

THE APPLICATION OF THE SHOCK
SPECTRUM DERIVED DAMAGE BOUNDARY
THEORY TO THE EVALUATION OF THE
SHOCK TRANSMISSIBILITY OF
CORRUGATED BOARD

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ABSTRACT

This study demonstrates the use of a new theory in shock analysis. This theory was derived from the concept of shock spectrum by Robert E. Newton at Monterey Research Laboratories, Inc.

The author treats corrugated board as a damageable item and locates damage boundaries for A-, B-, and C-flute corrugated board at various static stress levels. These boundaries show the dividing line between shocks which alter and eventually crush the flutes and those shocks which have no effect on the flute structure. Various damaging shocks were applied to the corrugated board samples. The effects of these shocks on the item on the opposite side of the corrugated board were found to be greatly amplified in most cases.

THE APPLICATION OF THE SHOCK SPECTRUM DERIVED
DAMAGE BOUNDARY THEORY TO THE EVALUATION OF
THE SHOCK TRANSMISSIBILITY OF CORRUGATED BOARD

By

Douglas Gregory McCall

A THESIS

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DEDICATION

To my loving wife, Pat, for her patient understanding
and her undying confidence.

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INTRODUCTION

The analysis of transient acceleration pulses has been an important area of study in packaging for many years. When an item is dropped or receives a shock in some manner, it may break or become damaged. It has been known that a soft material placed around an item can reduce the magnitude of the acceleration felt by the item. The ratio of the applied acceleration to the acceleration felt by the item is referred to as the transmissibility of the material. The transmissibility of a material is not always less than one, i.e., the acceleration experienced by the item is not always reduced by the material used as a cushion. In some cases the acceleration experienced by the article is many times the applied acceleration. For this reason, it is important to understand the relationship between the shock and the transmissibility of a material.

The newly expounded Damage Boundary Theory, which is based on a concept of shock spectrum, greatly simplifies the analysis method of measuring the amount of acceleration which an article experiences from various input accelerations. The theory is primarily used to define the input shocks applied directly to an article which will cause a predetermined amount of damage or acceleration to an element of that article.

In this paper the theory is used to define the shocks which will alter, i.e., crush, the flute structure of corrugated board.

Corrugated fibreboard has been growing in use since 1912 and is widely accepted for use as a shipping container for a myriad of products. Investigations have been made of the effect on products shipped in corrugated containers due to various environments. It is the intent of this study to investigate the shocks which cause the board itself to become damaged. The transmissibility of the board changes once it has been damaged. This result is also examined.

EQUIPMENT

The following equipment and apparatus were used to gather the data presented in this document.

1. Shock Machine - Monterey Research Laboratories Model MRL 3636
2. Universal Programmer - Monterey Research Laboratories Model MRL 2680 - Adjusted for square wave pulses
3. Gas Regulator - Monterey Research Laboratories
4. Felt Half Sine Programmer - Monterey Research Laboratories
5. High Strength Plastic Half Sine Programmers - Monterey Research Laboratories
6. Piezoelectric Accelerometers - (2) Kistler Model 808A
7. Charge Amplifiers - (2) Kistler Model 503
8. Band Pass Filter - Krohn-Hite Model 330M
9. Storage Oscilloscope - Tektronix Model 564 with Model 3B3 Time Base and Model 3A72 Dual Amplifier Plug-in Units
10. Laminated Maple Plywood Block - 8-inch cube with provisions for mounting an accelerometer at its geometrical center and for attaching various amounts of weight - Michigan State University Packaging Laboratories

PROCEDURE

An accelerometer was mounted in the plywood block so that transient acceleration pulses applied to the block in a vertical direction could be monitored. As illustrated in Figure 1, the block, with an 8" x 8" sample of corrugated board under it, was placed on the shock table of the shock machine so that shocks could be applied to the lower surface of the board. A metal bar was secured over the block and made immovable by securing a nut above the bar and then one below it. This restrained the block from moving upward away from the table or the corrugated board and restrained the bar from moving toward the table, which would have increased the effective weight of the block during the shock. Another accelerometer was attached directly to the shock table and was used to monitor the shocks which the table received. The shocks which the table received were the shocks which were applied to the bottom surface of the corrugated board. A series of five identical shocks were applied to a given sample of corrugated board. Initially shocks with high ratios of acceleration to velocity change were applied using a single felt programmer. A new sample of corrugated board was inserted for each series of five drops. The velocity change of the shock was increased for each successive series of five drops by incrementing the

drop height 1/8 inch until the magnitude of the response acceleration monitored in the block on the corrugated sample varied by more than 10 percent of its value on the first drop. It was assumed that if this variation occurred, the flute structure was permanently altered. This procedure was followed at static stresses of 0.13, 0.28, 0.38, and 0.52 psi on A-, B-, and C-flute 200-pound test corrugated board. The velocity change was determined from the drop height and the coefficient of restitution for each programmer.

Using rectangular pulses with low ratios of acceleration to velocity change generated with a square wave programmer, the acceleration was incremented by increasing the pressure in the programmer by 100 psi after each series of five successive drops on the same sample until the response varied more than 10 percent. This procedure was followed using the static stresses and board sizes stated in the previous paragraph from a drop height of 25 inches.

The high strength plastic programmers were used to generate shocks which caused a definite variation in the response shock. The shocks were applied as before to the four static stresses on each board size in series of five identical inputs. Drop heights of 3, 6, 9, and 12 inches were used.

SCHEMATIC DIAGRAM OF TESTING APPARATUS

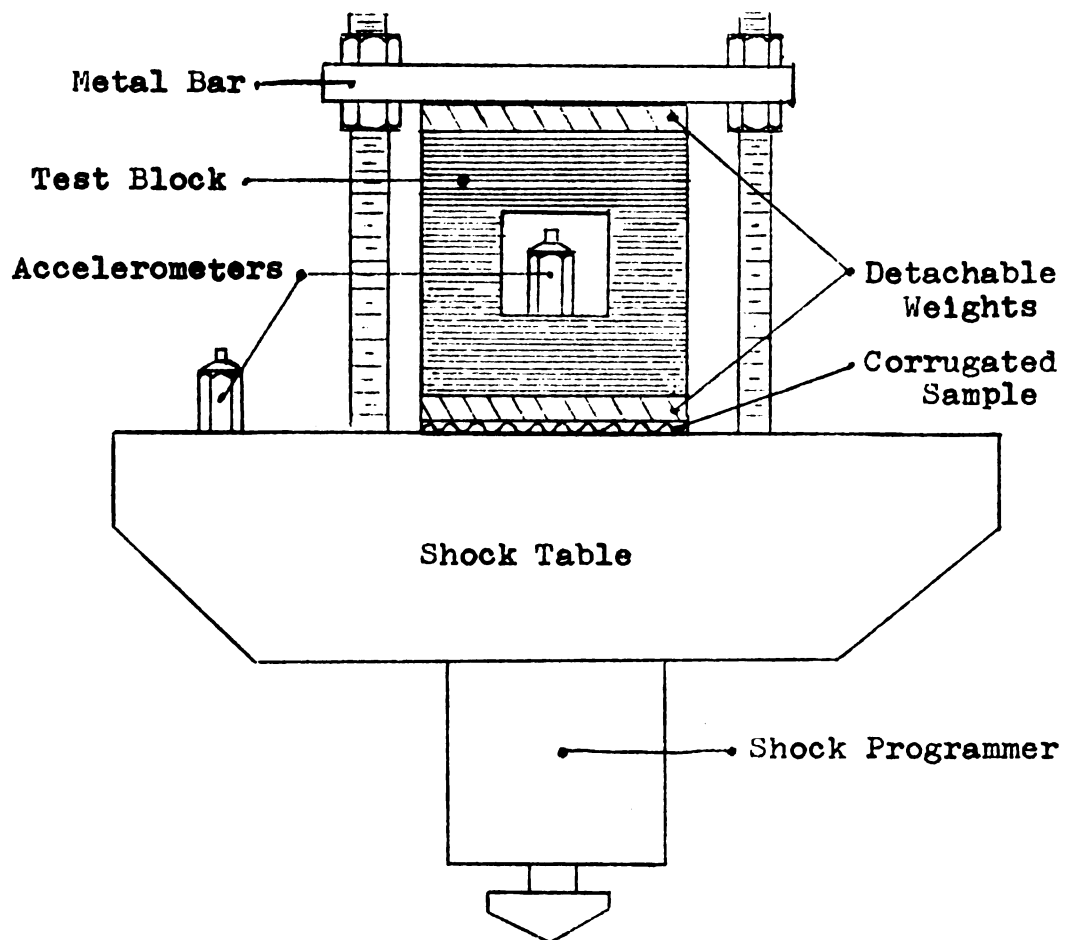


Figure 1

Table 1

Response on A-flute Board to Shocks with
High Acceleration to Velocity Change Ratios

Flute Size	Static Stress (psi)	Drop Ht. (in.)	Input			Response Acceleration (g)				
			Pro- gram- mer	Acc. (g)	Vel. Change (1ps)	1	2	3	4	5
A	0.52	3/8	Felt	33	27.5	33	34	33	33	33
"	"	1/2	"	36	31.8	36	34	34	32	32
"	0.38	1/2	"	36	31.8	36	36	36	36	36
"	"	5/8	"	47	35.6	47	46	45	46	45
"	"	5/8	"	44	35.6	44	45	45	45	44
"	"	3/4	"	53	39.0	53	50	48	46	46
"	"	7/8	"	56	42.1	56	52	50	48	47
"	0.28	5/8	"	55	35.6	55	55	55	55	55
"	"	3/4	"	60	39.0	60	60	60	58	57
"	"	7/8	"	63	42.1	63	62	62	62	62
"	"	1	"	64	45.0	64	63	62	62	62
"	"	1-1/8	"	74	47.8	74	68	60	60	58
"	0.13	1	"	76	45.0	76	76	76	76	76
"	"	1-1/8	"	88	47.8	88	88	88	88	88
"	"	1-1/4	"	95	50.4	93	95	95	95	95
"	"	1-3/8	"	100	52.8	100	98	100	100	102
"	"	1-1/2	"	106	55.1	106	110	109	112	110
"	"	1-1/2	"	116	55.1	116	118	122	127	126
"	"	1-3/4	"	120	59.6	120	122	122	137	140
"	"	2	"	128	63.7	128	132	138	140	142

Table 2

Response on B-flute Board to Shocks with
High Acceleration to Velocity Change Ratios

Flute Size	Static Stress (psi)	Drop Ht. (in.)	Input			Response Acceleration (g)				
			Pro- gram- mer	Acc. (g)	Vel. Change (ips)	1	2	3	4	5
B	0.52	1	Felt	82	45.0	82	82	82	82	82
"	"	1-1/4	"	88	50.4	88	87	88	88	84
"	"	1-3/8	"	87	52.8	87	92	99	102	104
"	"	1-1/2	"	100	55.1	100	114	120	118	128
"	0.38	1	"	72	45.0	72	72	72	72	72
"	"	1-1/2	"	112	55.1	112	112	111	111	112
"	"	1-5/8	"	118	57.3	118	118	118	120	120
"	"	1-3/4	"	120	59.6	120	120	120	122	120
"	"	1-7/8	"	120	61.7	120	122	120	132	140
"	0.28	2	"	155	63.7	155	155	155	155	155
"	"	2-1/8	"	118	65.6	118	115	111	111	111
"	"	2-1/4	"	160	76.6	160	155	158	155	168
"	0.13	2-1/2	"	185	71.1	185	185	185	185	185
"	"	3	"	220	77.9	220	210	220	215	220
"	"	3-1/2	"	240	84.2	240	235	240	240	240
"	"	3-3/4	"	240	87.1	240	235	232	228	220
"	"	4	"	260	90.0	260	260	250	235	220

Table 3

Response on C-flute Board to Shocks with
High Acceleration to Velocity Change Ratios

Flute Size	Static Stress (psi)	Drop Ht. (in.)	Pro- gram- mer	Input		Response Acceleration (g)				
				Acc. (g)	Vel. Change (ips)	1	2	3	4	5
C	0.52	1/2	Felt	43	31.8	43	43	43	43	43
"	"	5/8	"	52	35.6	52	48	48	48	48
"	"	5/8	"	50	35.6	50	52	50	50	50
"	"	3/4	"	52	39.0	52	53	56	58	60
"	"	3/4	"	54	39.0	54	56	56	55	56
"	0.38	5/8	"	42	35.6	42	42	42	42	42
"	"	1	"	66	45.0	66	65	66	67	66
"	"	1	"	68	45.0	68	68	68	68	68
"	"	1	"	68	45.0	68	67	66	66	67
"	"	1-1/8	"	72	47.8	72	72	70	67	64
"	"	1-1/4	"	74	50.4	74	69	68	67	65
"	0.28	1-1/8	"	78	47.8	78	84	82	82	82
"	"	1-1/4	"	94	50.4	94	92	92	88	87
"	"	1-3/8	"	96	52.8	96	93	91	89	86
"	"	2	"	97	63.7	97	93	90	89	87
"	0.13	1-1/4	"	96	50.4	96	96	96	96	96
"	"	1-1/2	"	116	55.1	116	120	119	118	120
"	"	1-3/4	"	128	59.6	128	130	130	128	128
"	"	2	"	135	63.7	135	138	138	137	136
"	"	2-1/4	"	147	67.6	147	145	155	162	163

Table 4

Response on A-flute Board to Shocks with
Low Acceleration to Velocity Change Ratios

Flute Size	Static Stress (psi)	Drop Ht. (in)	Pro- gram- mer	Input		Response Acceleration (g)				
				Acc. (g)	Vel. Change (ips)	1	2	3	4	5
A	0.52	25	Square	27	220	27	27	27	27	27
"	"	"	"	30	"	30	80	-	-	-
"	0.38	"	"	36	"	36	36	36	36	36
"	"	"	"	38	"	38	38	38	38	130
"	"	"	"	52	"	110	-	-	-	-
"	0.28	"	"	46	"	46	46	46	46	46
"	"	"	"	48	"	55	60	65	68	70
"	"	"	"	50	"	60	63	70	80	-
"	0.13	"	"	78	"	78	78	78	78	78

Table 5

Response on B-flute Board to Shocks with
Low Acceleration to Velocity Change Ratios

Flute Size	Static Stress (psi)	Drop Ht. (in.)	Input			Response Acceleration (g)				
			Pro- gram- mer	Acc. (g)	Vel. Change (ips)	1	2	3	4	5
B	0.52	25	Square	60	220	60	60	60	60	60
"	"	"	"	64	"	64	64	64	124	-
"	"	"	"	68	"	68	68	68	68	130
"	0.38	"	"	56	"	56	56	56	56	56
"	"	"	"	72	"	72	72	72	72	72
"	0.28	"	"	75	"	75	75	75	75	75
"	0.13	"	"	45	"	45	45	45	45	45
"	"	"	"	64	"	64	64	64	64	64
"	"	"	"	76	"	76	76	76	76	76

Table 6

Response on C-flute Board to Shocks with
Low Acceleration to Velocity Change Ratios

Flute Size	Static Stress (psi)	Drop Ht. (in.)	Input			Response Acceleration (g)				
			Pro- gram- mer	Acc. (g)	Vel. Change (ips)	1	2	3	4	5
C	0.52	25	Square	36	220	36	36	36	36	36
"	"	"	"	40	"	40	40	40	40	40
"	"	"	"	54	"	54	80	100	-	-
"	0.38	"	"	46	"	46	46	46	46	48
"	"	"	"	48	"	48	48	48	48	112
"	"	"	"	56	"	56	56	85	96	110
"	"	"	"	60	"	76	80	88	94	-
"	"	"	"	72	"	72	114	-	-	-
"	0.28	"	"	75	"	75	75	75	75	75
"	0.13	"	"	76	"	76	76	76	76	76

Table 7

Response on A-flute Board to Large Magnitude Shocks

Flute Size	Static Stress (psi)	Drop Ht. (in.)	Input		Response Acceleration (g)				
			Pro- gram- mer	Acc. (g) Vel. Change (ips)	1	2	3	4	5
A	0.52	9		380 112	1000	-	-	-	-
"	"	6		250 91.8	150 1700	3000	2600	3100	
"	"	3		130 64.9	80 100	700	1000	1000	
"	0.38	12		500 130	1300	-	-	-	-
"	"	9		380 112	450 3800	-	-	-	
"	"	6		250 91.8	135 1900	2400	-	2500	
"	"	3		130 64.9	80 120	240		800	
"	0.28	12		500 130	700 4500	-	-	-	
"	"	9		380 112	250 2300	-	-	-	
"	"	6		250 91.8	150 320	1400	2000	2300	
"	"	3		120 64.9	90 135	170	170	540	
"	0.13	12		420 130	1100 2000	3000	5000	8000	
"	"	9		360 112	340 350	550	500	1500	
"	"	6		250 91.8	220 300	300	420	420	
"	"	3		140 64.9	140 135	140	140	140	

Table 8

Response on B-flute Board to Large Magnitude Shocks

Flute Size	Static Stress (psi)	Drop Ht. (in.)	Input		Response Acceleration (g)					
			Pro-gram-mer	Acc. (g)	Vel. Change (ips)	1	2	3	4	5
B	0.52	9		380	112	1000	-	-	-	-
"	"	6		250	91.8	180	1500	2800	3000	3500
"	"	3		130	64.9	130	160	330	700	1000
"	0.38	12		500	130	1300	-	-	-	-
"	"	9		380	112	400	2000	-	-	-
"	"	6		250	91.8	220	600	1800	2500	2600
"	"	3		130	64.9	120	180	180	170	400
"	0.28	12		500	130	700	4500	-	-	-
"	"	9		380	112	370	800	-	-	-
"	"	6		250	91.8	250	400	800	1900	2000
"	"	3		120	64.9	150	150	160	180	195
"	0.13	12		420	130	1900	4000	2600	3100	3000
"	"	9		370	112	450	500	600	500	630
"	"	6		250	91.8	280	240	270	320	380
"	"	3		140	64.9	145	150	155	155	155

Table 9

Response on C-flute Board to Large Magnitude Shocks

Flute Size	Static Stress (psi)	Drop Ht. (in.)	Input		Response Acceleration (g)					
			Pro- gram- mer	Acc. (g)	Vel. Change (1ps)	1	2	3	4	5
C	0.52	9		380	112	1000	-	-	-	-
"	"	6		250	91.8	140	1400	2200	2400	2400
"	"	3		130	64.9	80	140	400	800	900
"	0.38	12		500	130	1500	-	-	-	-
"	"	9		380	112	280	2700	-	-	-
"	"	6		250	91.8	260	900	1900	2100	2700
"	"	3		130	64.9	100	150	300	750	1000
"	0.28	12		500	130	400	3600	-	-	-
"	"	9		380	112	300	1800	-	-	-
"	"	6		250	91.8	200	550	1600	2800	2800
"	"	3		120	64.9	105	140	150	155	160
"	0.13	12		420	130	700	1600	4000	5000	3800
"	"	9		370	112	320	440	580	450	720
"	"	6		250	91.8	320	340	360	390	400
"	"	3		140	64.9	140	140	140	140	140

ANALYSIS

On the basis of the largest shocks whose response varied less than 10 percent, damage boundaries were drawn which showed the dividing line between shocks which did not cause the flute structure to be altered and those which did (Figures 3, 6, 9). The horizontal portion of the damage boundary,¹ referred to by the author as the acceleration boundary, was determined directly from the data where pulses with low acceleration velocity change ratios were used. The curved portion of the damage boundary, referred to by the author as the transition boundary, connects the horizontal and vertical portions of the damage boundary and is theoretically a $\frac{1}{4}$ sine wave. The vertical portion of the damage boundary, referred to as the velocity change boundary, was determined from points which were actually on the transition boundary by applying a correction factor derived in Appendix I.

The information necessary to determine the damage boundaries for some combinations of static stress and flute size was unobtainable from the equipment used. However, utilizing a three-dimensional concept of damage shown in Figure 2 for each flute size, a reasonable prediction was made of the unobtainable damage boundaries in the following

¹Robert E. Newton, Fragility Assessment Theory and Test Procedure (Monterey, 1968), p. 11.

manner. From the obtainable damage boundaries for A-flute board plotted in three dimensions it was assumed that, without any shock being applied, a specific level of stress for each type of board would alter the flute structure. Hence, for any given amount of static stress less than this specific level, the amount of acceleration which must be experienced by the block to produce the level of stress necessary to alter the flutes can be calculated. From this assumption a relationship between the acceleration boundary and static stress was determined for each board size (Appendix II) and plotted on the side view of the damage boundaries (Figures 5, 8, 11).

It was also assumed that before any crushing or alteration of the flutes take place that a high spring rate exists for a sample of corrugated board.¹ Using a spring rate for each board size as determined from the obtainable damage boundaries, a relationship between the velocity change boundary and static stress was determined for each board size (Appendix III) and plotted on the top view of the damage boundaries (Figures 4, 7, 10). Using these relationships determined, damage boundaries were predicted for the combinations of static stress and flute size where these damage boundaries were unobtainable from the data.

Having thus obtained damage boundaries for all combinations of static stress and flute size, the effect

¹This spring rate is high enough so that a corrugated board sample is effectively solid, and any shocks applied are transmitted through the board without alteration.

of the various input shocks which caused wide variations in the response shocks was examined. To do this, the input shocks for a given static stress and flute size were plotted with the damage boundary corresponding to that static stress and flute size (Figures 12-23). Values of response acceleration which were less than the applied acceleration, were underlined.

Table 10

Largest Shocks Whose Response Varied Less than 10 Percent

Flute Size	Static Stress (psi)	Low Acc/Vel Ratio		High Acc/Vel Ratio		
		Acc. (g)	Vel. Change (ips)	Acc. (g)	ΔV (ips)	Adj. ΔV (ips)
A	0.52	27	220	33	27.5	23.9
	0.38	36	"	47	35.6	27.8
	0.28	46	"	64	45.0	36.3
	0.13	76+	"	116	55.1	-
B	0.52	60	220	88	50.4	41.8
	0.38	72+	"	120	59.6	-
	0.28	76+	"	118	65.6	-
	0.13	76+	"	240	84.2	-
C	0.52	40	220	50	35.6	28.7
	0.38	46	"	68	45.0	37.5
	0.28	76+	"	94	50.4	-
	0.13	76+	"	135	63.7	-

Table 11
Points Used to Define Damage Boundaries

Flute Size	Static Stress	Point on Acceleration Boundary		Transition- Acc. Boundary Intersection		Point on Transition Boundary		Transition- Vel. Boundary Intersection	
		Acc. (g)	ΔV (ips)	Acc. (g)	ΔV (ips)	Acc. (g)	ΔV (ips)	Acc. (g)	ΔV (ips)
A	0.52	27	220	27	37.6	33	27.5	54	23.9
	0.38	36	220	36	43.7	47	35.6	72	27.8
	0.28	46	220	46	57.0	64	45.0	92	36.4
B	0.52	60	220	60	65.7	88	50.4	120	41.8
C	0.52	36	220	36	45.1	50	35.6	72	28.7
	0.38	46	220	46	58.9	68	45.0	92	37.5

SCHEMATIC DIAGRAM OF THREE DIMENSIONAL DAMAGE BOUNDARY

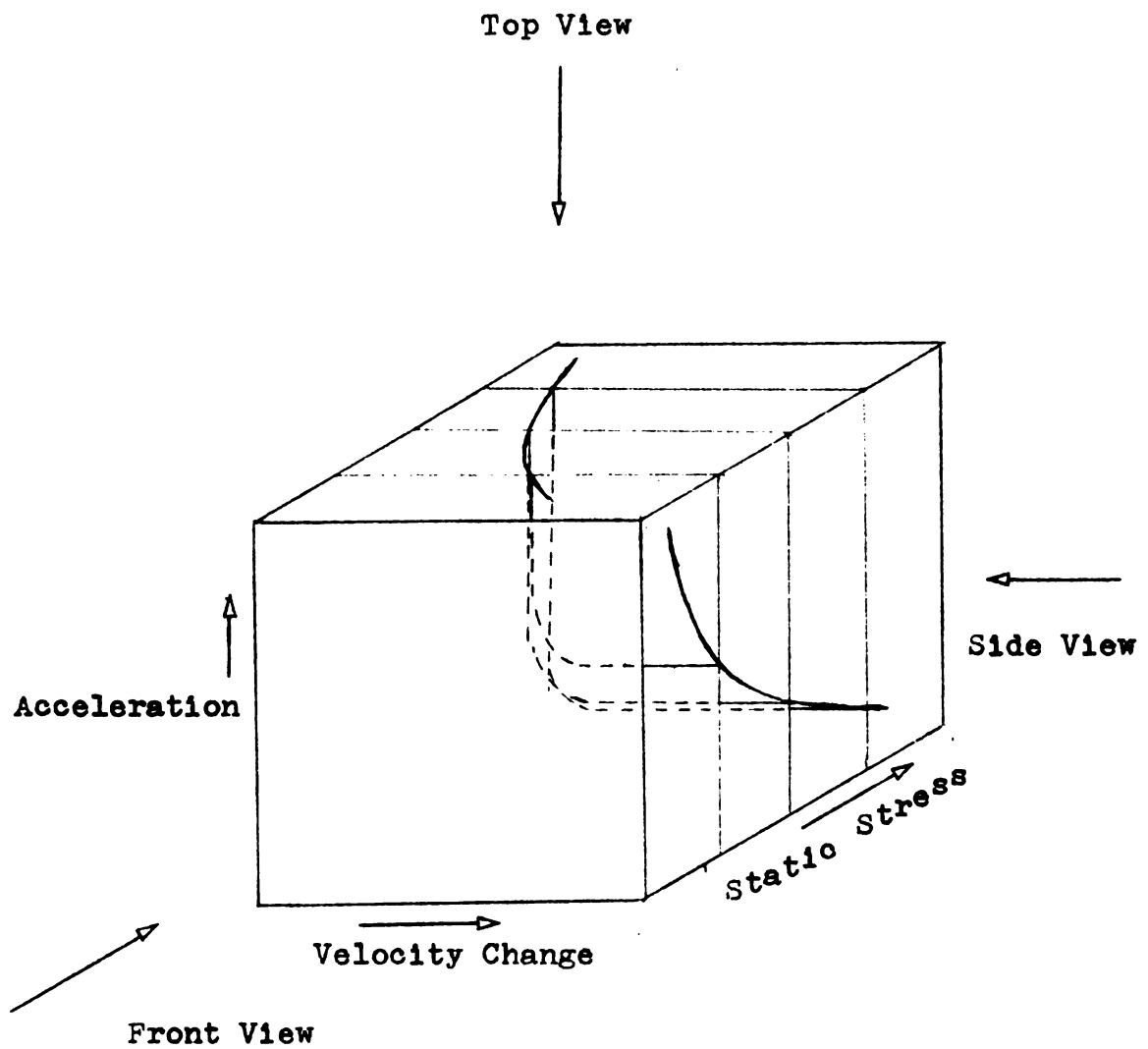


Figure 2

Figure 3.
A-flute Damage Boundary, Front View

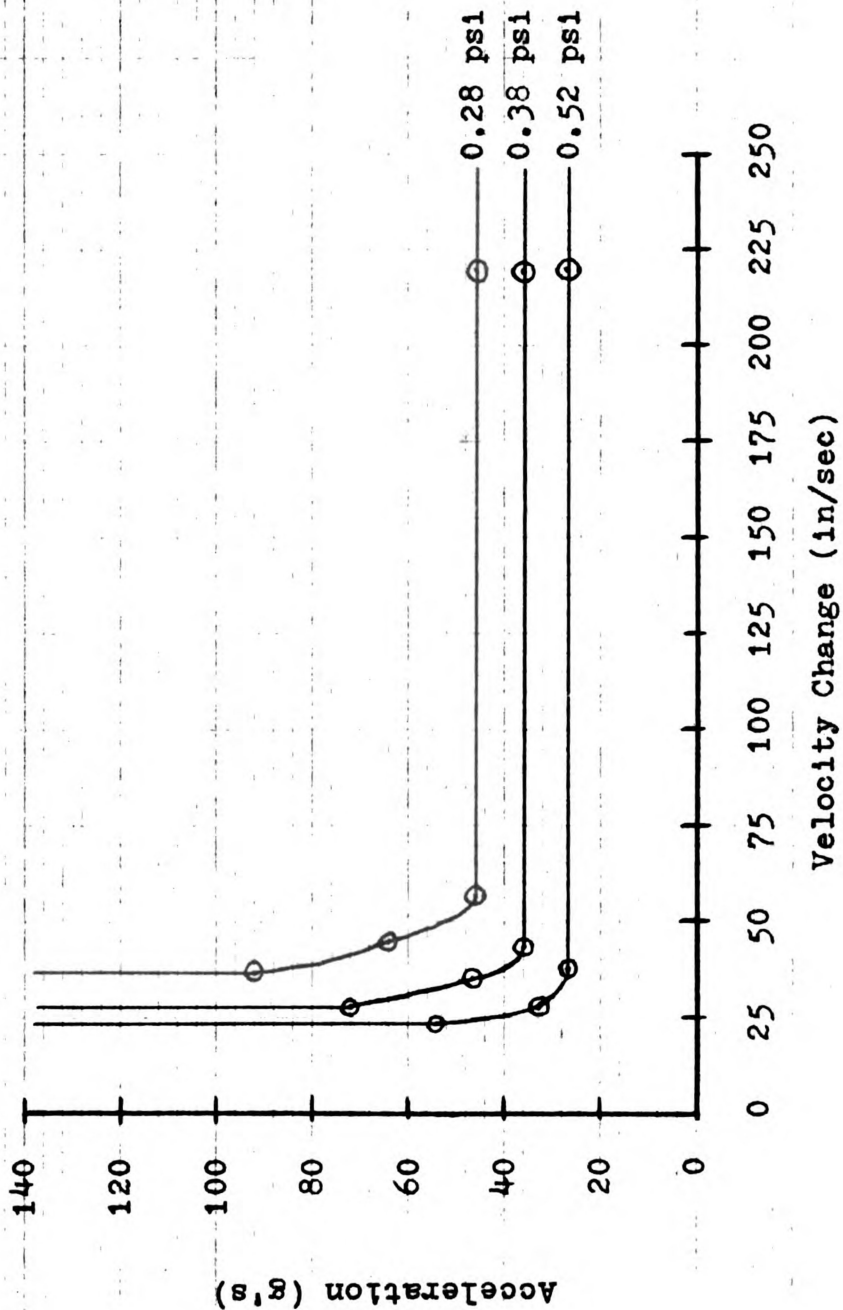


Figure 4.

A-flute Damage Boundary, Top View

- Predicted Relationship

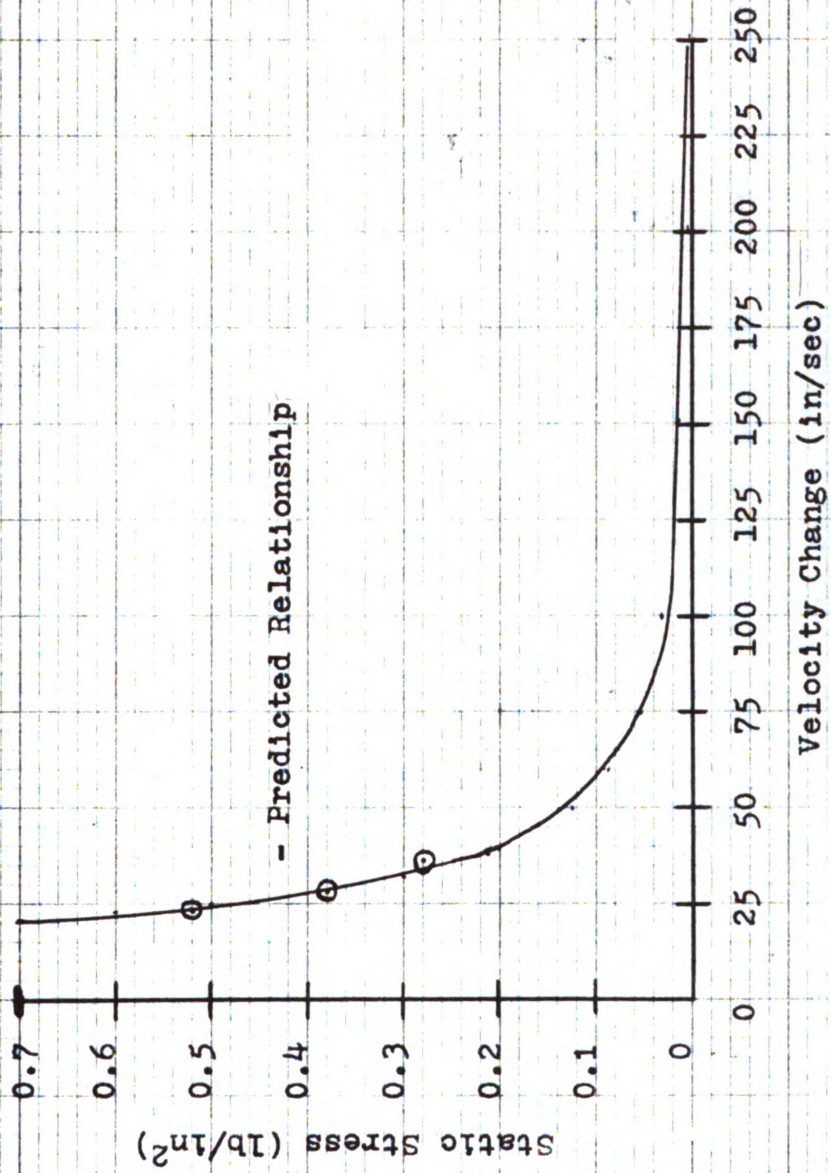


Figure 5.

A-flute Damage Boundary, Side View

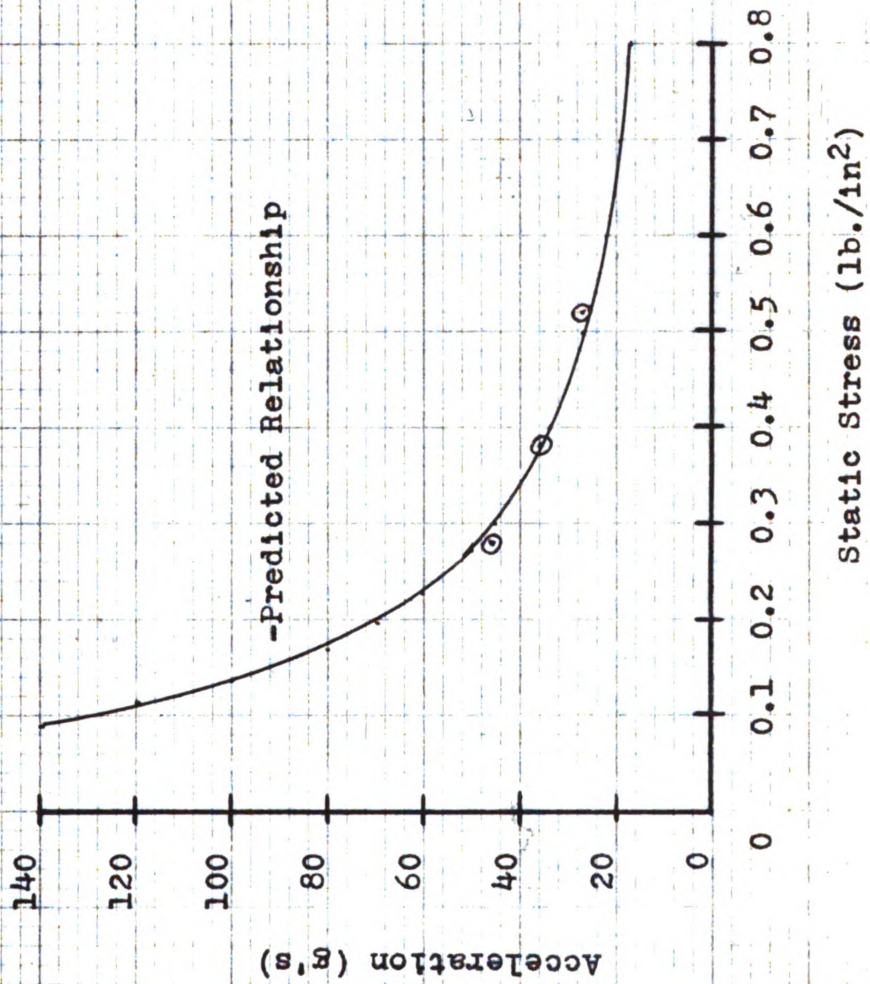


Figure 6.

B-flute Damage Boundary, Front View

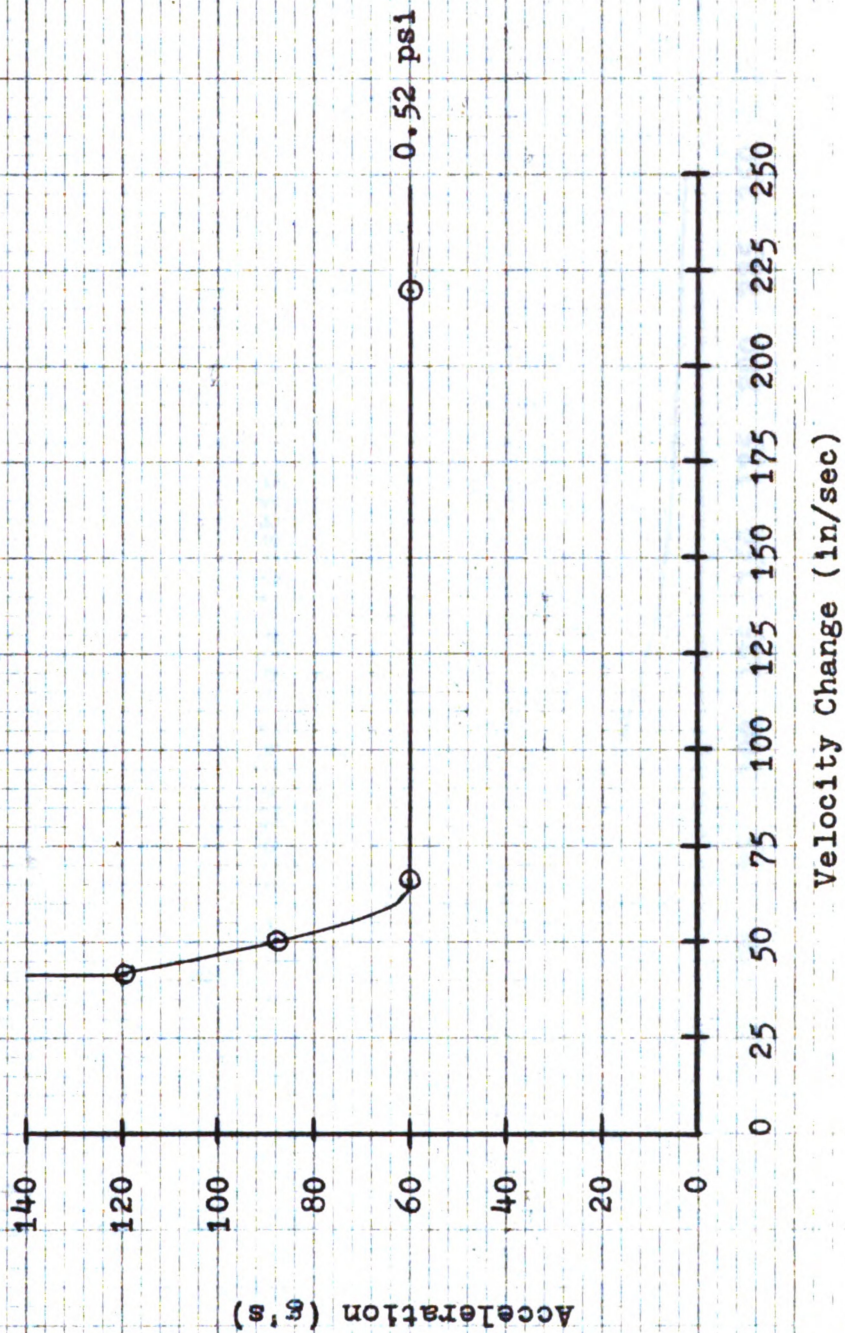


Figure 7.

B-flute Damage Boundary, Top View

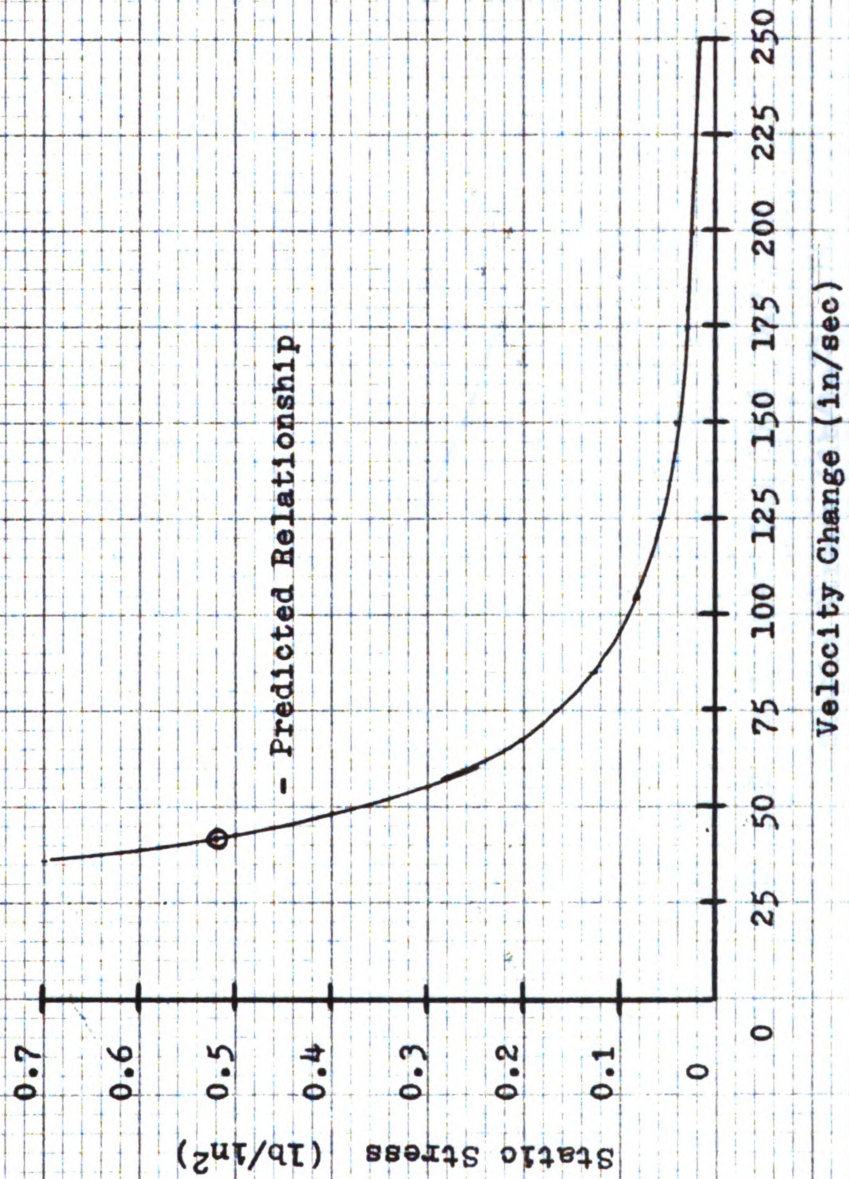


Figure 8.

B-flute Damage Boundary, Side View

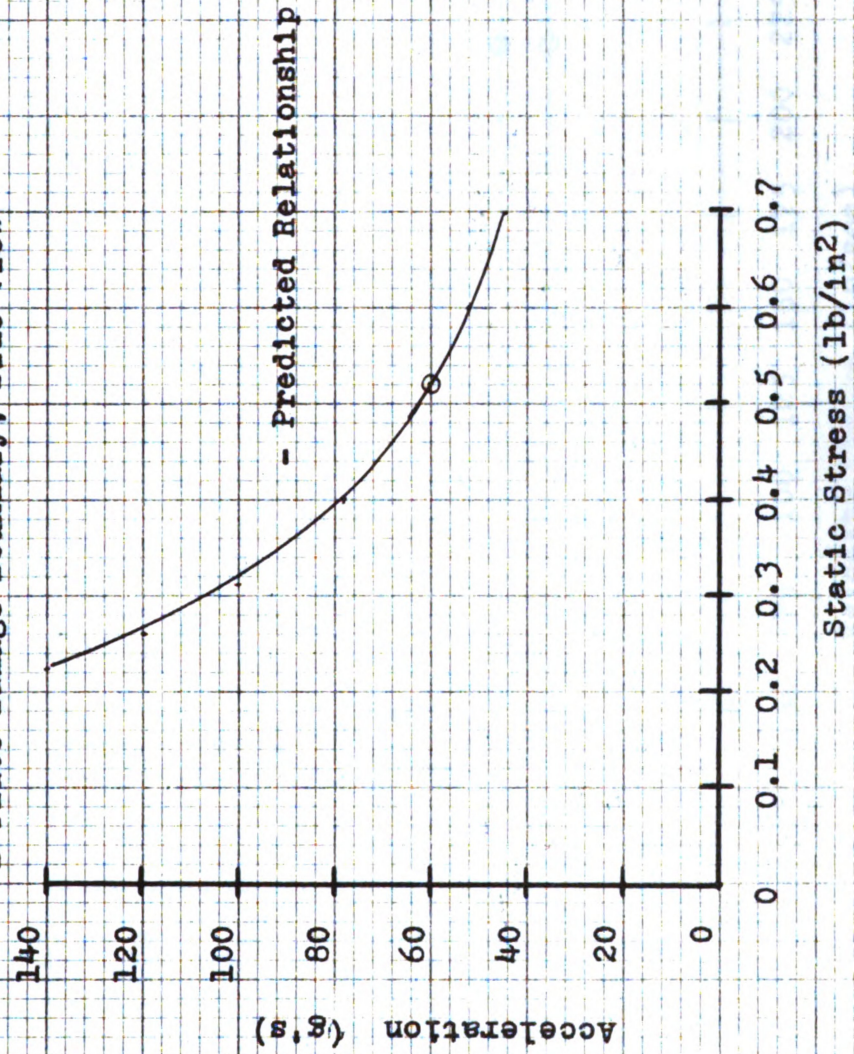


Figure 9.

C-flute Damage Boundary, Front View

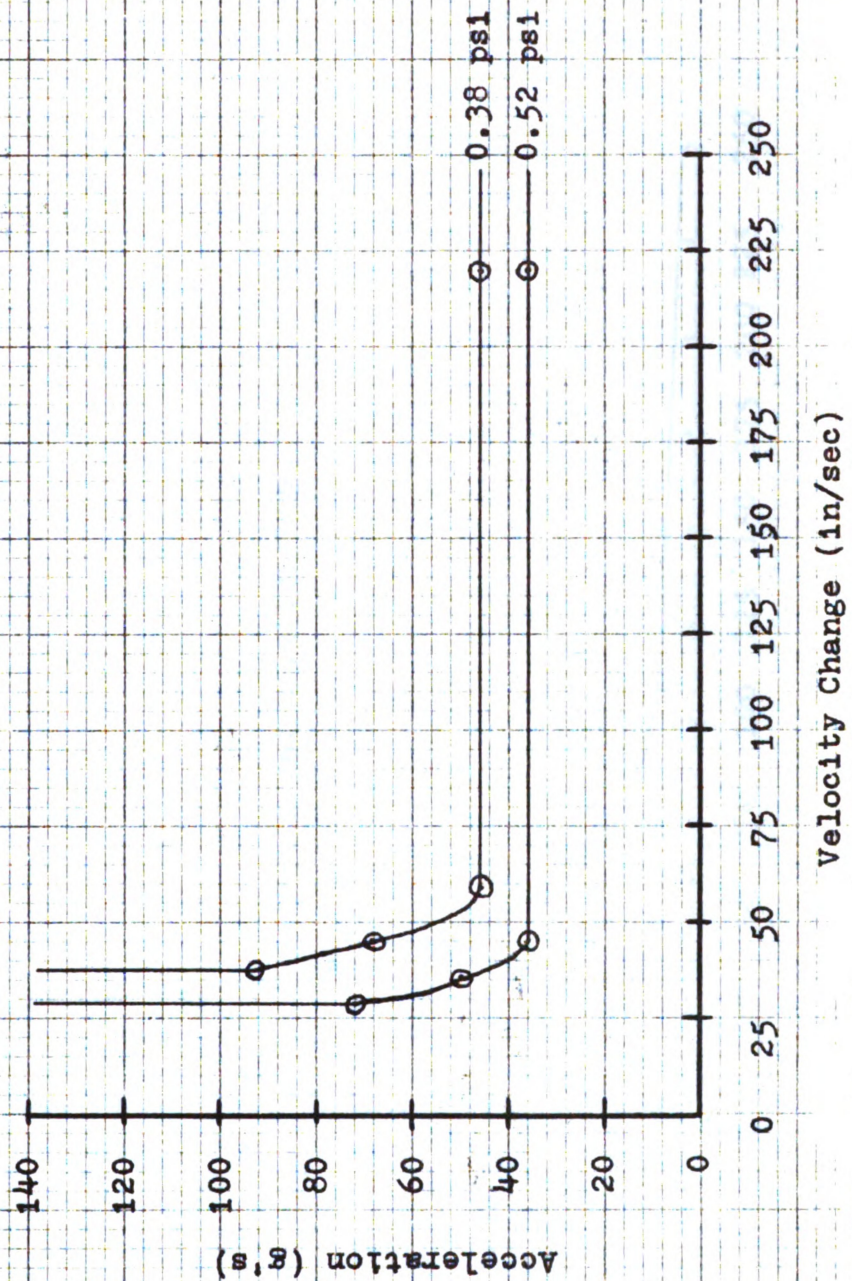


Figure 10.

C-flute Damage Boundary, Top View

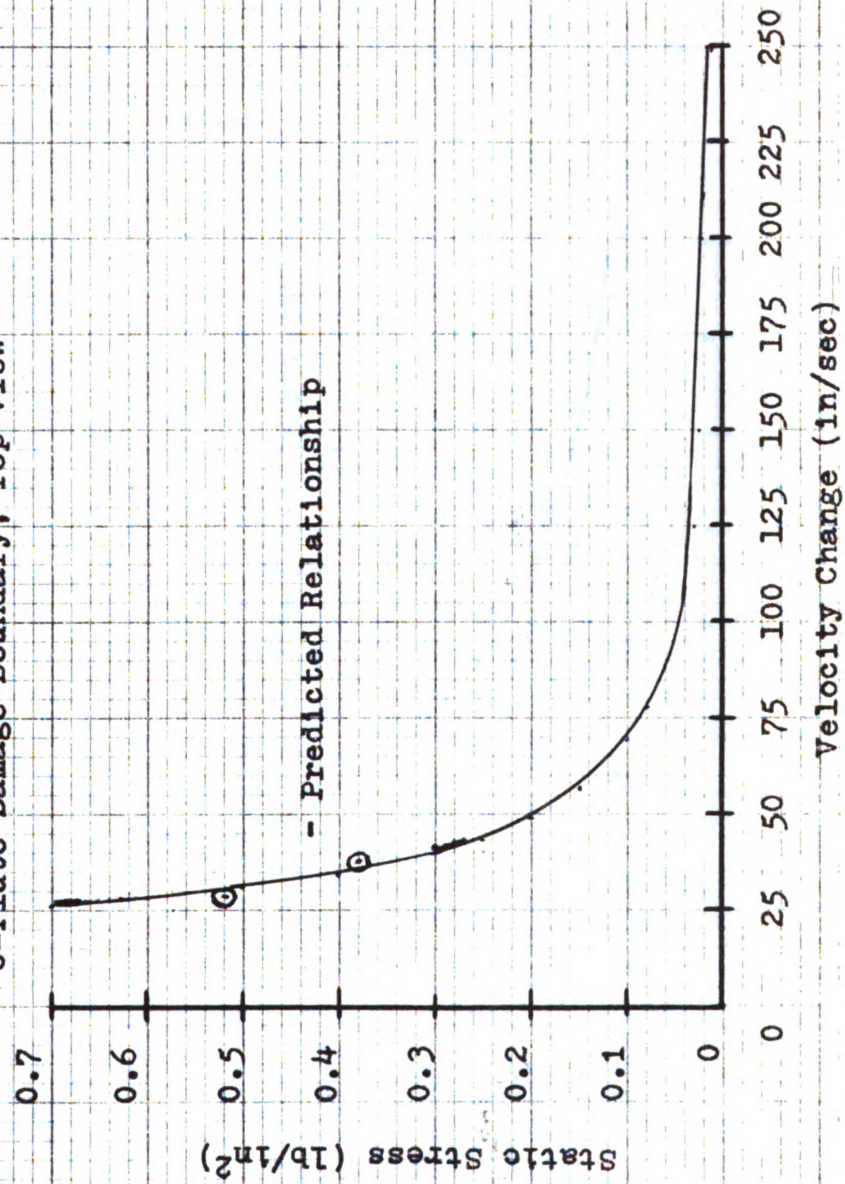


Figure 11.

C-flute Damage Boundary, Side View

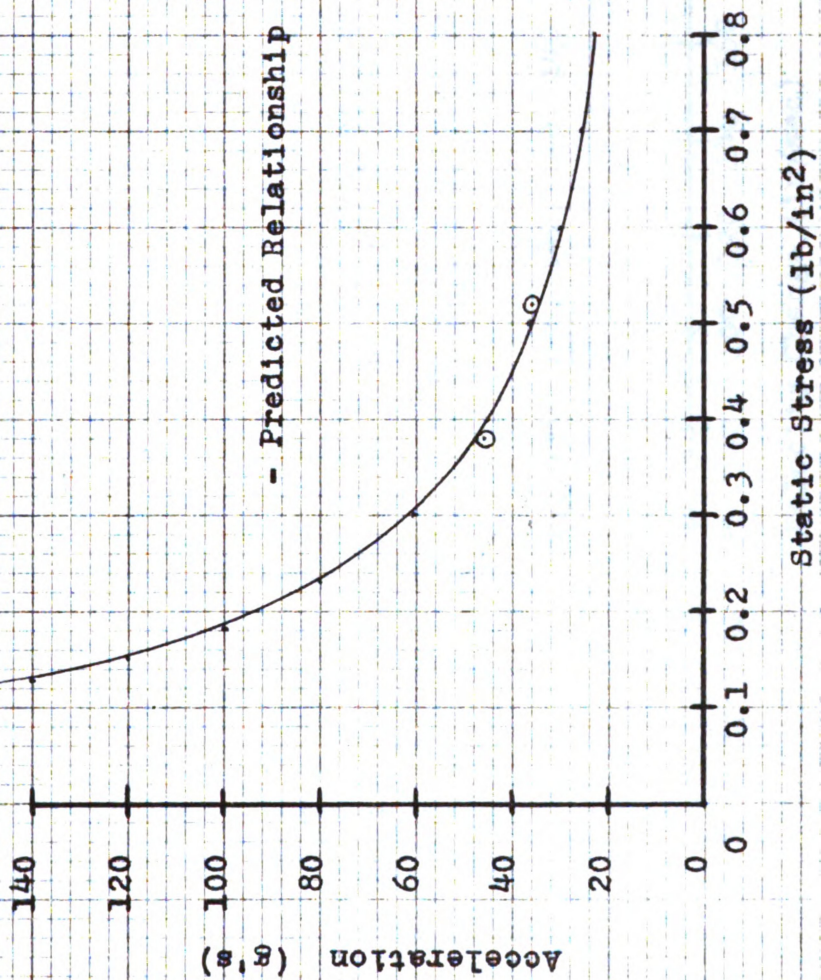


Figure 12.

Selected Input Shocks Within The A-flute Damage Boundary
At A Static Stress of 0.13, Showing Response Accelerations For Repeated Inputs

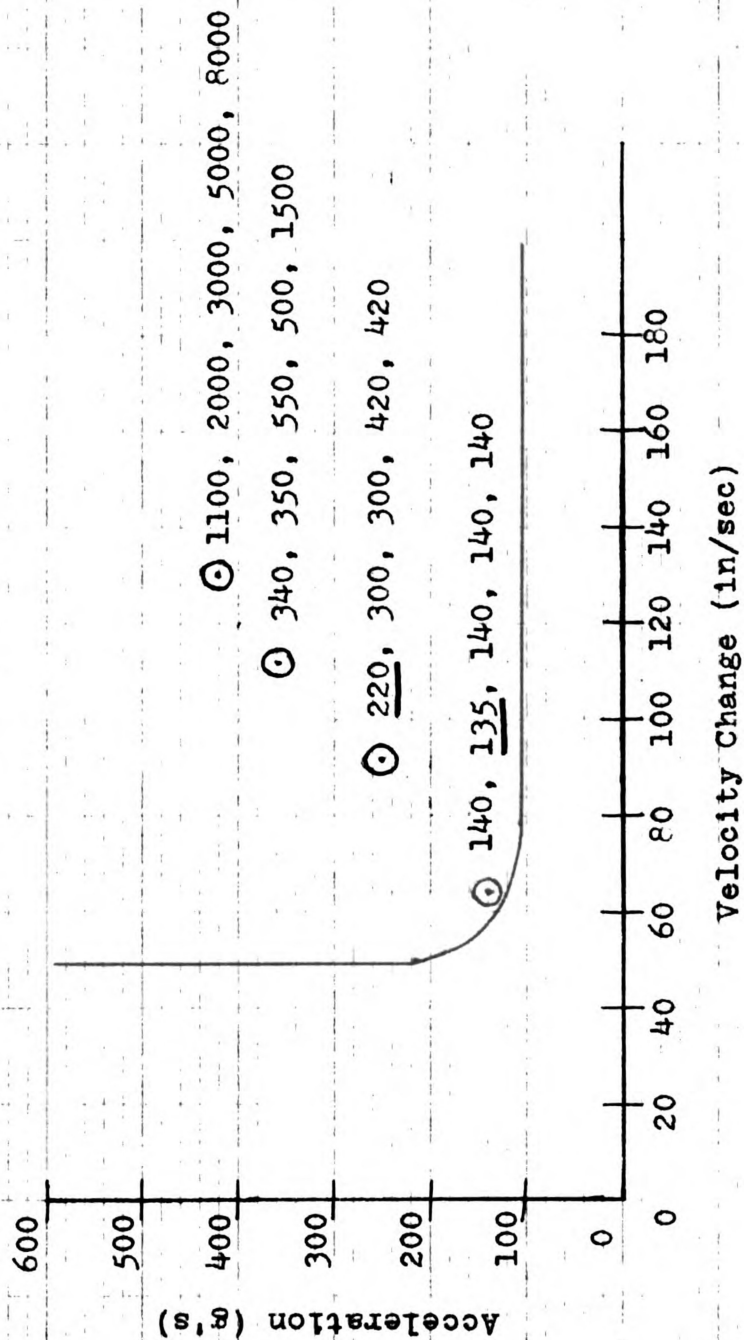


Figure 13.

Selected Input Shocks Within The A-flute Damage Boundary

At a Static Stress of 0.28, Showing Response Accelerations For Repeated Inputs

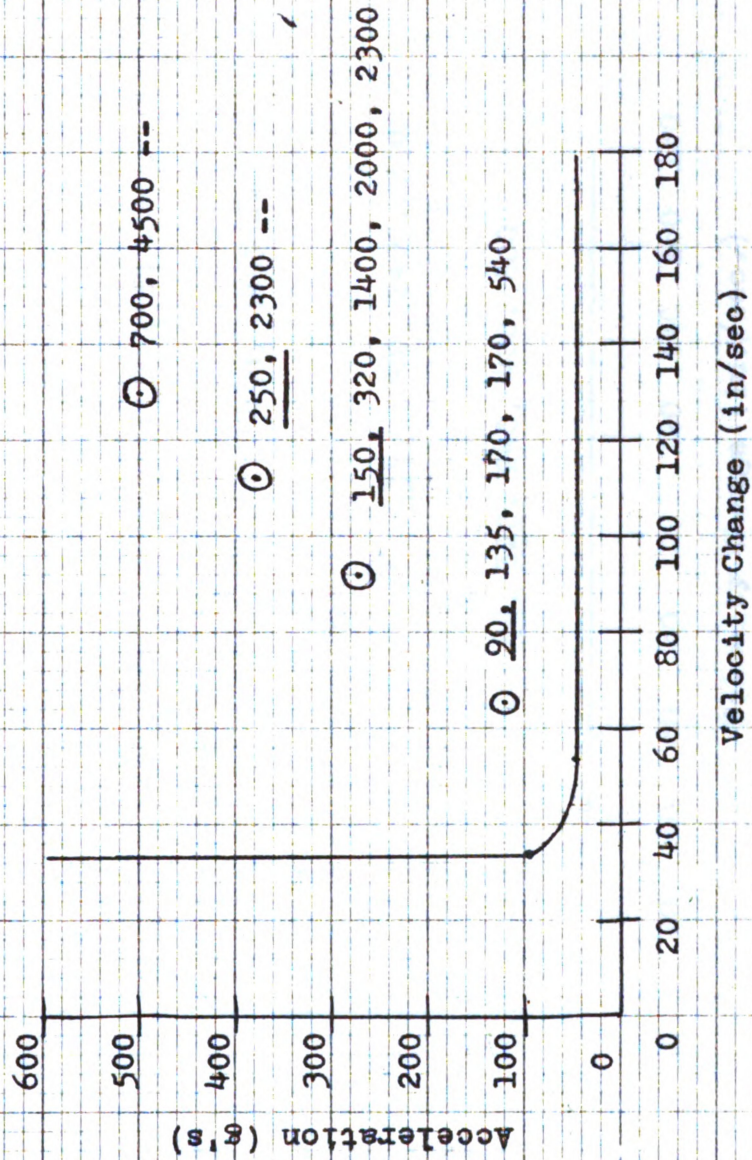


Figure 14.

Selected Input Shocks Within The A-flute Damage Boundary
At a Static Stress of 0.38, Showing Response Accelerations For Repeated Inputs

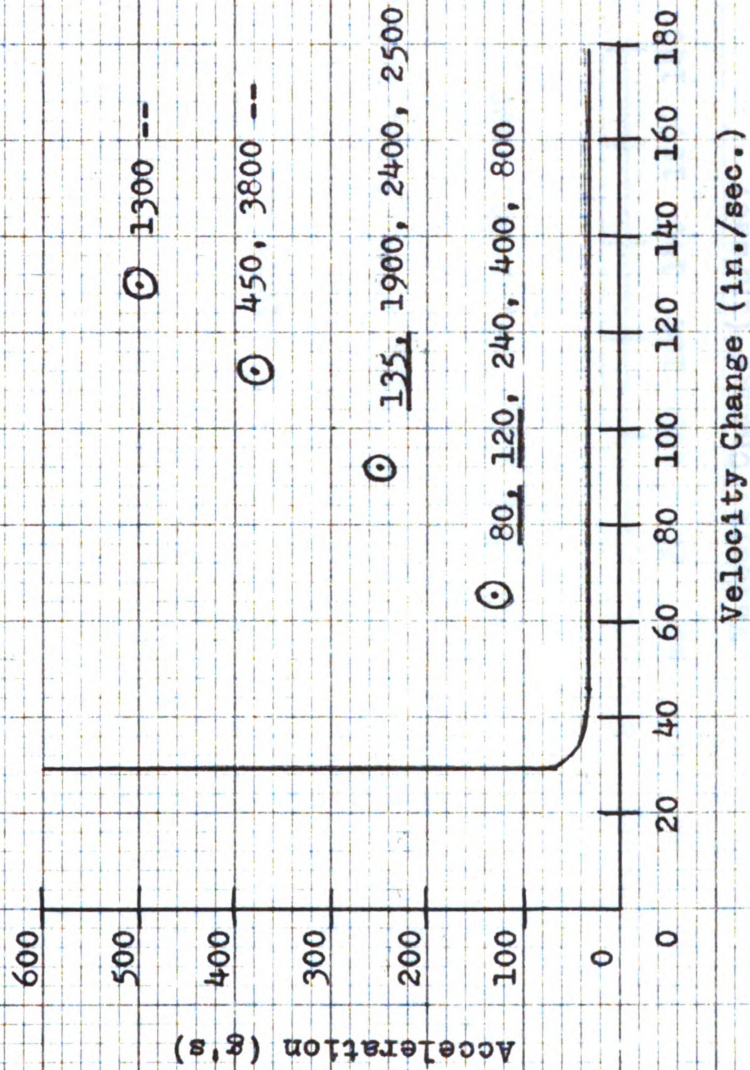


Figure 15.

Selected Input Shocks Within The A-flute Damage Boundary

At a Static Stress of 0.52, Showing Response Accelerations For Repeated Inputs

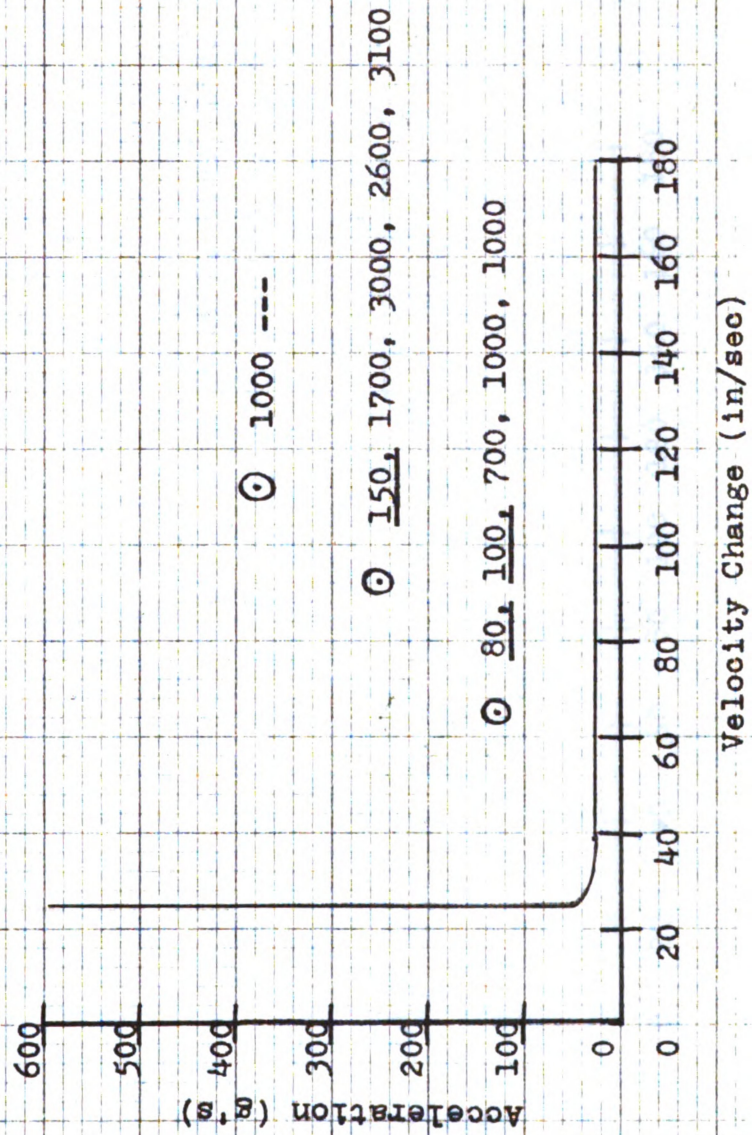


Figure 16.

Selected Input Shocks Within The B-flute Damage Boundary

At a Static Stress of 0.13, Showing Response Accelerations For Repeated Inputs

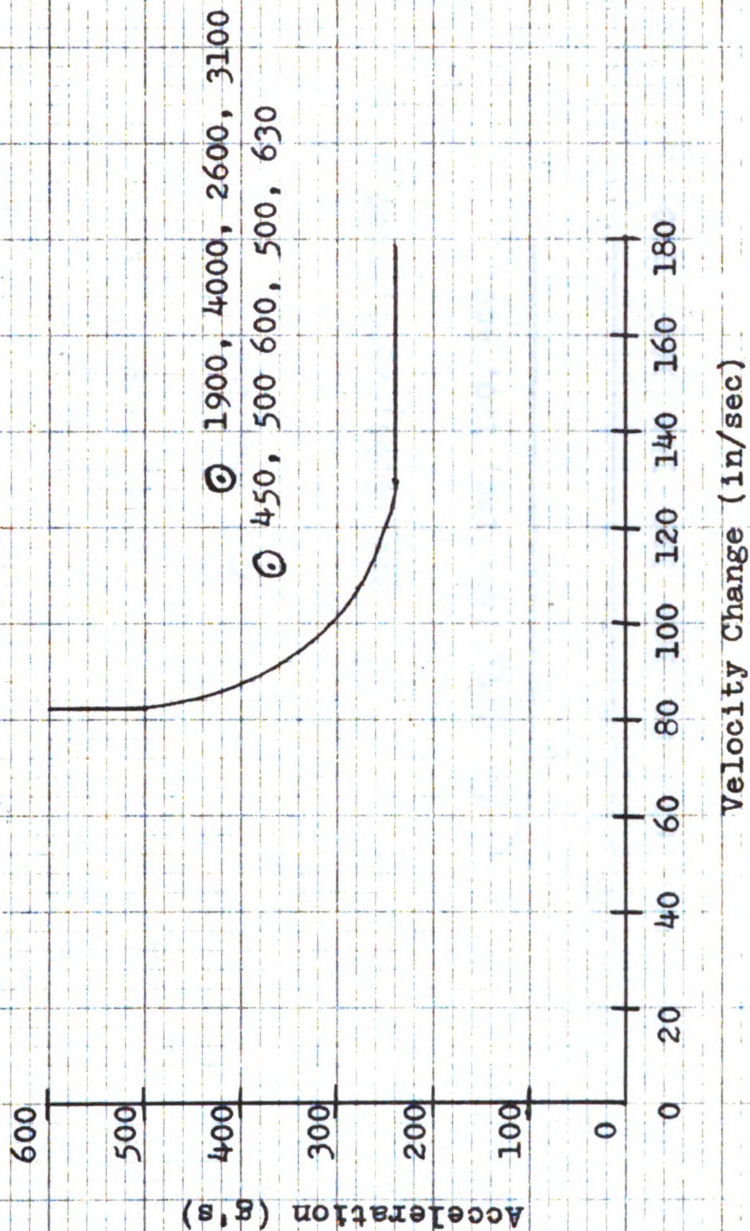
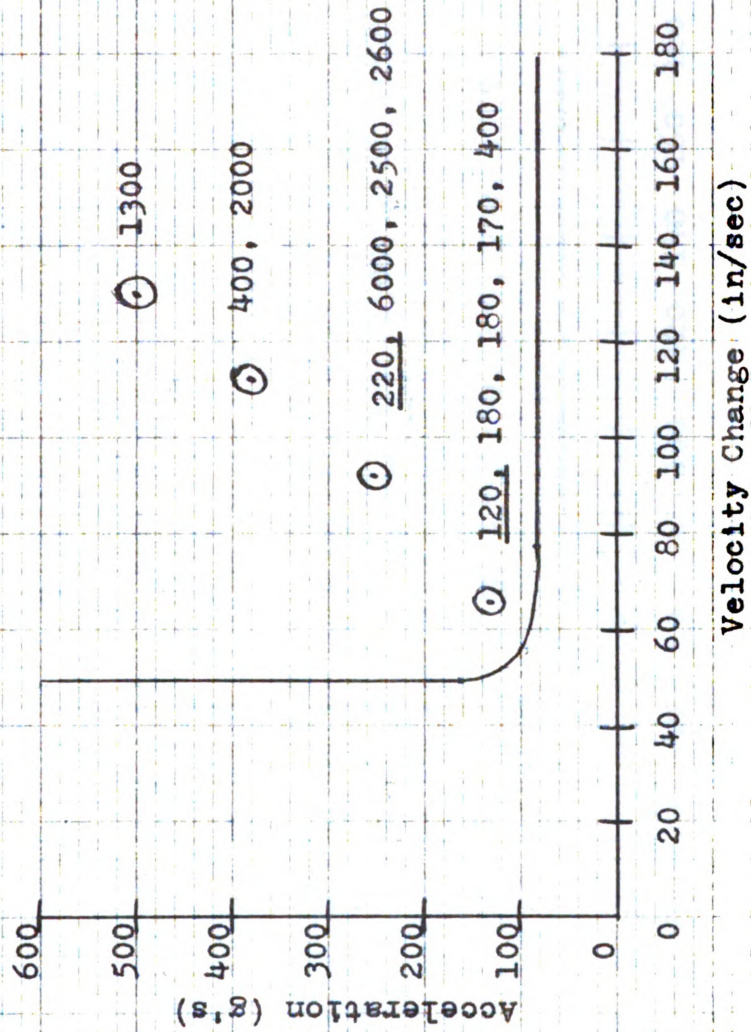


Figure 18.

Selected Input Shocks Within The B-flute Damage Boundary

At a Static Stress of 0.38, Showing a Response Acceleration For Repeated Inputs



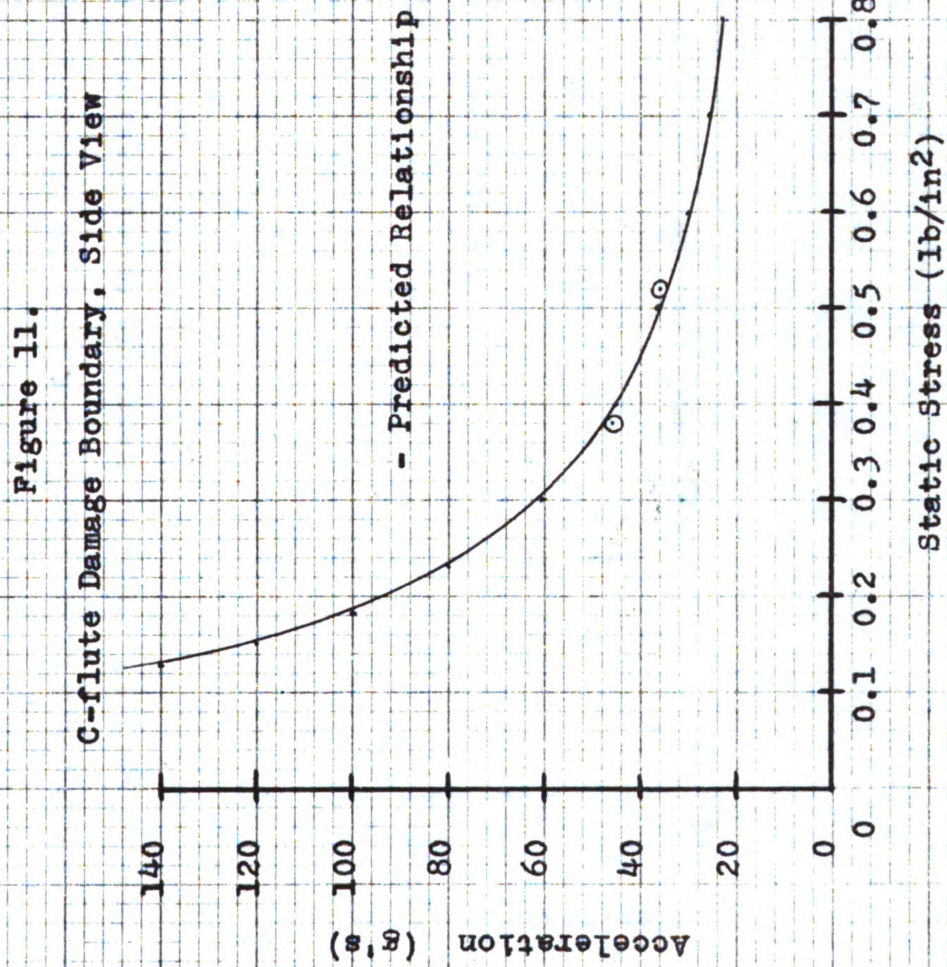


Figure 12.

Selected Input Shocks Within The A-flute Damage Boundary
At A Static Stress of 0.13, Showing Response Accelerations For Repeated Inputs

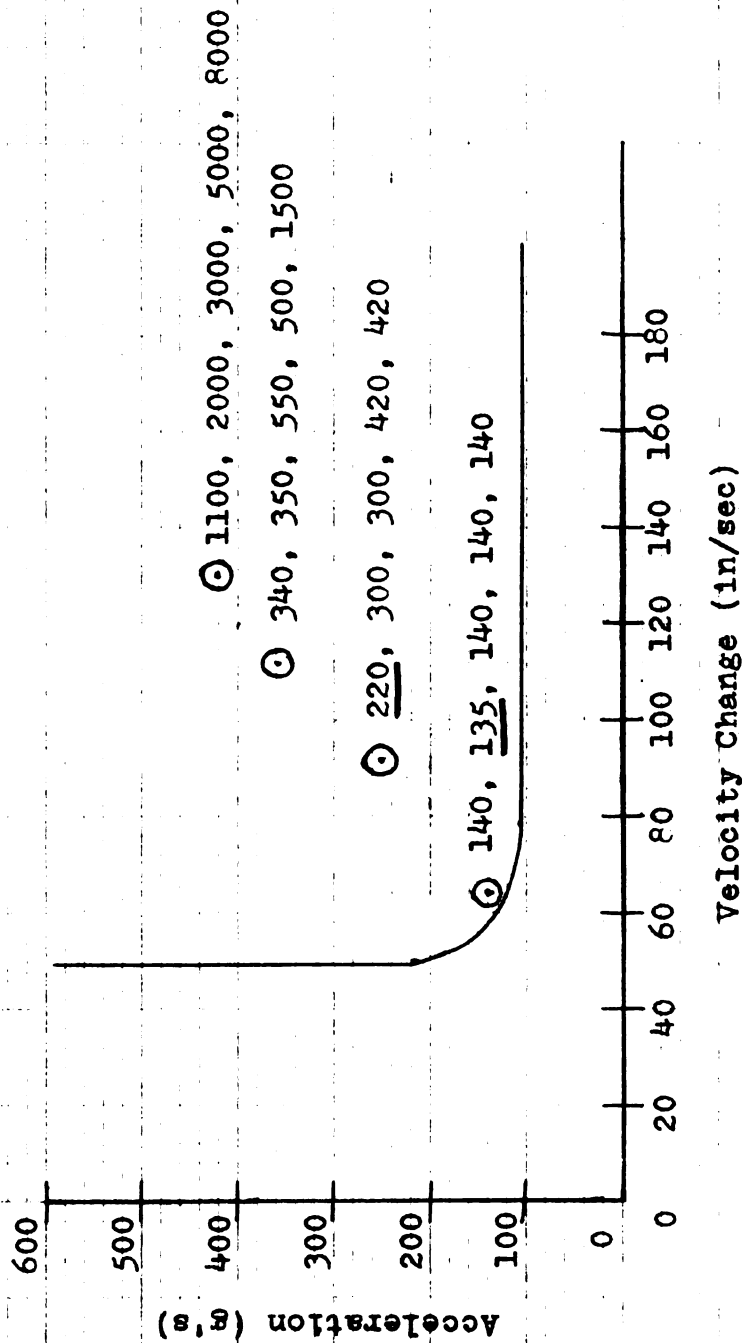


Figure 13.

Selected Input Shocks Within The A-flute Damage Boundary
At a Static Stress of 0.28, Showing Response Accelerations For Repeated Inputs

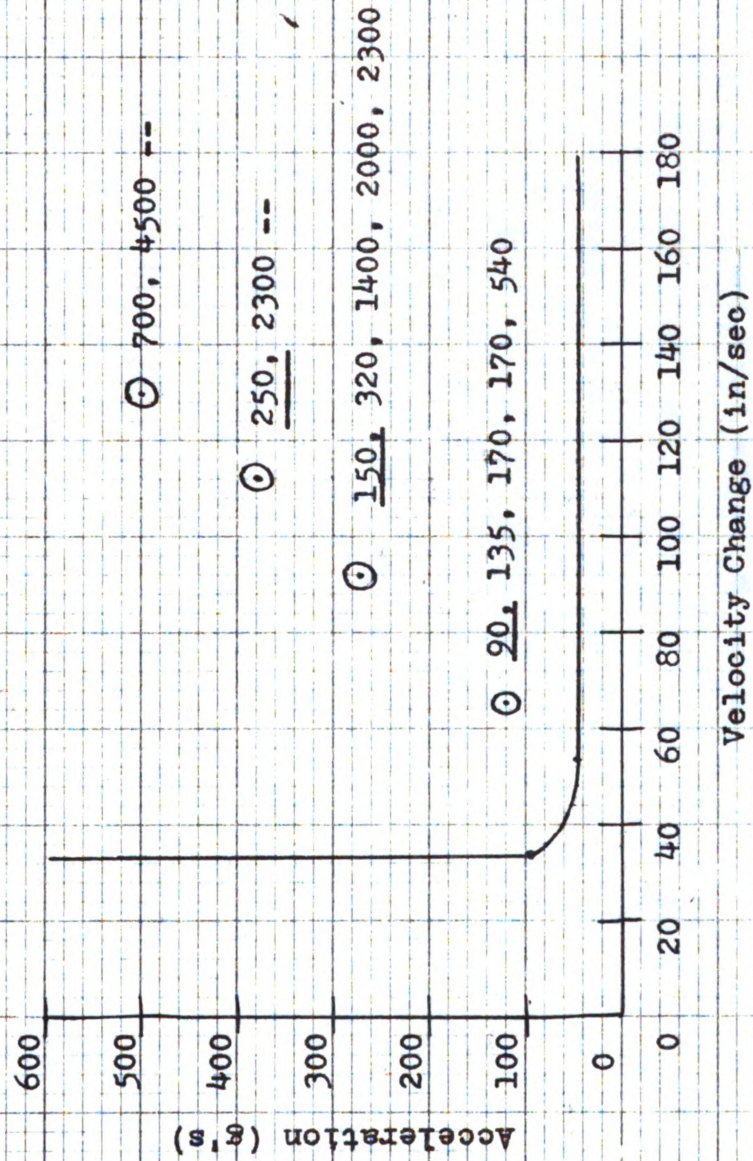


Figure 14.

Selected Input Shocks Within The A-flute Damage Boundary
At a Static Stress of 0.38, Showing Response Accelerations For Repeated Inputs

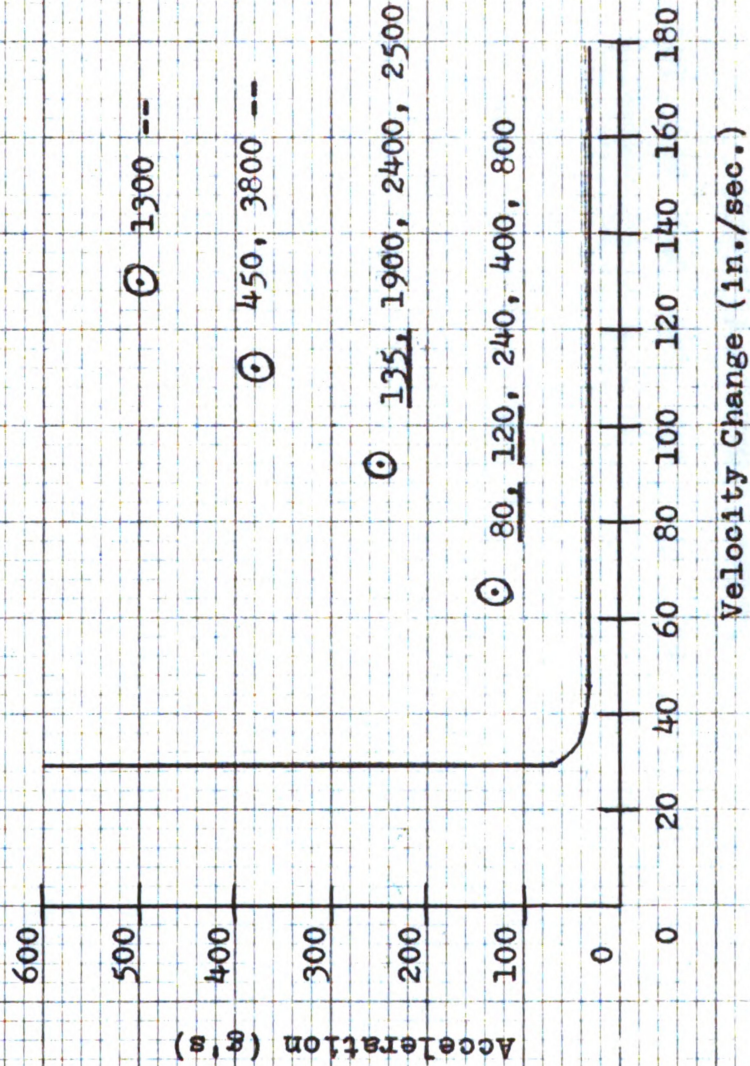


Figure 15.

Selected Input Shocks Within The A-flute Damage Boundary

At a Static Stress of 0.52, Showing Response Accelerations For Repeated Inputs

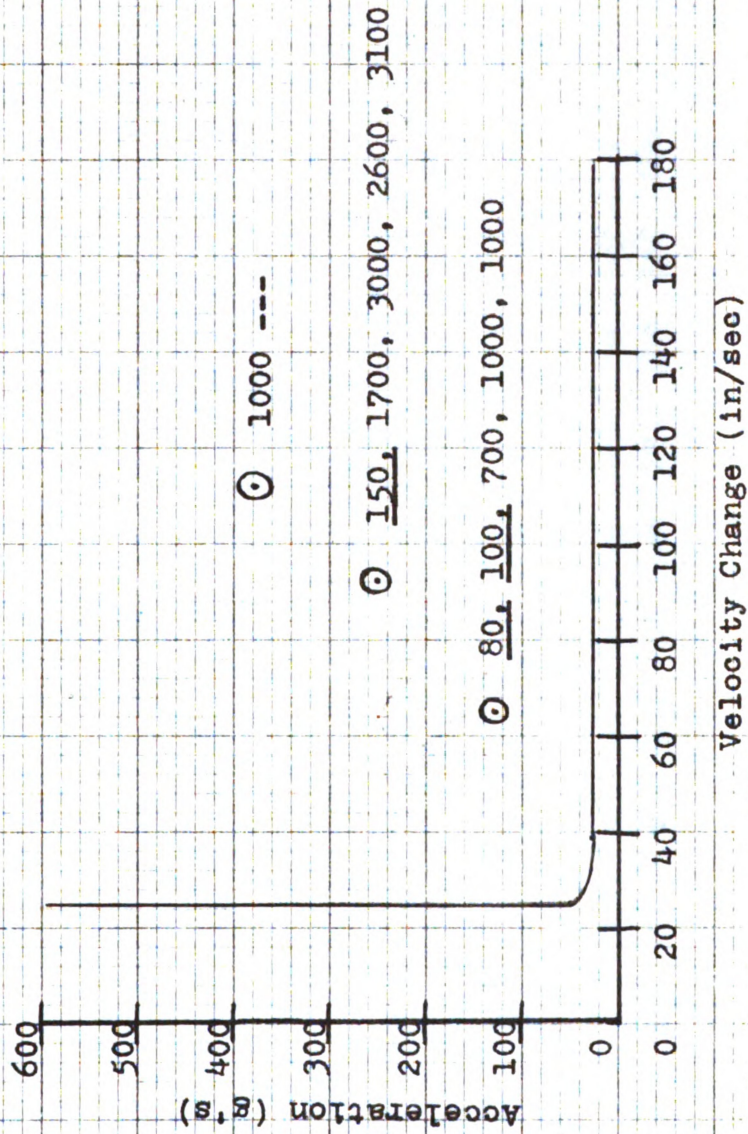


Figure 16.

Selected Input Shocks Within The B-flute Damage Boundary

At a Static Stress of 0.13, Showing Response Accelerations For Repeated Inputs

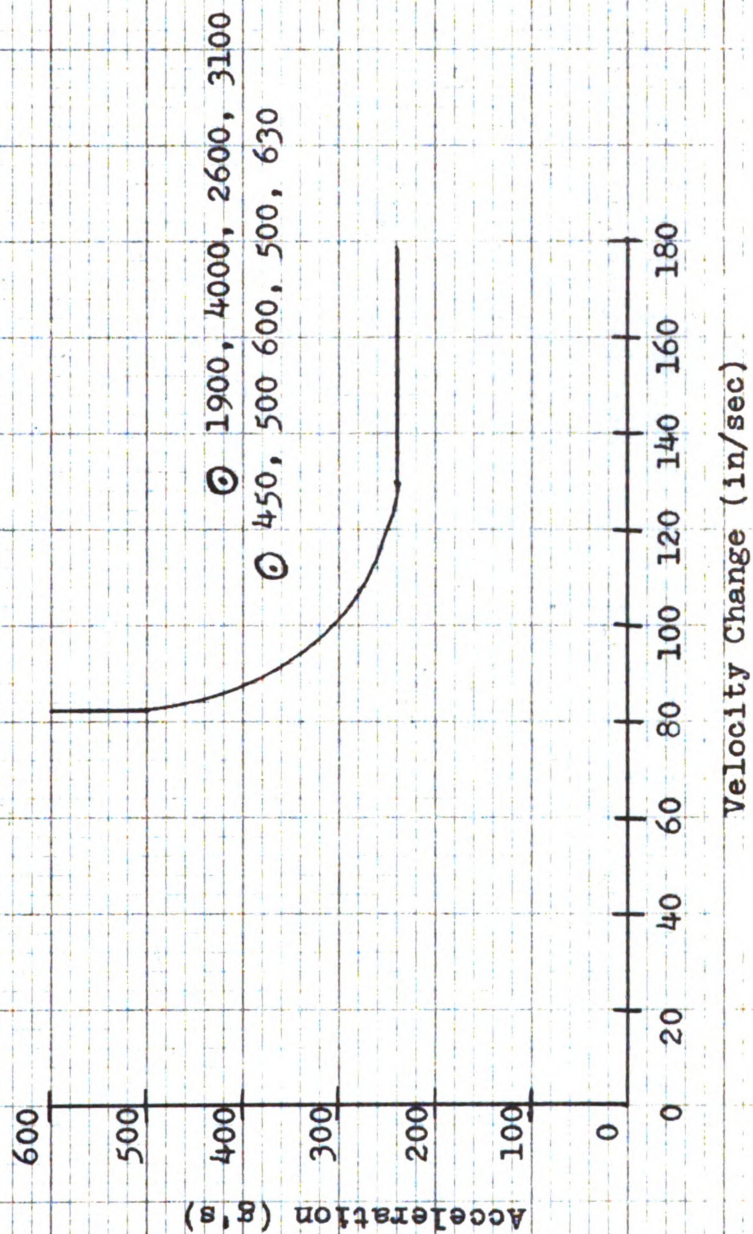


Figure 18.

Selected Input Shocks Within The B-flute Damage Boundary

At a Static Stress of 0.38, Showing a Response Acceleration For Repeated Inputs

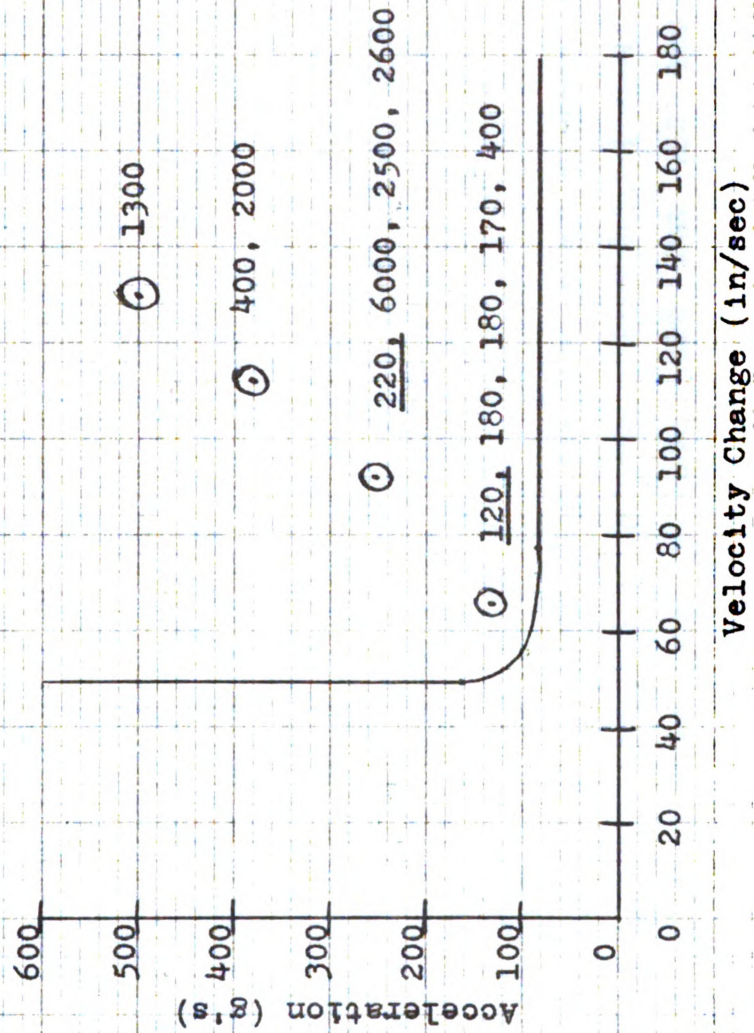


Figure 18.

Selected Input Shocks Within The B-flute Damage Boundary

At a Static Stress of 0.38, Showing a Response Acceleration For Repeated Inputs

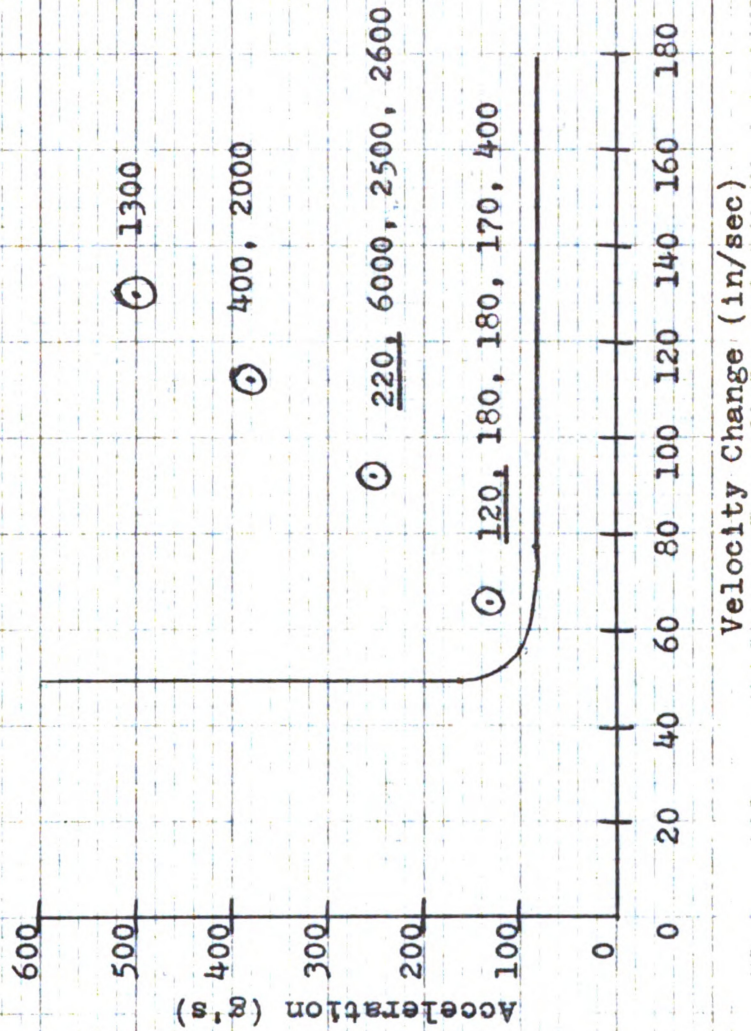


Figure 19.

Selected Input Shocks Within The B-flute Damage Boundary
At a Static Stress of 0.52, Showing Response Acceleration For Repeated Inputs

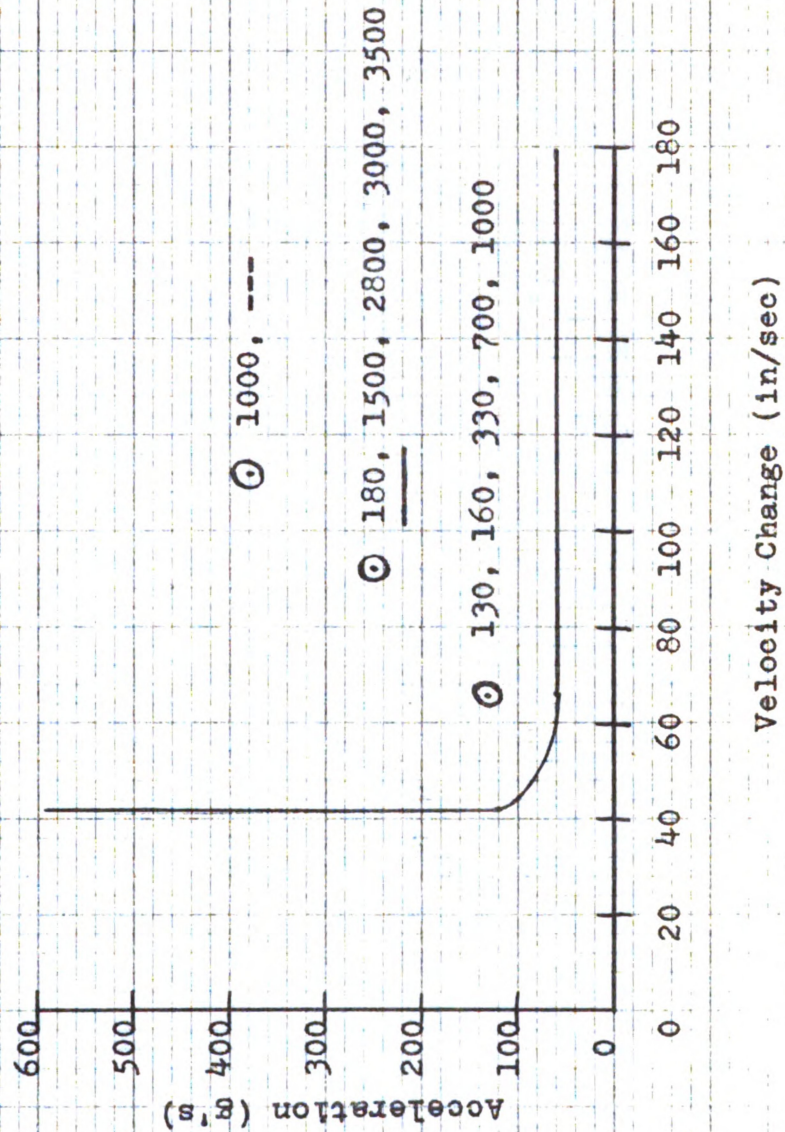


Figure 20.

Selected Input Shocks Within The C-flute Damage Boundary
At a Static Stress of 0.13, Showing Response Accelerations For Repeated Inputs

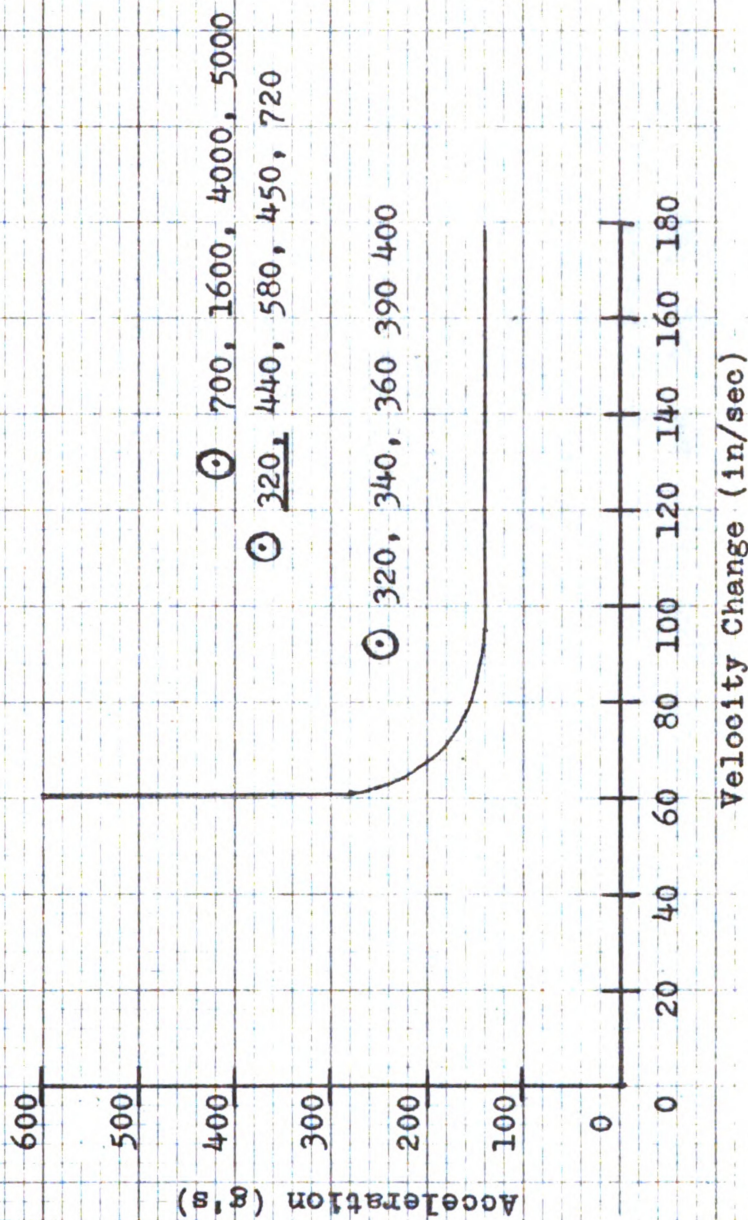


Figure 21.

Selected Input Shocks Within The C-flute Damage Boundary
 At a Static Stress of 0.28, Showing Response Accelerations For Repeated Inputs

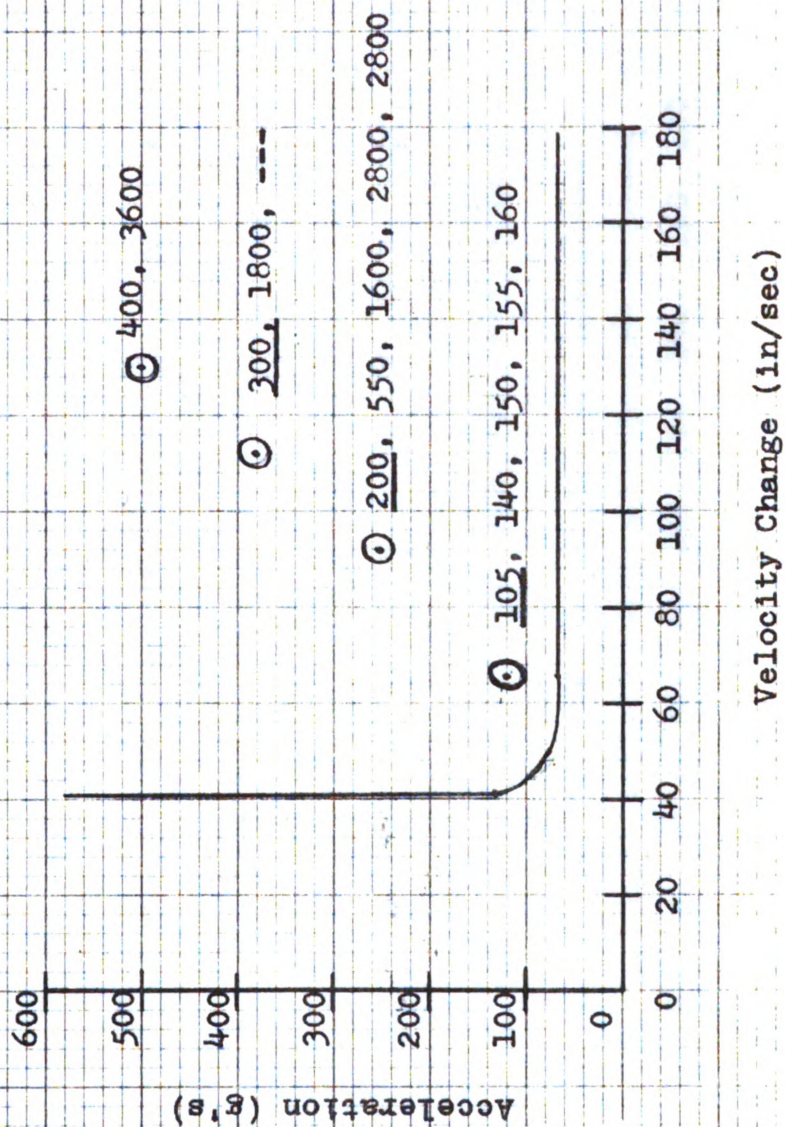


Figure 22.

Selected Input Shocks Within The C-flute Damage Boundary
At a Static Stress of 0.38, Showing Response Accelerations For Repeated Inputs

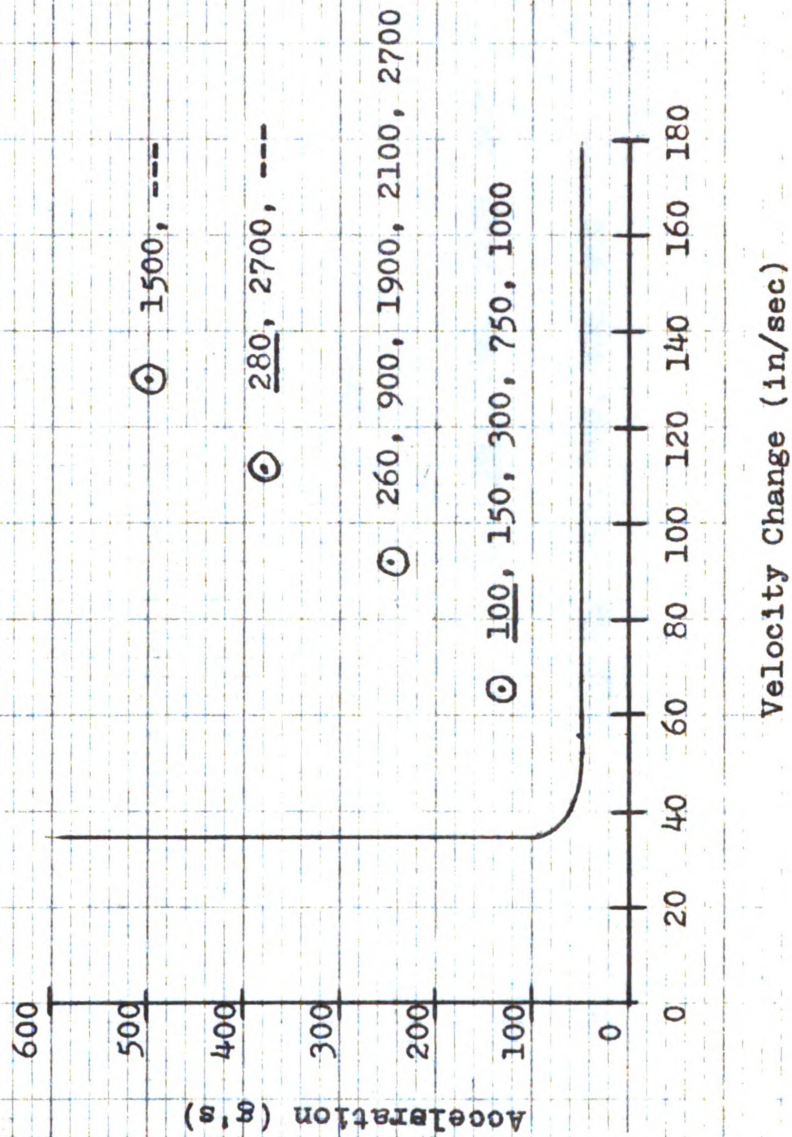
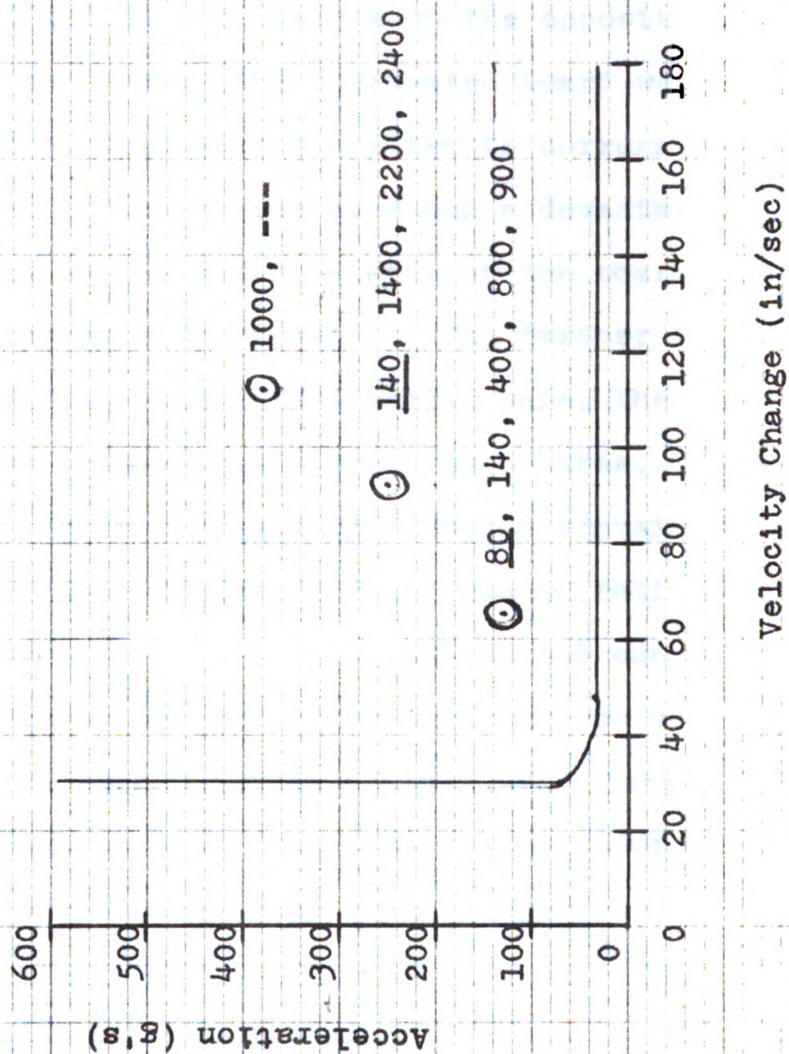


Figure 23.

Selected Input Shocks Within The C-flute Damage Boundary

At a Static Stress of 0.52, Showing Response Accelerations For Repeated Inputs



CONCLUSIONS

Any shocks applied to corrugated board which were outside of its damage boundary did not affect the flutes and had the same effect on the article on the opposite side of the corrugated board as if the corrugated board were solid. It was evident that shocks applied to corrugated board which were within the damage area had a devastating effect on the object on the opposite side of the board, especially if the shocks were repeated. The farther away from the damage boundary these input shocks were, the fewer shocks were necessary to completely crush the flutes.

Shocks applied to corrugated board when a container is dropped have a high acceleration-velocity change ratio. In order for these shocks to crush the flutes of the container they would have to cross the damage boundary in the velocity-sensitive range. The range of drop heights which would generate shocks with sufficient velocity change to cross the damage boundaries investigated here would be from 0.8 inches for A-flute at a static stress of 0.52 psi to 9.1 inches for B-flute at a static stress of 0.13 psi. These values are for articles which experience no rebound. Any rebound experienced by an article will cause these drop heights to be less. Drops which are not flat will also cause these heights to be less because the weight of the article must be supported by a

smaller area of board which effectively increases the static stress. It was shown that less velocity change was required to alter the flutes if the static stress was increased. From these observations it is expected that a great majority of package drops will result in alteration of the flute structure, and subsequent shocks will be amplified when experienced by the object on the opposite side of the corrugated board.

Since drops occur with random orientation, it is possible that a package would not receive more than one impact at the same part of its container. This would warrant a further consideration of first impacts. For input shocks in a small range close to the damage boundary there is some cushioning effect from the corrugated board on the first impact. This is due to the flutes being crushed by the shock, which causes the shock to be lengthened in time and reduced in magnitude. Repeated shocks or shocks which are outside of this range are sufficient to crush all of the flutes, allowing the objects on both sides of the board to collide.

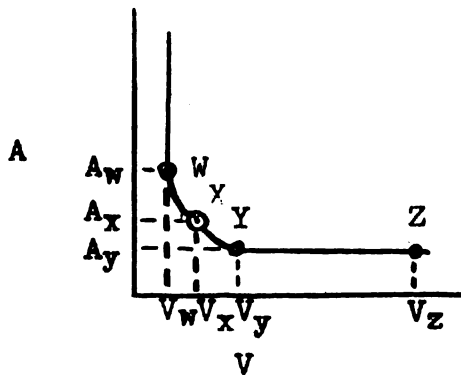
According to Rule 41 of the Uniform Freight Classification, the maximum weight allowable in a box constructed of 200-pound test singlewall board is 65 pounds. The sum of the dimensions cannot exceed 75 inches. Assuming a minimum of three inches for any one dimension, the maximum static stress in a 200-pound test singlewall container would be 0.723 psi, and the minimum static stress would be 0.050 psi. Based on this and the predicted relationships derived in

Appendix III, the range of drop heights which will cause enough velocity change to allow damage of the board is from 0.571 to 23.6 inches. In actual practice, this range will be much lower since this range is also based on no rebound and perfectly flat drops.

APPENDIX I

DERIVATION OF A FORMULA WHICH GIVES THE VELOCITY
CHANGE PORTION OF A DAMAGE BOUNDARY WHEN ONLY A POINT
ON THE TRANSITION AND A POINT ON THE ACCELERATION PORTION
OF THE DAMAGE BOUNDARY ARE KNOWN

Given a damage boundary with the following points
and line segments:



VW - Velocity Change Boundary

WY - Transition

YZ - Acceleration Boundary

W - Desired Point (A_w, V_w)

X - Known Point (A_x, V_x)

Y - Desired Point (A_y, V_y)

Z - Known Point (A_z, V_z)

The arc WXY is a $\frac{1}{4}$ sine wave with its origin at W and
its peak at Y, therefore

$$\frac{V_x - V_w}{V_y - V_w} = \frac{\sin^{-1} \left[\frac{A_w - A_x}{A_w - A_y} \right]}{\sin^{-1}(1)}$$

From damage boundary theory:

$$A_y = A_z, \quad A_w = 2A_z, \quad V_y = \frac{\pi}{2} V_w$$

Substituting into Eq. (1) and solving for V_w :

$$V_w = \frac{V_x}{\left\{ \left(\frac{\pi}{2} - 1 \right) \frac{\sin^{-1} \left[\frac{2A_z - A_x}{A_z} \right]}{\sin^{-1}(1)} \right\} + 1}$$

Allowing that the angles will be specified in degrees, Eq. (2) becomes:

$$V_w = \frac{V_x}{\left\{ (0.006342) \sin^{-1} \left[\frac{2A_z - A_x}{A_z} \right] \right\} + 1}$$

SAMPLE CALCULATION

For A-flute board at a static stress of 0.28 (Fig. 3, Table 10)

$$A_z = 46$$

$$A_x = 64$$

$$V_z = 220$$

$$V_x = 45.0$$

$$\sin^{-1} \frac{92-64}{46} = \sin^{-1} (0.61) = 37.6$$

$$V_w = \frac{45.0}{(0.006342) (37.6) + 1}$$

$$V_w = 36.3$$

Since $V_y = \frac{\pi}{2} V_w$ and $A_w = 2A_z$, all values for points W, X, Y, and Z are defined.

APPENDIX II

RELATIONSHIP BETWEEN THE ACCELERATION PORTION OF THE DAMAGE BOUNDARY AND STATIC STRESS

The amount of stress which would alter the flutes with no shock is the product of the static stress and the shock in g's experienced by the weight which caused the static stress. Since the acceleration which the weight experienced is twice the input acceleration for shocks along the acceleration boundary, this critical stress, S_c , for A-flute board is:

$$\begin{aligned} S_c &= (SS)(2A_p/g) \\ &= 28.0 \text{ psi for shocks applied at } 0.52 \text{ psi} \\ &= 27.4 \text{ psi for shocks applied at } 0.38 \text{ psi} \\ &= 25.8 \text{ psi for shocks applied at } 0.28 \text{ psi} \end{aligned}$$

Since this critical stress should be a constant for a given board size, the best estimate of that constant would be the average of the three values.

$$\bar{S}_c = 27.1 \text{ psi}$$

The relationship between the acceleration boundary and static stress for A-flute board becomes:

$$(SS)(2A_p/g) = 27.1$$

and the value of the acceleration boundary is given by:

$$A_p/g = 13.55/SS$$

The value of the acceleration boundary is then:

$$A_p/g = 13.55/SS$$

Similarly, equations can be found for the other two board sizes:

$$A_p/g = 31.2/SS \text{ for B-flute}$$

$$A_p/g = 18.1/SS \text{ for C-flute}$$

These relationships are plotted on the side view of their respective damage boundaries (Fig. 5, 8, and 11).

APPENDIX III

RELATIONSHIP BETWEEN THE VELOCITY CHANGE PORTION OF THE DAMAGE BOUNDARY AND STATIC STRESS

From damage boundary theory it is know that

$$\Delta V_1 = \frac{1}{2\pi} \frac{A_c}{f_c} \quad (1)$$

where ΔV_1 = limiting velocity change for the
velocity change boundary, in./sec.

A_c = response acceleration which begins
to cause flute alteration, in./sec.²

f_c = frequency of test block on corrugated
sample when flutes are unaltered

Substituting $f_c = \frac{1}{2\pi} \frac{k}{m}$,

$$A_c = 2A_p \quad ,$$

and $SS = mg/64$ = static stress, psi

into Eq. (1) and solving for k,

$$k = 98800 (A_p/g)^2 SS / (\Delta V_1)^2. \quad (2)$$

For A-flute board $A_p/g = 13.5/SS$ from Appendix III and

$$k = 1.82 \times 10^7 / \Delta V_1^2 SS \quad (3)$$

Solving Eq. (3) at the various static stresses,

$$k = 61300 \text{ lb./in. at } 0.52 \text{ psi}$$

$$k = 62000 \text{ lb./in. at } 0.38 \text{ psi}$$

$$k = 49000 \text{ lb./in. at } 0.28 \text{ psi}$$

For purposes of extrapolation, it is assumed that k is a constant over the range of static stress in consideration and the best estimate of its value is the average of these three values.

$$\bar{k} = 57400 \text{ lb./in. for A-flute board.}$$

Substituting this value back into equation (3) and solving for ΔV_1 ,

$$\Delta V_1 = 17.8 / SS^{+\frac{1}{2}}$$

Similar equations for the other two board sizes can be obtained:

$$\text{B-flute } \Delta V_1 = 30.2 / SS^{+\frac{1}{2}}$$

$$\text{C-flute } \Delta V_1 = 21.9 / SS^{+\frac{1}{2}}$$

These equations are plotted on the top view of their respective damage boundaries (Figures 4, 7, and 10).

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