EPS test samples at 12 in., 18 in., 24 in., 30 in., 36 in., and 42 in. drop heights respectively. Table 8 (Appendix B) shows the averaged peak acceleration levels (g's) through 1.35 pcf EPS test samples at 36 in. drop height.

Generation of Cushion Curves

The first-drop peak acceleration levels obtained from both the Ribbed EPS and the Flat EPS for each test combination are plotted as cushion curves with peak acceleration level (g's) on the ordinate and static stress level on the abscissa. These cushion curves are presented in Figures 6, 8, 10, 12, 14, 16, and 18.

Peak acceleration levels (g's) of the second through the fifth drops obtained from both the Ribbed EPS and the Flat EPS after each test combination were averaged separately. The average values are also plotted as cushion curves and are shown in Figures 7, 9, 11, 13, 15, 17 and 19.

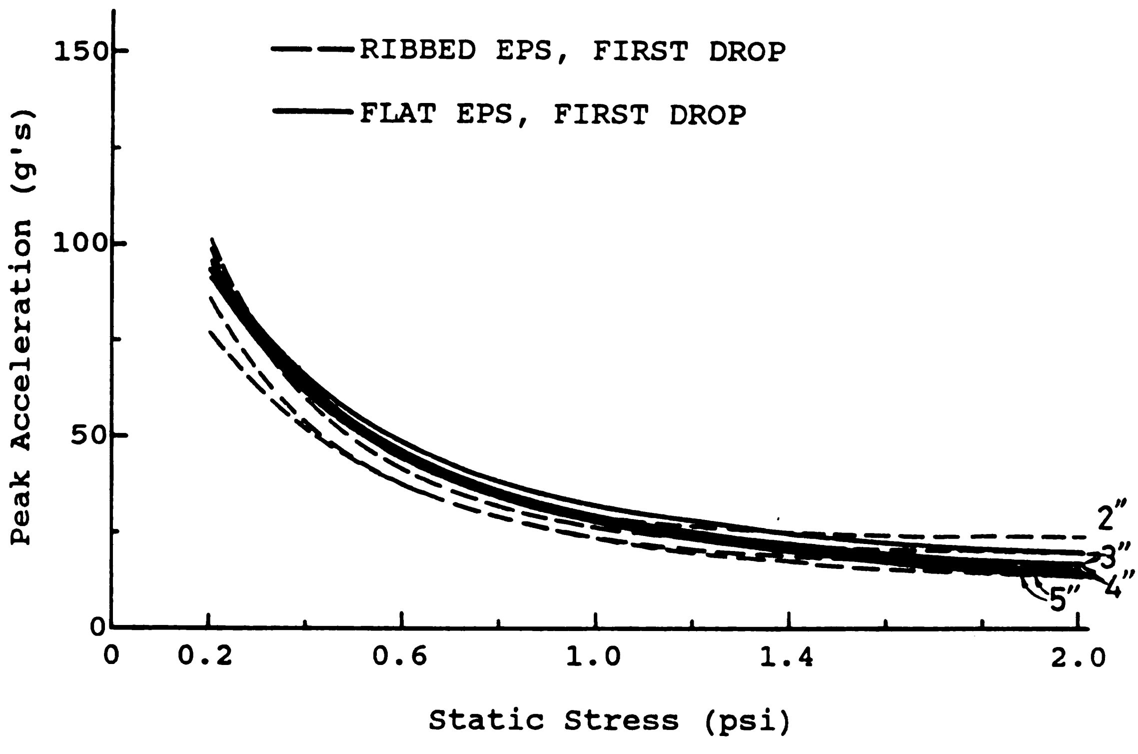


Figure 6. CUSHION CURVES FOR THE COMPARISON OF RIBBED EPS VERSUS FLAT EPS ON SHOCK TRANSMISSION AT 12 in. DROP HEIGHT (1.25 pcf Expanded Polystyrene)

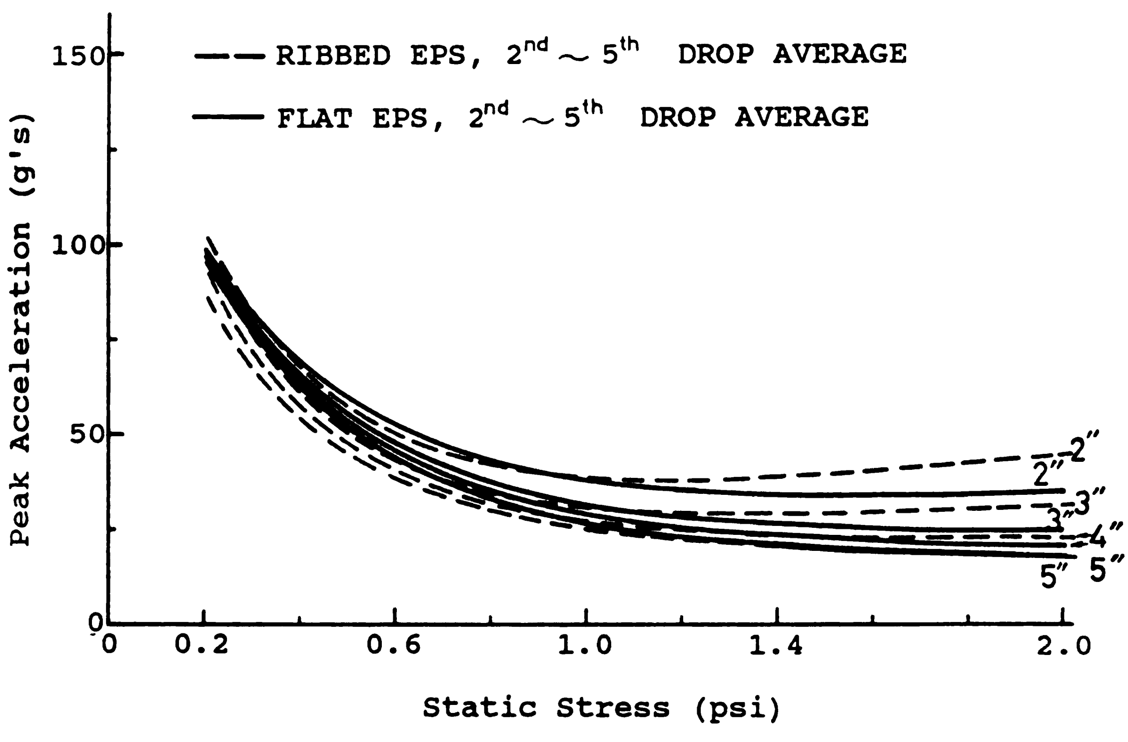


Figure 7. CUSHION CURVES FOR THE COMPARISON OF RIBBED EPS VERSUS FLAT EPS ON SHOCK TRANSMISSION AT 12 in. DROP HEIGHT (1.25 pcf Expanded Polystyrene)

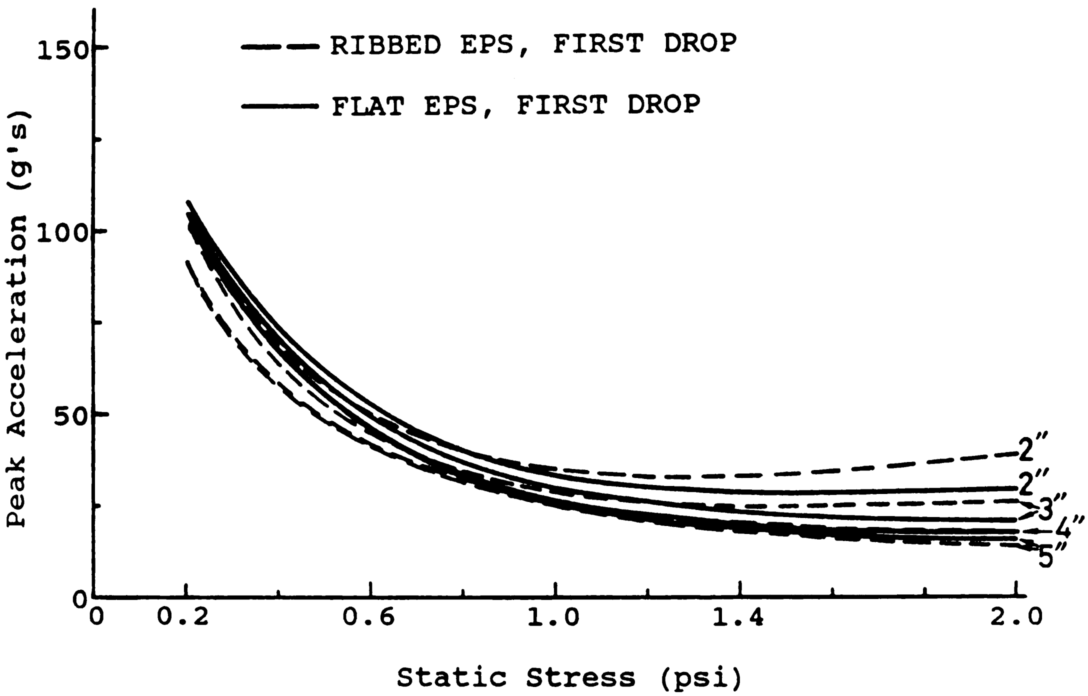


Figure 8. CUSHION CURVES FOR THE COMPARISON OF RIBBED EPS VERSUS FLAT EPS ON SHOCK TRANSMISSION AT 18 in. DROP HEIGHT (1.25 pcf Expanded Polystyrene)

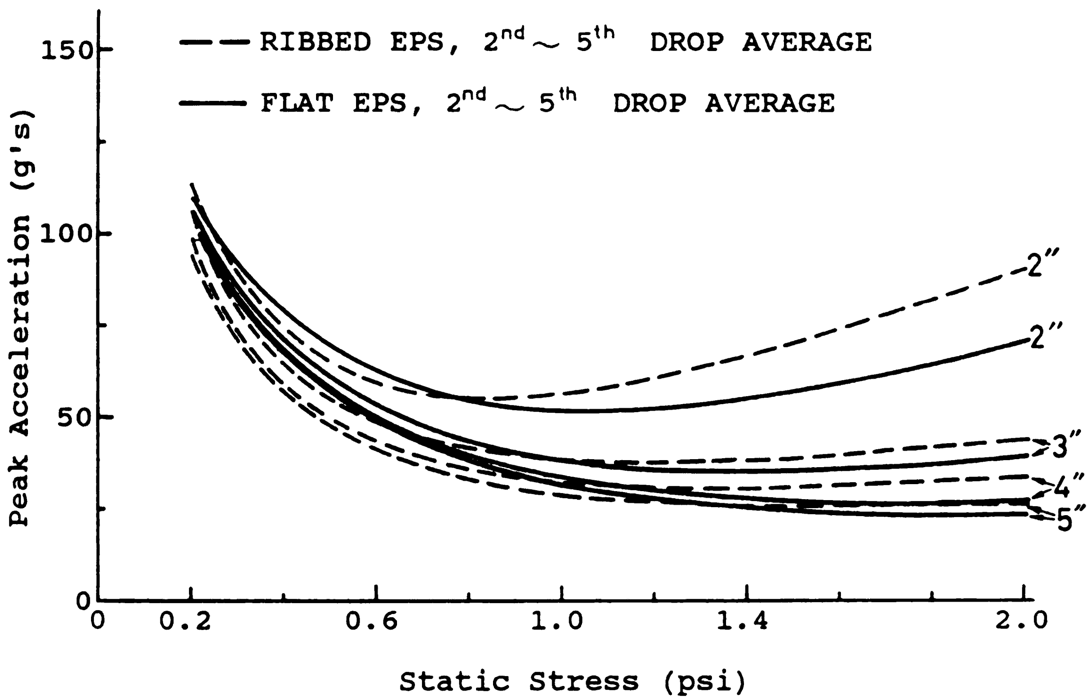


Figure 9. CUSHION CURVES FOR THE COMPARISON OF RIBBED EPS VERSUS FLAT EPS ON SHOCK TRANSMISSION AT 18 in. DROP HEIGHT (1.25 pcf Expanded Polystyrene)

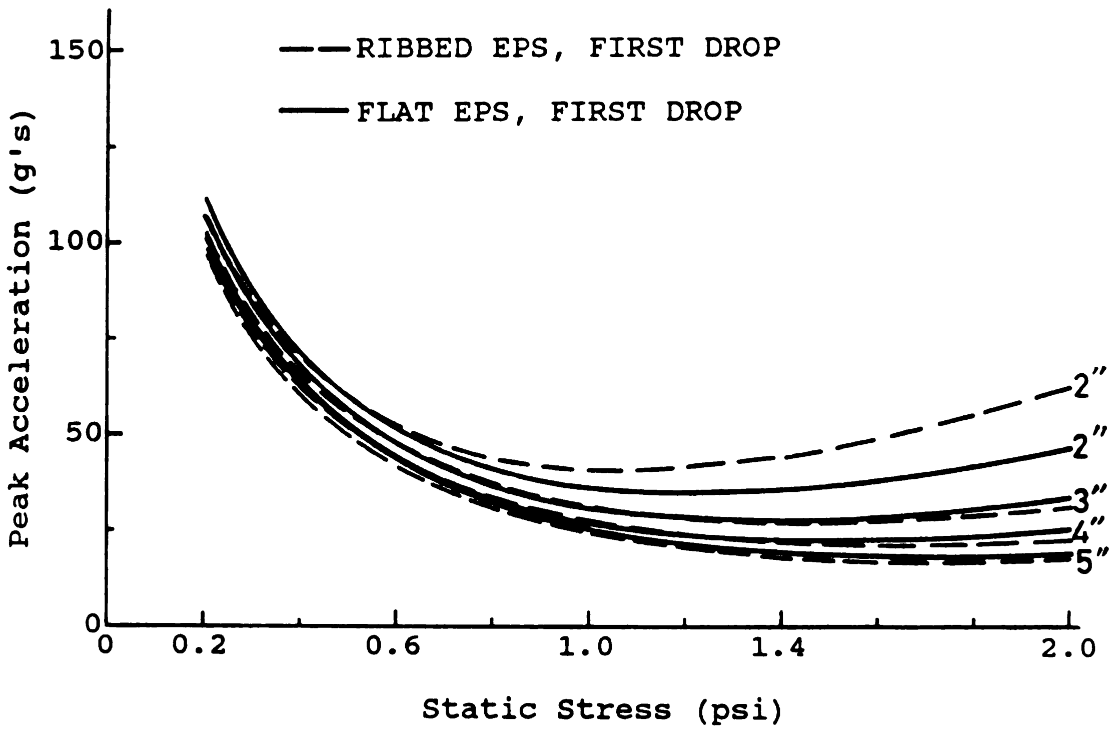


Figure 10. CUSHION CURVES FOR THE COMPARISON OF RIBBED EPS VERSUS FLAT EPS ON SHOCK TRANSMISSION AT 24 in. DROP HEIGHT (1.25 pcf Expanded Polystyrene)

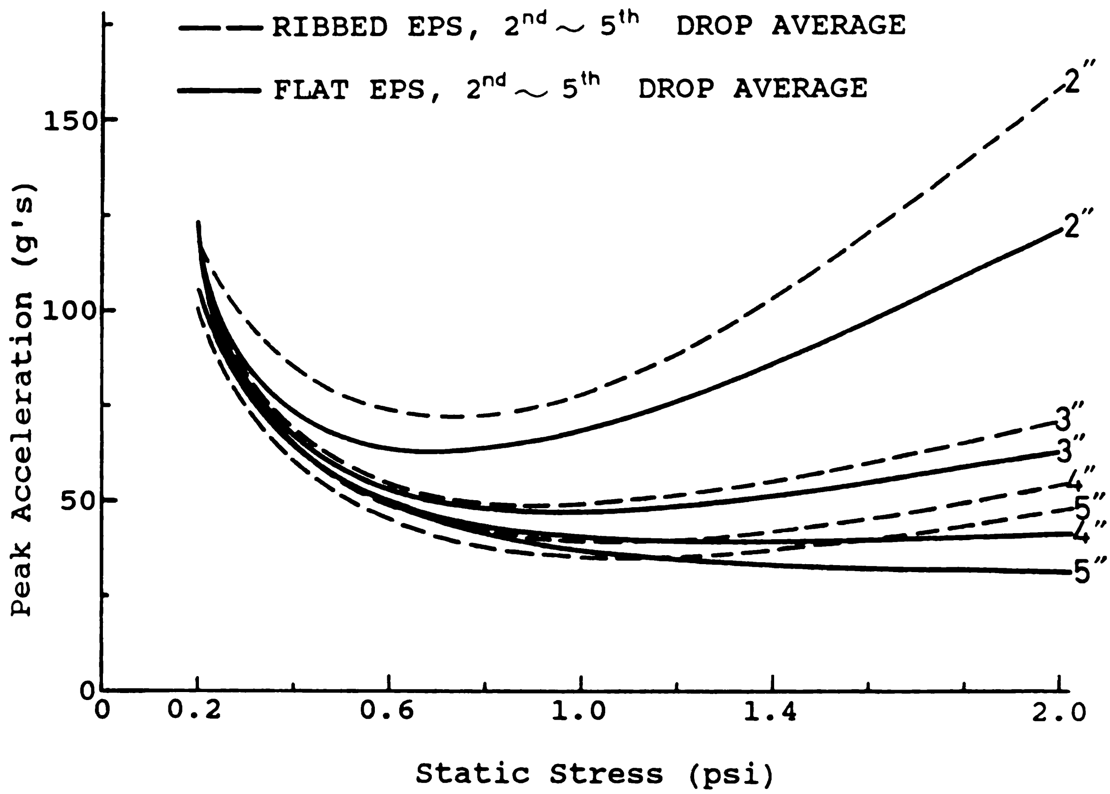


Figure 11. CUSHION CURVES FOR THE COMPARISON OF RIBBED EPS VERSUS FLAT EPS ON SHOCK TRANSMISSION AT 24 in. DROP HEIGHT (1.25 pcf Expanded Polystyrene)

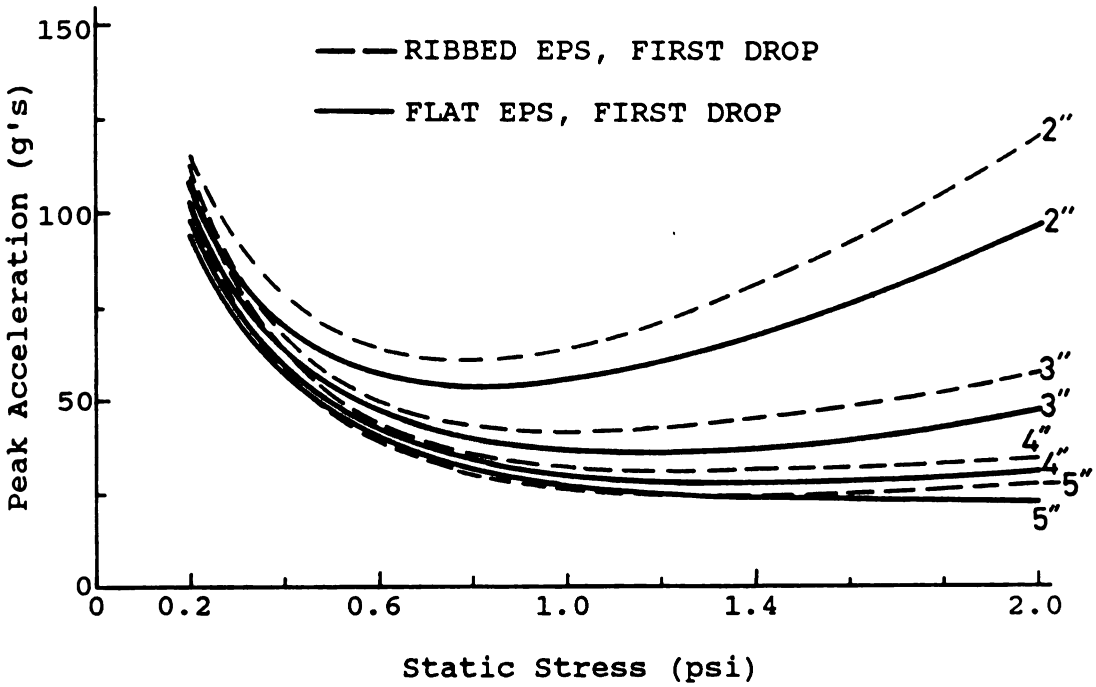


Figure 12. CUSHION CURVES FOR THE COMPARISON OF RIBBED EPS VERSUS FLAT EPS ON SHOCK TRANSMISSION AT 30 in. DROP HEIGHT (1.25 pcf Expanded Polystyrene)

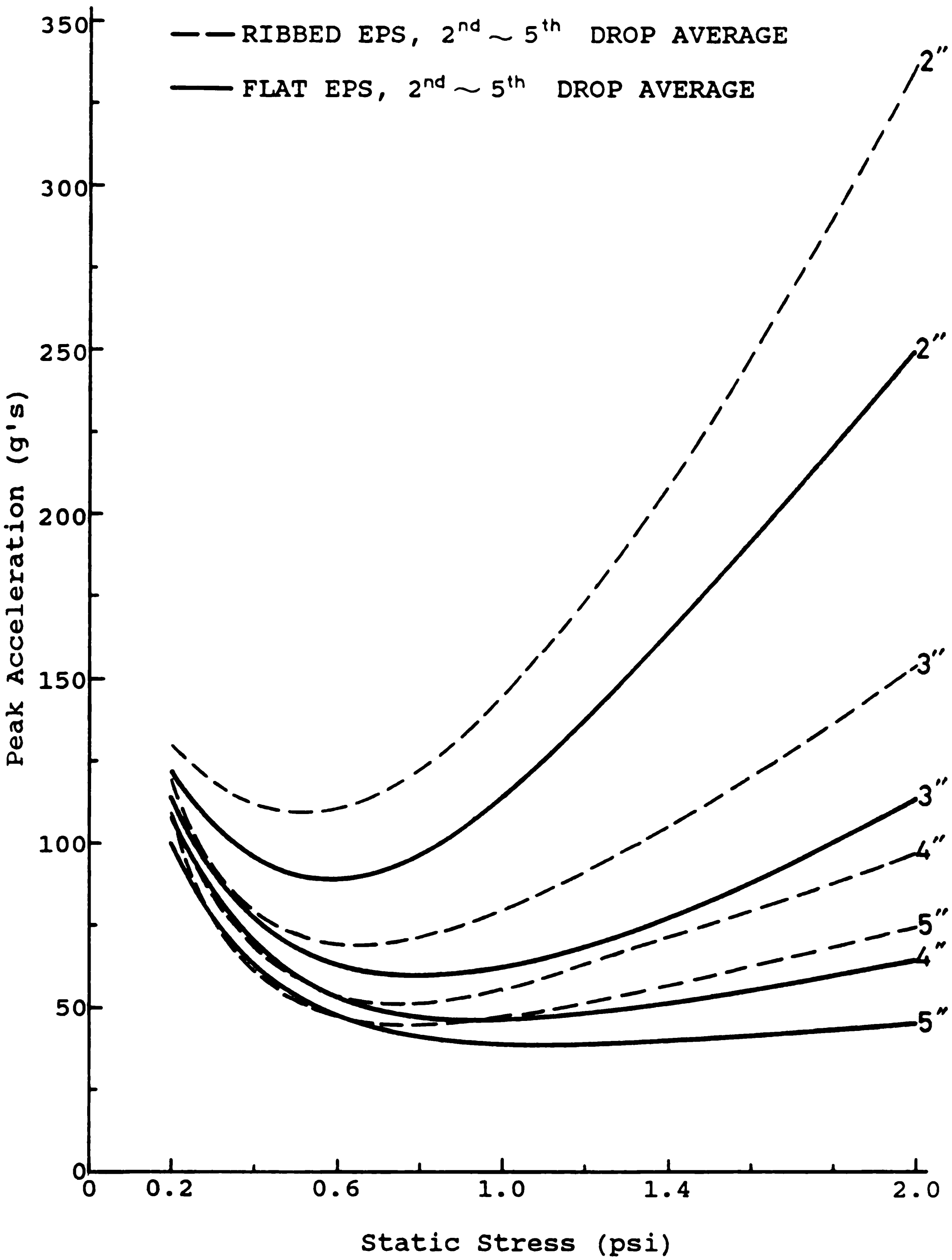


Figure 13. CUSHION CURVES FOR THE COMPARISON OF RIBBED EPS VERSUS FLAT EPS ON SHOCK TRANSMISSION AT 30 in. DROP HEIGHT (1.25 pcf Expanded Polystyrene)

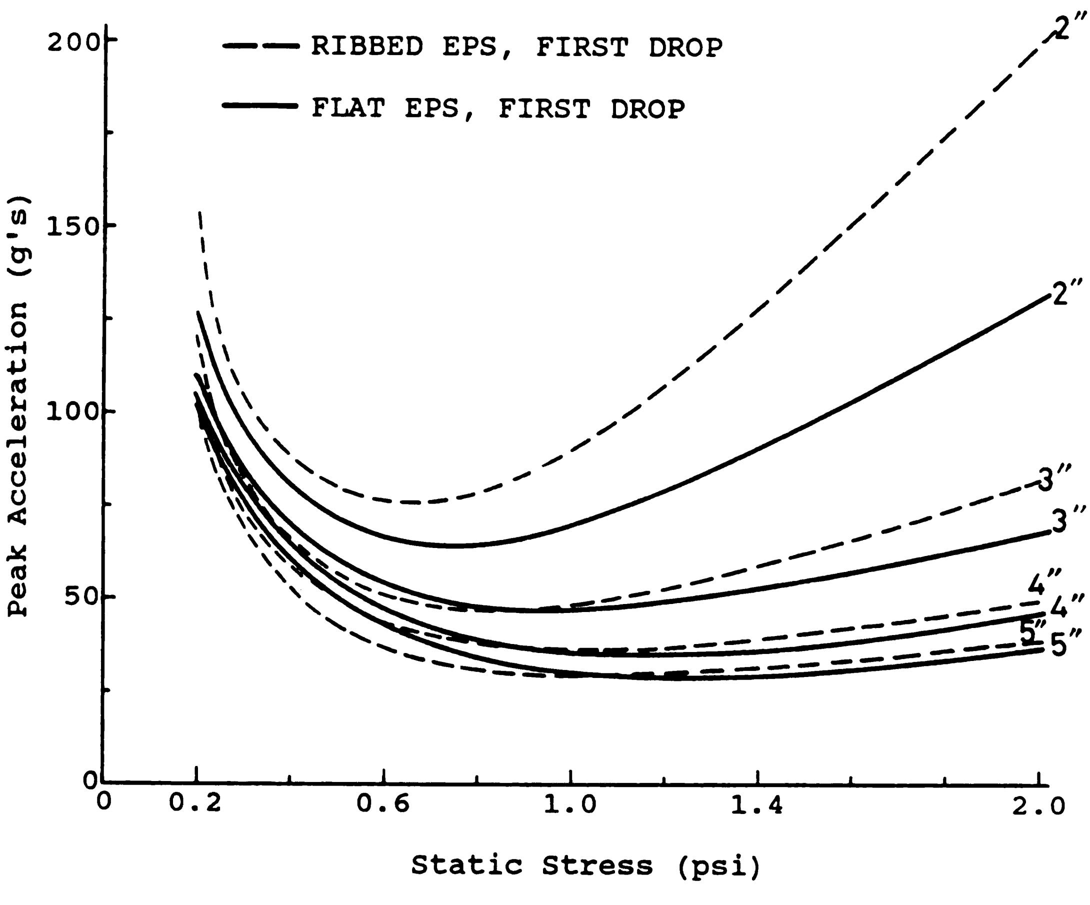


Figure 14. CUSHION CURVES FOR THE COMPARISON OF RIBBED EPS VERSUS FLAT EPS ON SHOCK TRANSMISSION AT 36 in. DROP HEIGHT (1.25 pcf Expanded Polystyrene)

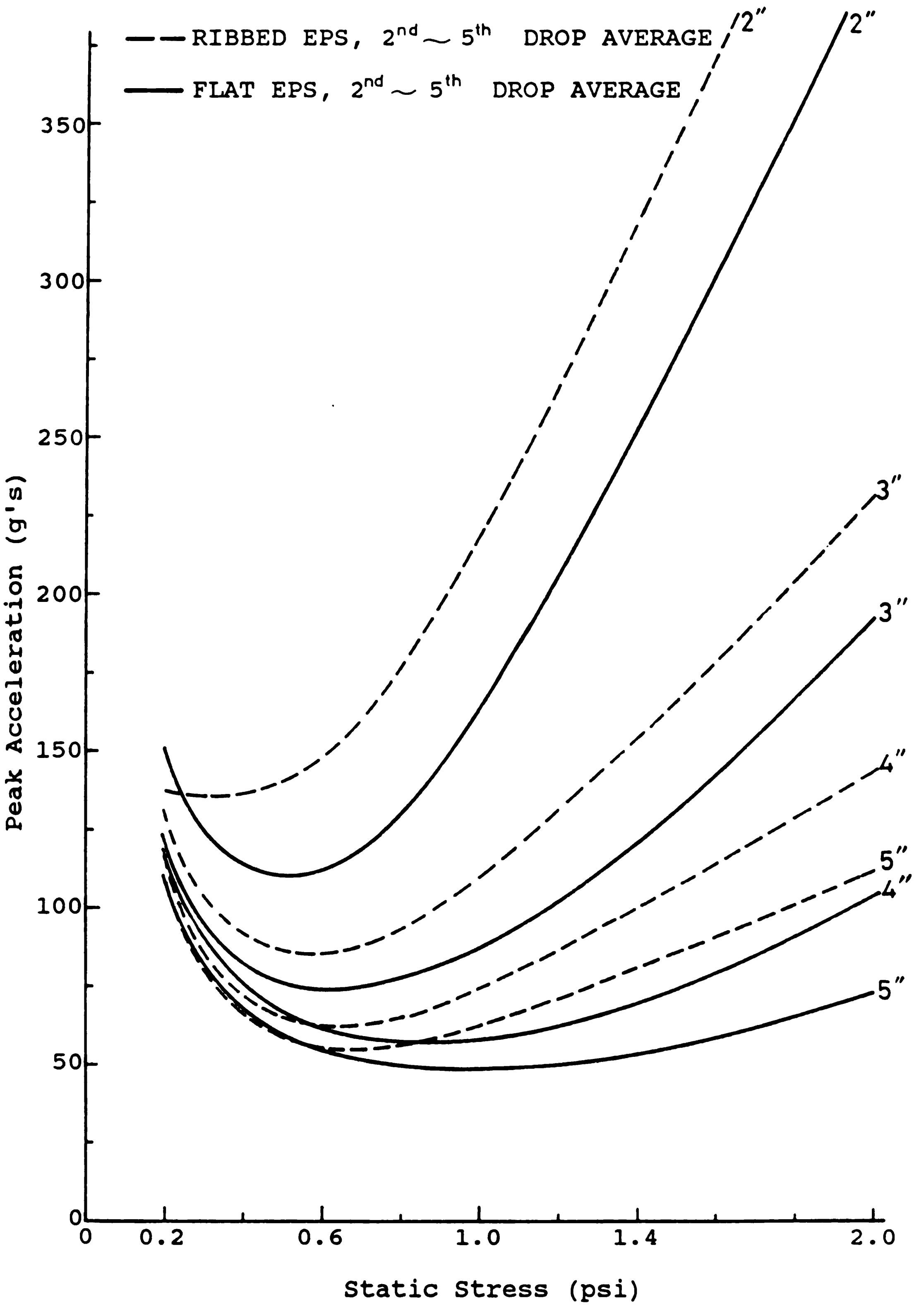


Figure 15. CUSHION CURVES FOR THE COMPARISON OF RIBBED EPS VERSUS FLAT EPS ON SHOCK TRANSMISSION AT 36 in. DROP HEIGHT (1.25 pcf Expanded Polystyrene)

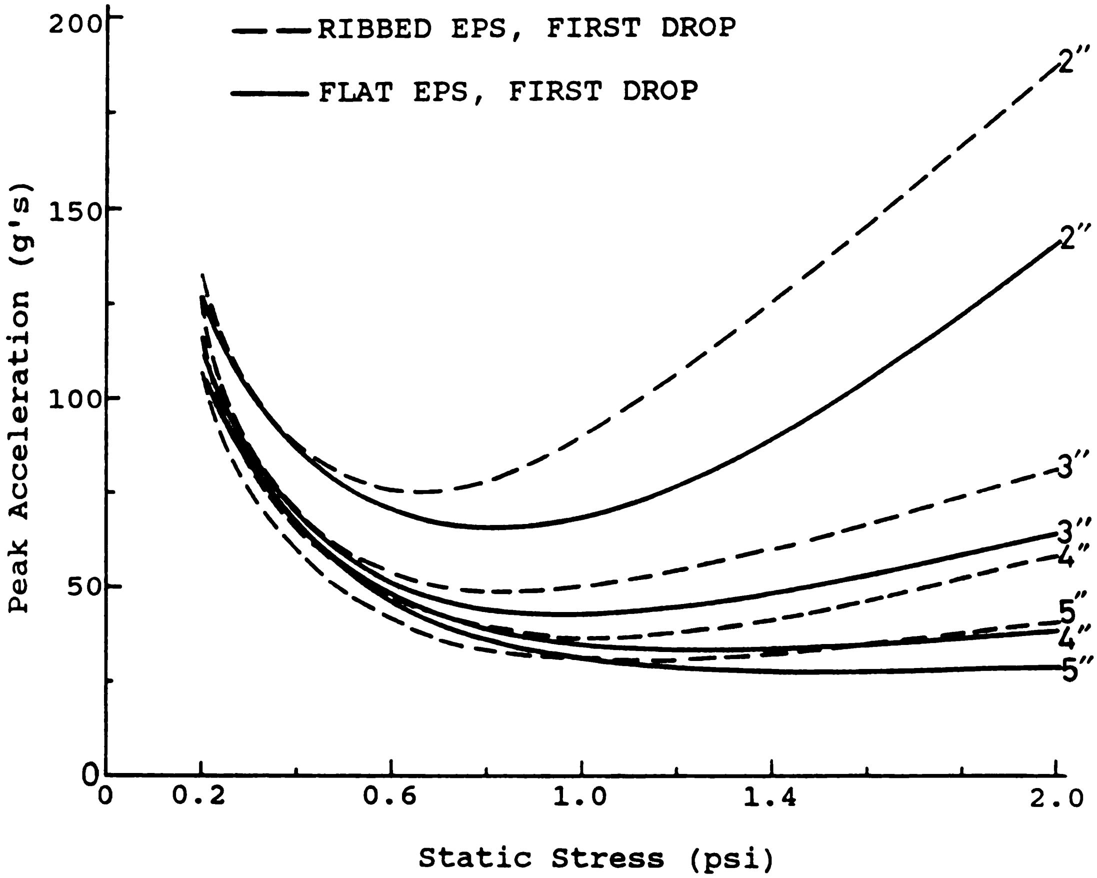


Figure 16. CUSHION CURVES FOR THE COMPARISON OF RIBBED EPS VERSUS FLAT EPS ON SHOCK TRANSMISSION AT 42 in. DROP HEIGHT (1.25 pcf Expanded Polystyrene)

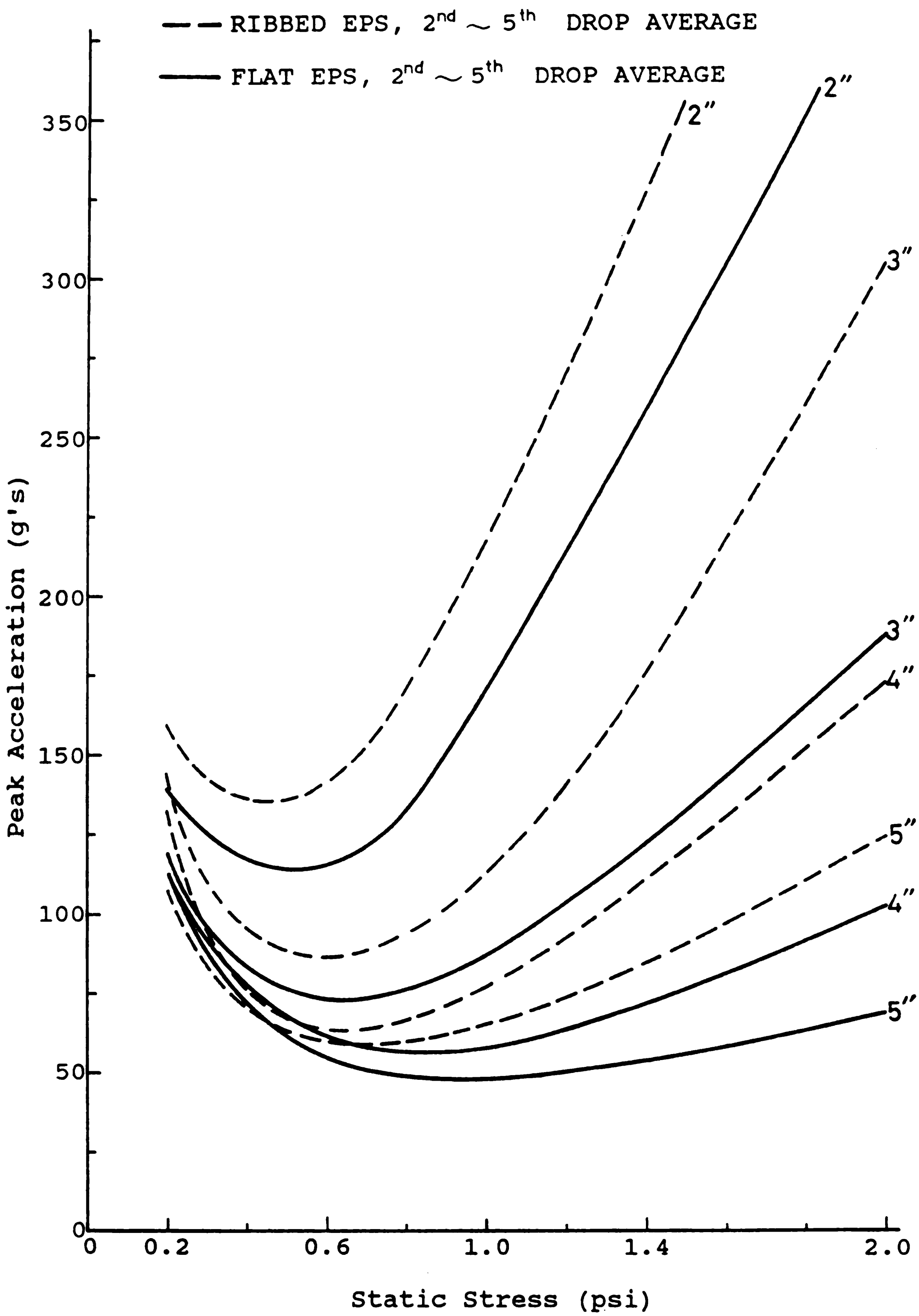


Figure 17. CUSHION CURVES FOR THE COMPARISON OF RIBBED EPS VERSUS FLAT EPS ON SHOCK TRANSMISSION AT 42 in. DROP HEIGHT (1.25 pcf Expanded Polystyrene)

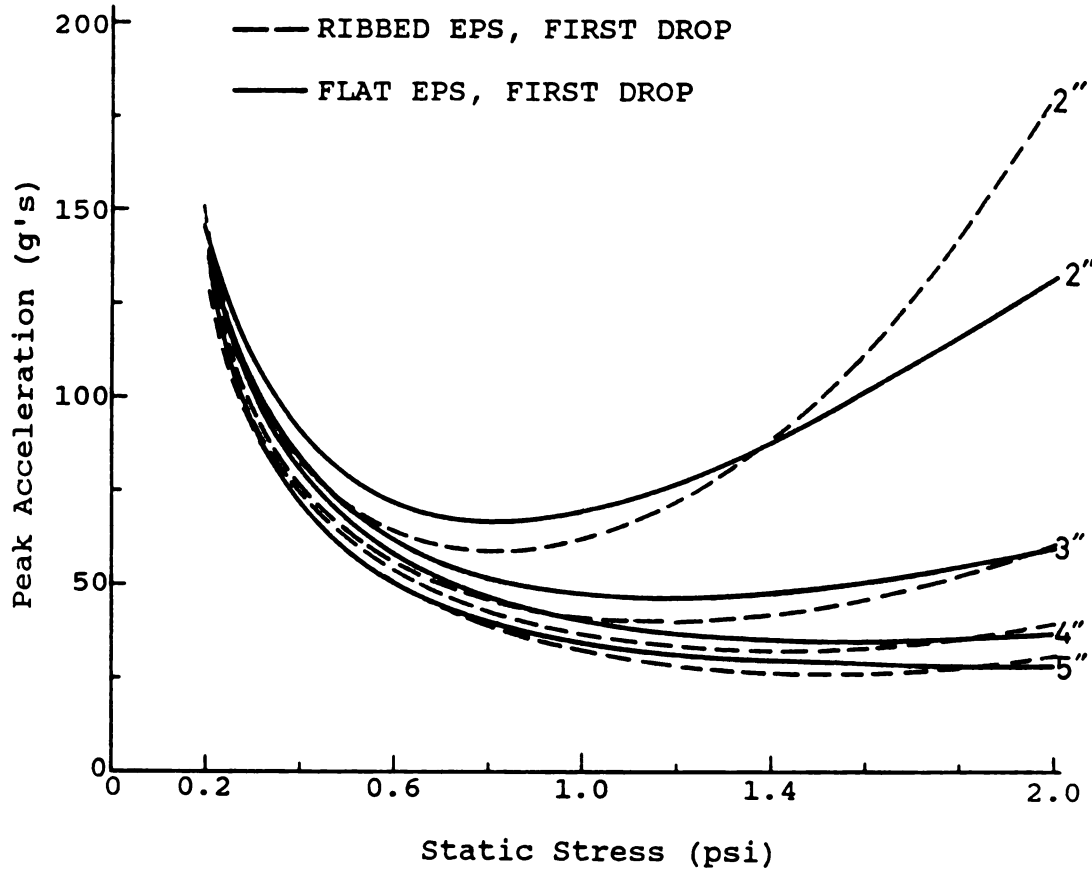


Figure 18. CUSHION CURVES FOR THE COMPARISON OF RIBBED EPS VERSUS FLAT EPS ON SHOCK TRANSMISSION AT 36 in. DROP HEIGHT (1.35 pcf Expanded Polystyrene)

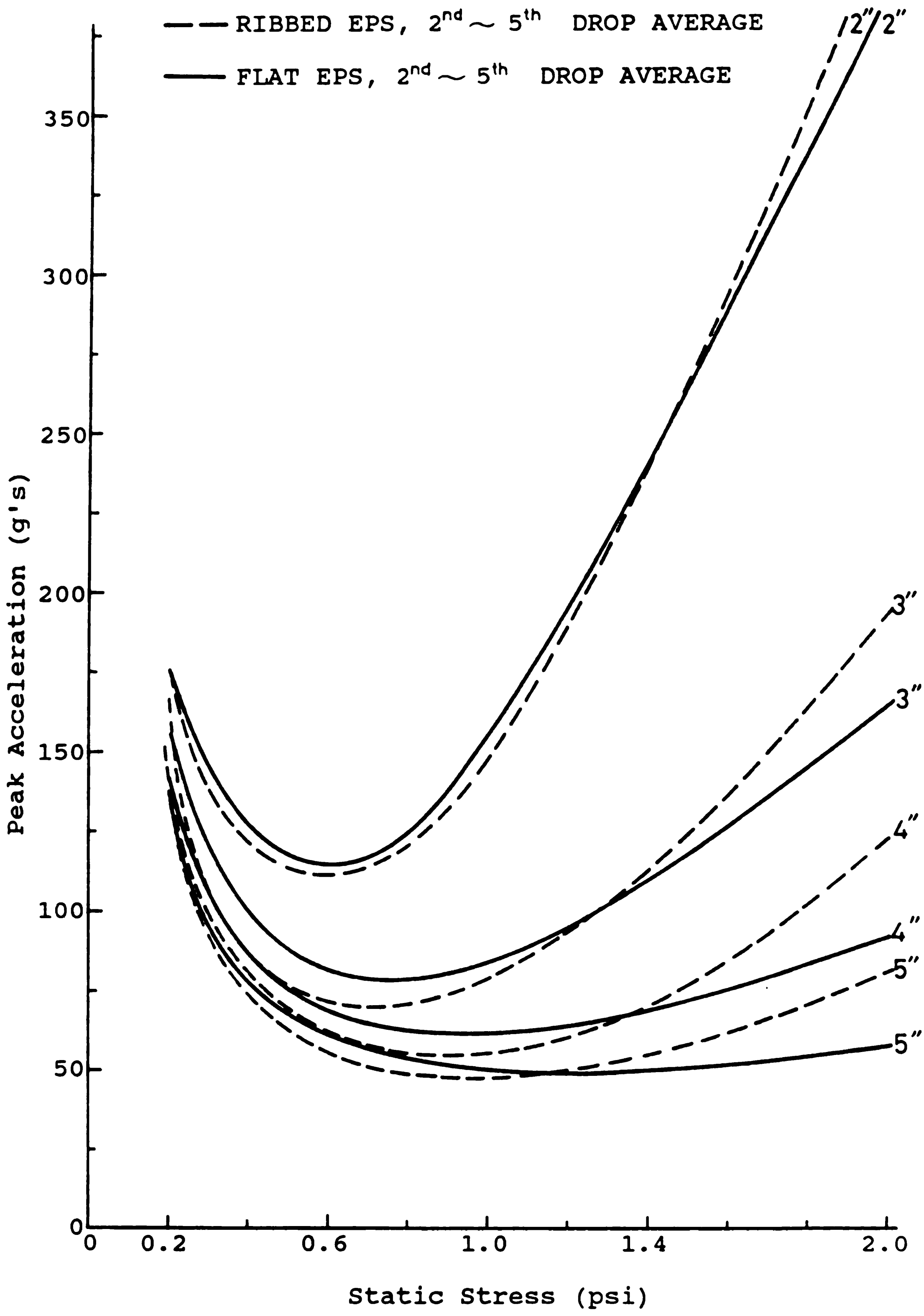


Figure 19. CUSHION CURVES FOR THE COMPARISON OF RIBBED EPS VERSUS FLAT EPS ON SHOCK TRANSMISSION AT 36 in. DROP HEIGHT (1.35 pcf Expanded Polystyrene)

Analysis of Variance (Completely Randomized Design)

Analysis of variance was applied to the raw data in order to explore the significance of the effect of the EPS shape in general, and the static stress level on shock transmission.

The data presented in Tables 2 through 8 (Appendix B) were analyzed in such a way that only the peak acceleration levels obtained from the Ribbed EPS and the Flat EPS samples of same density, thickness and drop height were compared. Thus a Completely Randomized Design by factorial effects where two variables (EPS shape and static stress level) were included.

A representative data set-up (i.e., 1.25 pcf EPS at 36 inches drop height) for the Completely Randomized Design Analysis of Variance is shown in Appendix C, while the results of Analysis of Variance are presented in Table 9.

Table 9. ANALYSIS OF VARIANCE (COMPLETELY RANDOMIZED DESIGN) OF ONE SAMPLE SET (3 inch 1.25 pcf EPS AT 36 inch DROP HEIGHT)

		FIRST DROP			2nd--5th DROP AVERAGE		
SOURCE	DF	SS	MS	F	SS	MS	F
TOTAL	29	18217.0			68763.4		
TREATMENT	9	18099.0			68502.0		
SHAPE	1	381.6	381.6	64.9**	3967.7	3967.5	303.6**
S. STRESS	4	17345.8	4336.5	735.0**	63213.9	15803.5	1209.1**
SHAPE x σ	4	371.5	92.9	15.7**	1320.7	330.2	25.3**
ERROR	20	118.0	5.9		216.3	13.1	

SS = Sum of square
DF = Degree of freedom
MS = Mean of square
F = F test value

The significance levels for the effect of EPS shape on peak acceleration level (g's) at each test combination are listed in Table 10.

Table 10. SIGNIFICANCE LEVEL OF EFFECT OF EPS SHAPE ON SHOCK TRANSMISSION (g's)

OVERALL THICKNESS (inch)		DROP HEIGHT (inch)						
		1.25 pcf EPS						1.35 pcf EPS
		12	18	24	30	36	42	36
2	FIRST DROP	ns	ns	**	**	**	**	*
	2nd--5th DROP AVERAGE	**	**	**	**	**	**	ns
3	FIRST DROP	ns	ns	ns	**	**	**	*
	2nd--5th DROP AVERAGE	ns	ns	**	**	**	**	**
4	FIRST DROP	**	**	**	**	ns	**	ns
	2nd--5th DROP AVERAGE	ns	*	**	**	**	**	*
5	FIRST DROP	*	**	**	**	ns	*	*
	2nd--5th DROP AVERAGE	**	**	ns	**	**	**	*

*, ** Significant at 5% and 1% level of probability respectively

ns Not significant

Pairwise Comparison of Ribbed EPS versus Flat EPS on Shock Transmission

In order to investigate the existence and significance of the difference between Ribbed EPS and Flat EPS on shock transmission , a Pairwise Comparison was performed. Peak acceleration levels obtained from Ribbed EPS and Flat EPS samples at each test combination were compared. Appendix D illustrates a Pairwise Comparison of Ribbed EPS versus Flat EPS on shock transmission for one sample set (i.e., 3 inch thick 1.25 pcf EPS at 36 inch drop height). Table 11 presents the significance levels for the differences between Ribbed EPS and Flat EPS on shock transmission at each test combination.

A comparison of Ribbed EPS versus Flat EPS on the final thicknesses of tested samples was conducted. A representative comparison of Ribbed EPS versus Flat EPS on the final thickness of one sample set (i.e., 1.25 pcf EPS at 24 inch drop height) is shown in Appendix E.

Table 11. SIGNIFICANCE LEVEL OF DIFFERENCE BETWEEN RIBBED EPS AND FLAT EPS ON SHOCK TRANSMISSION (g'S)

OVERALL THICKNESS (inch)		FIRST DROP							2th--5th DROP AVERAGE						
		1.25 pcf EPS						1.35 pcf EPS	1.25 pcf EPS						1.35 pcf EPS
		DROP HEIGHT (inch)							DROP HEIGHT (inch)						
		12	18	24	30	36	42	36	12	18	24	30	36	42	36
2	0.2 psi	ns	ns	ns	ns	**	ns	+	ns	ns	ns	ns	ns	*	ns
	0.6 psi	ns	ns	ns	*	*	**	++	+	ns	**	**	**	**	+
	1.0 psi	*	+	ns	*	*	**	+	ns	ns	ns	**	**	*	ns
	1.4 psi	ns	*	*	**	**	**	++	+	**	*	**	**	*	++
	2.0 psi	ns	**	**	**	**	**	**	**	**	**	**	**	**	ns
3	0.2 psi	*	ns	ns	*	ns	*	ns	ns	ns	**	ns	ns	*	ns
	0.6 psi	+	ns	ns	**	+	ns	ns	++	++	*	**	**	**	++
	1.0 psi	+	+	ns	**	*	*	+	++	ns	ns	**	**	**	++
	1.4 psi	ns	*	ns	**	*	**	++	ns	ns	+	**	**	**	ns
	2.0 psi	ns	ns	ns	*	**	**	ns	ns	++	*	**	**	**	**
4	0.2 psi	++	++	**	*	ns	ns	**	ns	ns	ns	ns	ns	**	+
	0.6 psi	+	+	ns	ns	ns	ns	ns	++	++	ns	ns	ns	ns	ns
	1.0 psi	ns	ns	ns	ns	ns	ns	ns	++	+	*	**	**	**	+
	1.4 psi	ns	ns	ns	*	ns	*	ns	ns	ns	**	**	**	**	+
	2.0 psi	ns	ns	**	**	ns	*	ns	ns	**	**	**	**	**	**
5	0.2 psi	ns	ns	*	*	ns	ns	ns	+	ns	+	ns	ns	ns	ns
	0.6 psi	ns	+	ns	ns	++	++	ns	ns	+	ns	ns	ns	ns	+
	1.0 psi	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	**	**	**	ns
	1.4 psi	ns	ns	+	ns	ns	*	++	ns	ns	*	**	**	**	ns
	2.0 psi	ns	+	+	*	ns	**	**	ns	ns	**	**	**	**	**

*, ** Ribbed EPS yielded higher g's over Flat EPS at 5% and 1% level of probability respectively

+, ++ Flat EPS yielded higher g's over Ribbed EPS at 5% and 1% level of probability respectively

ns Not significant

RESULTS

This study intended to explore the effect of the geometric shape of EPS on shock transmission. This section presents the results of the study. The results are described in the order of the two questions that lead to this investigation (see page 3).

With regard to the difference between Ribbed EPS and Flat EPS on shock transmission the following was observed. At low drop heights (i.e., between 12 and 24 inches) the peak acceleration levels obtained from Ribbed EPS and Flat EPS showed no significant difference, while peak accelerations differed significantly at greater drop heights (i.e., between 30 and 42 inches) in such a way that Ribbed EPS produced higher peak acceleration levels. Further, it appeared that Ribbed EPS yielded greater peak accelerations under high static stress levels (i.e., 1.4 psi and higher) than did Flat EPS.

Focussing on the difference between first drop and multiple drops on shock transmission the following observations were made.

Both Ribbed EPS and Flat EPS exhibited progressive increases in peak acceleration levels due to multiple drops. Each sequential drop caused an additional permanent deformation to the test specimen, making the spring constant (k) of the test specimen greater and the deflection (δst) of the cushion smaller. The peak acceleration level Gm can be expressed as follows (5);

$$Gm = \sqrt{\frac{2hk}{W}} \qquad \text{or} \qquad Gm = \sqrt{\frac{2h}{\delta st}}$$

where: Gm = peak acceleration

h = drop height

k = spring constant

W = weight of product or loading force

δst = static deflection of test specimen

The results of the comparison of Ribbed EPS versus Flat EPS on the final thickness showed that the difference between Ribbed EPS and Flat EPS final thicknesses at 12 in., 18 in. and 24 in. drop heights was not significant, while at at 30 in., 36 in. and 42 in. drop heights Ribbed EPS samples exhibited greater amount of permanent deformation.

Further, it was noticed that 5 inch thick Ribbed EPS samples fell apart after the fifth drop at 24 inch drop height, while at 30 inch or larger drop height, Ribbed EPS samples cracked severely after the third drop and fell apart completely after the fourth drop.

Finally, 1.35 pcf EPS yielded lower peak acceleration levels than 1.25 pcf EPS at 36 inch drop height and under high static stress levels (i.e., 1.4 psi and greater), while under low static stress levels (i.e., 1.0 psi and lower) 1.35 pcf PS produced greater peak accelerations than did 1.25 pcf EPS.

DISCUSSION

The purpose of this study was to investigate the influence of the geometric shape of EPS cushion on shock transmission. Both Ribbed EPS and Flat EPS samples of four different thicknesses were tested at six different drop heights under each of five static stress levels.

The results showed the following: 1) differences between Ribbed EPS and Flat EPS on peak acceleration levels exist, and they appear to depend on drop height and static stress level; 2) differences between first drop and multiple drops on peak acceleration levels are greater for Ribbed EPS than for Flat EPS.

The differences between Ribbed EPS and Flat EPS on shock transmission in general indicate that Ribbed EPS suffers a higher degree of permanent deformation under the same conditions than does Flat EPS. This finding implies that Flat EPS cushion curves can not be applied to Ribbed EPS cushion curves at drop heights of 30 inches and higher and/or under static stress levels of 1.4 psi and higher.

With regard to the results of first drop and multiple drops on shock transmission, greater increases in peak accelerations for multiple drops were found for Ribbed EPS as compared to that of Flat EPS. Thus, although Ribbed EPS and Flat EPS show the same tendency to produce higher peak acceleration levels due to multiple drops, Ribbed EPS cushions appear to suffer a higher degree of permanent deformation.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Cushion curves for Ribbed EPS and Flat EPS were constructed in this study. The results revealed differences between Ribbed EPS and Flat EPS on shock transmission depending on drop height and static stress level. It was observed that at smaller drop heights and lower static stress levels the peak acceleration levels obtained from Ribbed EPS and Flat EPS were similar. However, at larger drop heights or under high static stress levels, the cushion curves for Ribbed EPS and Flat EPS differed significantly. Therefore, it can be concluded that cushion curves developed on planks are inadequate to describe the cushioning behavior of Ribbed EPS under certain conditions.

This implies that the effect of ribs of EPS cushion must be taken into account as a factor in peak acceleration when designing a cushion package for a fragile article. Especially drop height, static stress level, and density of the Ribbed EPS cushion should be considered.

RECOMMENDATIONS

It is important to determine the effective bearing area properly when designing a Ribbed EPS cushion package. This is because changes in static stress levels depend on changes in effective bearing area (given that the loading force is maintained constant). Further, it is shown that static stress levels influence peak acceleration levels greatly.

With regard to density a denser EPS is recommended when designing a Ribbed EPS cushion package. This is because at larger drop heights (36 inches and higher) and/or under higher static stress levels (1.4 psi and higher) denser Ribbed EPS cushions suffer less permanent deformation from each drop, as shown by their lower peak acceleration levels.

IMPLICATIONS OF THIS STUDY

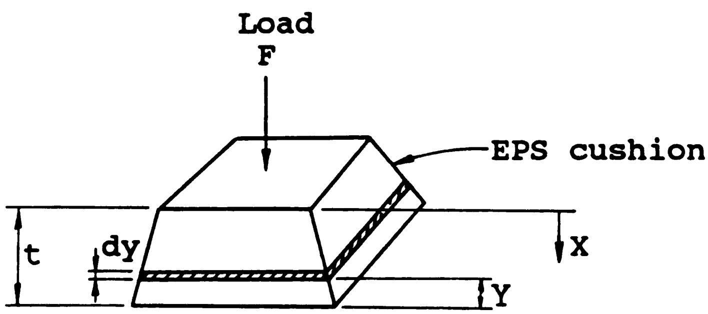
The main implications of this study are of practical value: knowledge of effect of Ribbing on shock transmission through Expanded Polystyrene cushion allows for more economical designing of Ribbed EPS cushion package with regard to time and material.

APPENDICES

APPENDIX A

DETERMINATION OF EFFECTIVE BEARING AREA FOR RIBBED EPS TEST SAMPLE

Assume that the spring constant, k, for EPS is linear in all cases. Consider a cushion with a variable crossection as shown below;



At any section of Y Hooke's Law applies so that

$$\sigma = \frac{F}{A} = E\epsilon = E\frac{dx}{dy}$$

where:
- t = Thickness of cushion
- σ = Static stress
- F = Loading force
- A* = Effective bearing area
- E = Young's modulus of elasticity
- ϵ = Strain
- dy = Elemental thickness
- dx = Compression of slice dy of cushion

Since $\frac{F}{A} = E\frac{dx}{dy}$,

$$dx = \frac{F}{EA}dy \qquad \text{Equation (1)}$$

Appendix A (Continued)

Integrating both sides of Equation (1)

$$\int_0^X dx = \int_0^t \frac{F}{EA} dy$$

The total deflection X of this cushion is

$$X = \frac{F}{E}\int_0^t \frac{dy}{A} \qquad \text{Equation (2)}$$

Equation (2) can be written as $F = \dfrac{E}{\int_0^t \frac{dy}{A}} X$ Equation (4)

If the crossectional area is constant, then Equation (3) reduces to $F = \frac{EA}{t}X$. Denoting by A^* the effective bearing area defined to be the area which gives the simple force/ deformation relation for a constant crossection,

$$\frac{F}{X} = \frac{EA^*}{t} = \frac{E}{\int_0^t \frac{dy}{A}} \qquad \text{Equation (4)}$$

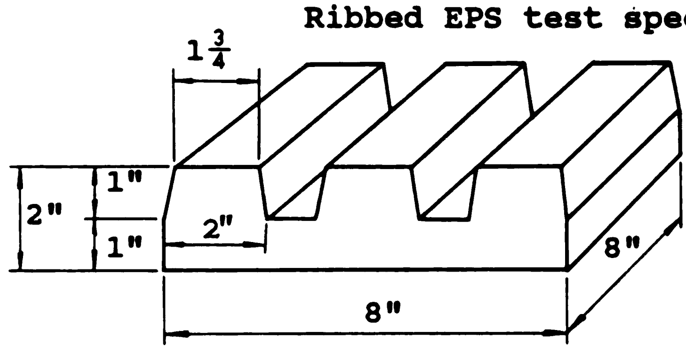
Therefore, the effective bearing area (A^*) is

$$A^* = \frac{t}{\int_0^t \frac{dy}{A}} \qquad \text{Equation (5)}$$

In this study, the effective bearing area for a 2 inch thick Ribbed EPS sample was determined using Equation (5) and the figure below;

Appendix A (Continued)

Ribbed EPS test specimen



The entire cushion specimen consists of two portions, the base and the three ribs, so that the integral in Equation (5) must be split into two parts;

$$\int_0^t \frac{dy}{A} = \int_0^1 \frac{dy}{64} + \int_1^2 \frac{dy}{A(y)}$$

where:

$$A(y) = 3 \times 8\left(\frac{9}{4} - \frac{y}{4}\right)$$

$$= 6(9-y)$$

$$= \int_0^1 \frac{dy}{64} + \int_1^2 \frac{dy}{6(9-y)}$$

$$= \frac{1}{64}\int_0^1 dy + \frac{1}{6}\int_1^2 \frac{dy}{9-y}$$

$$= \frac{1}{64} - \frac{1}{6}\mathrm{Ln}(9-y)\Big|_1^2$$

$$= \frac{1}{64} - \frac{1}{6}(\mathrm{Ln}7 - \mathrm{Ln}8)$$

$$= \frac{1}{64} - \frac{1}{6}\mathrm{Ln}\frac{7}{8}$$

$$= 0.03788$$

Appendix A (Continued)

The effective bearing area from Equation (5) is

$$A^* = \frac{t}{\int_0^t \frac{dy}{A}} = \frac{2}{0.03788} = 52.80 \text{ (sq in)}$$

Note that A^* is between the maximum area (64 in^2) and the minimum area (42 in^2) as expected.

The effective bearing areas for 3, 4, and 5 inch thick Ribbed EPS test samples were determined in the same way and the results are;

Overall thickness of Ribbed EPS (inch)	Effective bearing area (sq in)
3	47.19
4	42.57
5	38.12

APPENDIX B

Table 2. PEAK ACCELERATION TRANSMITTED THROUGH 1.25 pcf EXPANDED POLYSTYRENE AT 12 inch DROP HEIGHT

STATIC STRESS (psi)	DROP No.	PEAK ACCELERATION (g's)							
		2 inch		3 inch		4 inch		5 inch	
		FLAT	RIBBED	FLAT	RIBBED	FLAT	RIBBED	FLAT	RIBBED
0.2	1	96	98	94	100	93	76	90	85
	2	96	102	95	103	93	97	92	83
	3	98	101	97	98	94	92	94	86
	4	100	104	98	102	95	94	96	87
	5	103	101	100	102	97	98	97	82
	2-5 AVE	99	102	97	101	95	95	95	85
0.6	1	46	43	44	38	43	36	42	38
	2	49	48	40	40	44	39	43	38
	3	51	48	50	41	45	39	44	40
	4	52	50	47	42	47	41	46	39
	5	52	51	46	43	48	42	47	39
	2-5 AVE	51	49	47	42	46	40	45	39
1.0	1	33	28	28	25	28	25	26	27
	2	37	32	30	29	31	28	29	27
	3	41	38	32	31	32	29	30	28
	4	42	41	34	32	33	29	30	28
	5	44	44	35	32	33	30	30	28
	2-5 AVE	41	39	33	31	32	29	30	28
1.4	1	24	25	20	20	20	20	19	20
	2	29	32	24	25	21	22	22	20
	3	34	37	25	27	23	24	23	20
	4	36	42	27	28	25	25	24	21
	5	38	45	28	30	26	25	24	21
	2-5 AVE	34	39	26	28	24	24	23	21
2.0	1	20	24	16	17	16	14	15	14
	2	30	36	22	23	18	18	17	16
	3	35	44	26	27	21	20	19	17
	4	39	48	28	30	22	23	20	19
	5	41	51	29	32	23	26	21	20
	2-5 AVE	36	45	26	28	21	22	19	18

Appendix B (Continued)

Table 3. PEAK ACCELERATION TRANSMITTED THROUGH 1.25 pcf EXPANDED POLYSTYRENE AT 18 inch DROP HEIGHT

STATIC STRESS (psi)	DROP No.	PEAK ACCELERATION (g's)							
		2 inch		3 inch		4 inch		5 inch	
		FLAT	RIBBED	FLAT	RIBBED	FLAT	RIBBED	FLAT	RIBBED
	1	108	104	104	105	102	92	100	90
	2	109	114	105	104	102	93	100	93
0.2	3	110	111	105	105	103	100	99	97
	4	112	118	107	107	104	98	100	91
	5	113	110	108	107	105	99	101	97
	2-5 AVE	110	113	106	106	104	98	100	94
	1	51	48	46	41	46	39	45	41
	2	56	53	49	45	48	41	48	41
0.6	3	61	57	51	48	50	43	47	44
	4	64	60	52	49	50	44	49	44
	5	65	66	52	49	51	44	50	43
	2-5 AVE	61	59	51	48	50	43	49	43
	1	37	32	31	28	31	28	29	28
	2	46	47	35	33	32	29	22	29
1.0	3	53	55	40	36	34	32	34	29
	4	58	60	44	40	34	33	35	29
	5	60	63	46	44	36	34	36	30
	2-5 AVE	54	56	41	38	34	32	35	29
	1	28	33	23	25	21	22	21	18
	2	42	50	29	30	25	26	23	22
1.4	3	52	62	34	35	27	28	25	26
	4	57	68	38	40	30	30	27	28
	5	61	72	40	44	31	30	28	31
	2-5 AVE	53	63	35	37	28	29	26	27
	1	30	38	21	21	18	17	17	14
	2	51	71	32	34	25	28	21	20
2.0	3	65	86	39	43	29	34	25	26
	4	72	98	43	49	31	40	26	30
	5	79	106	45	54	32	43	27	32
	2-5 AVE	70	90	40	45	29	36	25	27

Appendix B (Continued)

Table 4. PEAK ACCELERATION TRANSMITTED THROUGH 1.25 pcf EXPANDED POLYSTYRENE AT 24 inch DROP HEIGHT

STATIC STRESS (psi)	DROP No.	PEAK ACCELERATION (g's)							
		2 inch		3 inch		4 inch		5 inch	
		FLAT	RIBBED	FLAT	RIBBED	FLAT	RIBBED	FLAT	RIBBED
0.2	1	112	108	105	104	101	98	100	97
	2	110	116	101	108	100	113	125	98
	3	112	118	102	112	105	105	125	99
	4	114	122	105	113	106	121	120	101
	5	113	117	110	119	107	122	120	103
	2-5 AVE	112	118	105	113	105	115	123	100
0.6	1	55	51	44	43	42	43	41	42
	2	56	62	47	50	45	46	47	44
	3	62	74	51	53	48	47	47	44
	4	66	78	54	55	49	49	49	46
	5	69	83	55	58	49	50	48	44
	2-5 AVE	63	74	52	54	48	48	48	45
1.0	1	42	43	33	32	31	29	31	29
	2	59	64	43	41	36	34	34	31
	3	71	75	48	47	40	37	35	33
	4	79	85	52	51	43	40	38	34
	5	85	91	54	56	44	41	39	38
	2-5 AVE	74	79	49	49	41	38	37	34
1.4	1	35	44	27	29	24	25	23	18
	2	66	73	38	42	32	30	27	29
	3	81	92	49	52	35	36	31	37
	4	91	108	55	60	39	41	33	42
	5	99	119	59	65	41	44	34	47
	2-5 AVE	84	98	50	55	37	38	31	39
2.0	1	48	65	29	32	22	24	20	20
	2	90	121	49	54	32	43	27	34
	3	118	153	61	69	40	55	31	47
	4	134	176	69	78	45	62	34	53
	5	144	192	73	85	46	69	36	59
	2-5 AVE	122	161	63	71	41	57	32	48

Appendix B (Continued)

Table 5. PEAK ACCELERATION TRANSMITTED THROUGH 1.25 pcf EXPANDED POLYSTYRENE AT 30 inch DROP HEIGHT

STATIC STRESS (psi)	DROP No.	PEAK ACCELERATION (g's)							
		2 inch		3 inch		4 inch		5 inch	
		FLAT	RIBBED	FLAT	RIBBED	FLAT	RIBBED	FLAT	RIBBED
0.2	1	107	115	101	113	99	109	92	102
	2	117	123	112	114	114	114	93	108
	3	123	126	117	118	108	120	98	107
	4	120	130	112	121	104	113	99	111
	5	129	140	114	112	107	118	99	111
	2-5 AVE	122	130	114	121	108	116	97	109
0.6	1	56	63	47	48	42	43	40	38
	2	75	91	56	59	49	48	43	39
	3	87	107	62	66	52	52	47	44
	4	95	118	66	71	55	54	49	48
	5	99	126	68	75	57	58	49	54
	2-5 AVE	89	111	63	68	53	53	47	46
1.0	1	56	66	37	41	30	32	27	26
	2	92	113	54	64	40	46	34	40
	3	111	142	62	78	47	54	39	48
	4	123	154	67	88	50	60	41	56
	5	132	173	70	96	52	65	42	60
	2-5 AVE	114	146	63	81	47	56	39	51
1.4	1	67	78	37	45	28	32	25	25
	2	126	154	59	76	42	54	33	43
	3	160	198	72	100	51	68	40	55
	4	181	229	80	114	56	79	42	63
	5	197	251	88	125	59	87	45	72
	2-5 AVE	166	208	75	104	52	72	40	58
2.0	1	96	120	47	57	30	34	23	39
	2	190	244	87	112	51	70	35	57
	3	239	326	109	146	62	92	39	73
	4	273	365	124	169	70	108	49	82
	5	294	416	136	191	73	119	53	89
	2-5 AVE	249	338	114	155	64	97	44	75

Appendix B (Continued)

Table 6. PEAK ACCELERATION TRANSMITTED THROUGH 1.25 pcf EXPANDED POLYSTYRENE AT 36 inch DROP HEIGHT

STATIC STRESS (psi)	DROP No.	PEAK ACCELERATION (g's)							
		2 inch		3 inch		4 inch		5 inch	
		FLAT	RIBBED	FLAT	RIBBED	FLAT	RIBBED	FLAT	RIBBED
0.2	1	127	154	106	120	108	105	104	100
	2	142	130	119	126	114	110	110	112
	3	150	139	127	131	119	117	112	114
	4	153	139	122	136	117	103	110	110
	5	157	145	127	136	118	104	109	112
	2-5 AVE	151	138	124	132	117	109	110	112
0.6	1	67	75	55	51	48	45	40	35
	2	93	119	67	69	55	55	49	43
	3	109	144	74	83	61	62	55	56
	4	118	158	78	91	64	66	57	61
	5	127	170	82	96	66	70	58	65
	2-5 AVE	112	148	75	85	62	63	55	56
1.0	1	70	89	47	48	36	36	30	29
	2	129	165	72	86	50	56	40	49
	3	162	214	88	108	58	71	47	61
	4	182	240	95	120	62	85	51	70
	5	197	259	102	128	67	90	54	79
	2-5 AVE	167	220	89	110	59	76	48	65
1.4	1	97	134	49	62	35	38	28	32
	2	196	241	89	115	57	74	44	60
	3	248	309	114	145	68	96	52	78
	4	280	356	128	168	73	111	58	81
	5	303	391	140	190	79	123	61	91
	2-5 AVE	257	324	118	155	69	101	54	78
2.0	1	125	185	70	81	46	51	38	38
	2	304	397	138	170	76	103	58	78
	3	395	495	180	186	98	140	70	104
	4	450	561	216	274	117	160	79	118
	5	489	602	244	306	136	180	87	152
	2-5 AVE	410	514	194	234	107	146	73	113

Appendix B (Continued)

Table 7. PEAK ACCELERATION TRANSMITTED THROUGH 1.25 pcf EXPANDED POLYSTYRENE AT 42 inch DROP HEIGHT

STATIC STRESS (psi	DROP No.	PEAK ACCELERATION (g's)							
		2 inch		3 inch		4 inch		5 inch	
		FLAT	RIBBED	FLAT	RIBBED	FLAT	RIBBED	FLAT	RIBBED
0.2	1	126	132	111	126	107	116	105	105
	2	130	148	115	131	110	138	110	108
	3	139	115	119	146	113	146	110	109
	4	141	162	120	147	113	128	113	112
	5	145	173	124	151	117	123	114	107
	2-5 AVE	139	160	119	144	113	134	112	109
0.6	1	66	75	51	53	48	45	46	35
	2	93	114	54	70	55	54	50	45
	3	110	138	74	84	61	61	54	57
	4	125	151	79	93	65	67	58	64
	5	134	162	84	97	66	70	58	73
	2-5 AVE	115	141	73	86	62	63	55	60
1.0	1	69	93	44	51	35	37	31	31
	2	129	166	66	88	48	56	40	55
	3	169	215	83	110	56	75	47	69
	4	200	243	97	126	62	87	50	82
	5	222	264	115	138	65	95	54	89
	2-5 AVE	180	222	90	116	58	78	48	74
1.4	1	87	125	47	60	33	41	28	36
	2	184	245	87	115	56	79	43	69
	3	249	311	112	149	68	103	51	89
	4	293	364	134	175	73	119	56	101
	5	320	398	154	197	81	133	61	109
	2-5 AVE	262	330	122	159	69	109	53	92
2.0	1	142	189	65	81	39	59	29	41
	2	303	370	138	164	77	123	52	86
	3	384	460	183	222	100	164	68	115
	4	437	518	209	259	116	199	76	142
	5	480	560	230	291	122	232	81	158
	2-5 AVE	401	477	190	312	104	180	69	125

Appendix B (Continued)

Table 8. PEAK ACCELERATION TRANSMITTED THROUGH 1.35 pcf EXPANDED POLYSTYRENE AT 36 inch DROP HEIGHT

STATIC STRESS (psi)	DROP No.	PEAK ACCELERATION (g's)							
		2 inch		3 inch		4 inch		5 inch	
		FLAT	RIBBED	FLAT	RIBBED	FLAT	RIBBED	FLAT	RIBBED
0.2	1	147	134	143	146	139	151	137	129
	2	166	195	153	161	141	148	138	132
	3	173	173	160	169	146	137	139	152
	4	181	169	160	166	145	131	138	162
	5	181	163	155	168	141	130	139	162
	2-5 AVE	175	175	157	166	143	137	139	152
0.6	1	72	63	63	55	58	53	50	51
	2	96	91	71	63	63	62	58	52
	3	111	108	80	69	69	62	61	52
	4	122	118	86	74	72	65	64	53
	5	130	128	89	78	74	68	65	55
	2-5 AVE	114	111	81	71	69	64	62	53
1.0	1	70	63	47	42	41	38	36	33
	2	119	110	69	60	51	47	45	38
	3	152	144	84	76	60	54	49	46
	4	169	171	91	87	66	60	51	51
	5	181	187	97	96	69	63	54	57
	2-5 AVE	155	153	85	80	62	56	50	48
1.4	1	88	72	46	40	36	32	31	25
	2	176	145	79	74	53	47	40	40
	3	235	198	100	98	67	62	46	52
	4	269	233	111	117	75	74	50	61
	5	290	262	120	131	80	83	55	68
	2-5 AVE	243	209	102	105	69	66	48	55
2.0	1	131	185	60	62	36	40	28	32
	2	281	312	123	136	68	87	46	60
	3	380	408	163	186	88	120	58	78
	4	435	465	190	220	102	135	65	88
	5	468	505	210	243	113	149	68	99
	2-5 AVE	391	422	171	196	93	123	59	81

APPENDIX C

DATA SET-UP FOR ANALYSIS OF VARIANCE (COMPLETELY RANDOMIZED DESIGN) OF ONE SAMPLE SET (1.25 pcf EPS)

DROP HEIGHT = 36 inch OVERALL THICKNESS OF EPS = 3 inch

EPS SHAPE	STATIC STRESS (psi)	PEAK ACCELERATION (g's)							
		FIRST DROP				2nd--5th DROP AVERAGE			
					TOTAL				TOTAL
	0.2	106	112	101	319	124	121	127	372
	0.6	55	55	54	164	77	74	76	227
FLAT	1.0	47	47	46	140	90	89	88	267
	1.4	47	49	53	149	118	119	117	354
	2.0	70	71	68	209	193	196	195	584
	0.2	124	119	117	360	140	126	130	396
	0.6	51	50	51	152	86	85	85	256
RIBBED	1.0	49	48	48	145	110	110	109	329
	1.4	62	63	62	187	153	162	151	466
	2.0	81	83	80	244	232	240	230	702

APPENDIX D

PAIRWISE COMPARISON OF RIBBED EPS VERSUS FLAT EPS ON SHOCK TRANSMISSION (g's) OF ONE SAMPLE SET (1.25 pcf EPS)

DROP HEIGHT = 36 inch OVERALL THICKNESS OF EPS = 3 inch

STATIC STRESS (psi)	FIRST DROP			2nd--5th DROP AVERAGE		
	RIBBED	FLAT	DIFF.	RIBBED	FLAT	DIFF.
	124	106	18	140	124	16
	119	112	7	126	121	5
0.2	117	101	16	130	127	3
			41			24
	$t = \frac{\bar{d}}{Sd} = \frac{13.67}{3.38} = 4.04$ ns			$t = \frac{\bar{d}}{Sd} = \frac{8}{4.4} = 1.98$ ns		
	51	55	-4	86	77	9
	50	55	-5	85	74	11
0.6	51	54	-3	85	76	9
			-12			29
	$t = \frac{\bar{d}}{Sd} = \frac{-4}{0.58} = -6.90$ +			$t = \frac{\bar{d}}{Sd} = \frac{9.67}{0.67} = 14.22$ **		
	49	47	2	110	90	20
	48	47	1	110	89	21
1.0	48	46	2	109	88	21
			5			62
	$t = \frac{\bar{d}}{Sd} = \frac{1.67}{0.33} = 5.50$ *			$t = \frac{\bar{d}}{Sd} = \frac{20.67}{0.33} = 62.63$ **		
	62	47	15	153	118	35
	63	49	14	162	119	43
1.4	62	53	9	151	117	34
			38			112
	$t = \frac{\bar{d}}{Sd} = \frac{12.67}{1.86} = 6.81$ *			$t = \frac{\bar{d}}{Sd} = \frac{37.33}{2.85} = 13.10$ **		
	81	70	11	232	193	39
	83	71	12	240	196	44
2.0	80	68	12	230	195	35
			35			118
	$t = \frac{\bar{d}}{Sd} = \frac{11.67}{0.33} = 35.35$ **			$t = \frac{\bar{d}}{Sd} = \frac{39.33}{2.60} = 15.13$ **		

APPENDIX E

COMPARISON OF RIBBED EPS VERSUS FLAT EPS ON THE FINAL THICKNESS OF ONE SAMPLE SET (1.25 pcf EPS AT 24 inch DROP HEIGHT)

STATIC STRESS (psi)	INITIAL THICKNESS=2 in. (50.8 mm) FINAL THICKNESS (mm)			INITIAL THICKNESS=3 in. (76.2 mm) FINAL THICKNESS (mm)		
	RIBBED	FLAT	DIFF.	RIBBED	FLAT	DIFF.
0.2	47.40	47.90	-0.50	97.80	99.20	-1.40
0.6	42.60	43.20	-0.60	91.15	91.10	-0.05
1.0	40.20	41.20	-1.00	87.20	88.50	-1.30
1.4	39.30	39.40	-0.10	83.60	83.13	-0.47
2.0	38.10	37 80	-0.30	81.05	81.10	-0.05
			-1.90			-2.33

$$t=\frac{\bar{d}}{Sd}=\frac{-0.380}{0.222}=-1.712 \text{ ns}$$

$$t=\frac{\bar{d}}{Sd}=\frac{-0.460}{0.374}=-1.246 \text{ ns}$$

STATIC STRESS (psi)	INITIAL THICKNESS=4 in. (101.6 mm) FINAL THICKNESS (mm)			INITIAL THICKNESS=5 in. (127.0 mm) FINAL THICKNESS (mm)		
	RIBBED	FLAT	DIFF.	RIBBED	FLAT	DIFF.
0.2	72.25	73.20	-0.95	122.90	124.80	-1.90
0.6	65.77	66.50	-0.73	116.00	116.53	-0.53
1.0	62.80	63.93	-1.13	111.80	109.73	2.07
1.4	60.35	60.50	-0.15	109.75	106.67	3.08
2.0	60.17	58 10	2.07	104.00	102.87	1.13
			-0.89			3.85

$$t=\frac{\bar{d}}{Sd}=\frac{-0.178}{0.586}=-0.304 \text{ ns}$$

$$t=\frac{\bar{d}}{Sd}=\frac{-0.777}{0.894}=-0.869 \text{ ns}$$

$t_{.10(4)} = 2.132$ $t_{.05(4)} = 3.182$ $t_{.01(4)} = 5.841$

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