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THE CRUSHING STRENGTH OF PAPER HONEYCOMB

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13. ABSTRACT

The effects of entrapped air on the apparent crushing strength of paper honeycomb are studied. A definite increase in strength can be attributed to the compression of the entrapped air but the magnitude of the increase depends on a number of factors, such as, specimen dimensions, orientation of the glue lines with respect to the edges of the specimen, and the treatment, if any, of the cut edges of the test samples. Strength is increased if the glue lines are parallel to rather than perpendicular to the long edges of the rectangular specimens. Taping the edges which are perpendicular to the glue lines reduces blowout and increases compressive strength.

Failures of isolated single paper honeycomb cells as a result of internal pressurization occur at a pressure of approximately 5 psi. These failures are always a result of delamination at the joint. No paper ruptures, and no glue failures have been observed.

The crushing strengths of paper honeycomb samples subjected to impacts in which the impact velocity is inclined with respect to the cell walls, is reduced as the angle of inclination increases. The reduction is essentially insignificant until the angle of inclination exceeds 10%. Recommendations are made for taking these various characteristics of paper honeycomb into consideration in the design of cushioning systems.

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Entrapped			0			
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Insulation			4			
Cushioning			4			

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THE CRUSHING STRENGTH OF PAPER HONEYCOMB

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FOREWORD

This work was performed under US Army Natick Laboratories Contract No. DAAG 17-70-C-0127 during the period of 1 Apr 70 - 31 Mar 72. The Project No. was 1F162203D195 entitled "Exploratory Development of Airdrop Systems", and the Task No. was 13 entitled "Impact Phenomena". Mr. Marshall S. Gustin of the Airdrop Engineering Laboratory served as the Project Officer.

The effort is part of a continuing investigation directed toward obtaining a better understanding of the failure mechanism of energy dissipater materials, and the response of airdroppable supplies and equipment to airdrop impact phenomena; and toward obtaining improved airdrop energy dissipater materials and techniques.

This report is concerned with the conduct of experimental studies of Paper Honeycomb Material MIL-H-9884, used for cushioning airdrop loads against the effects of ground impact. Studies were made to determine (a) the role that entrapped air in the honeycomb cells plays in the energy dissipation process and (b) the crushing strength of honeycomb subjected to nonvertical crushing forces.

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ABSTRACT

The effects of entrapped air on the apparent crushing strength of paper honeycomb are studied. A definite increase in strength can be attributed to the compression of the entrapped air but the magnitude of the increase depends on a number of factors, such as, specimen dimensions, orientation of the glue lines with respect to the edges of the specimen, and the treatment, if any, of the cut edges of the test samples. Strength is increased if the glue lines are parallel to rather than perpendicular to the long edges of rectangular specimens. Taping the edges which are perpendicular to the glue lines reduces blowout and increases compressive strength.

Failures of isolated single paper honeycomb cells as a result of internal pressurization occur at a pressure of approximately 5 psi. These failures are always a result of delamination at the joint. No paper ruptures, and no glue failures have been observed.

The crushing strengths of paper honeycomb samples subjected to impacts in which the impact velocity is inclined with respect to the cell walls, is reduced as the angle of inclination increases. The reduction is essentially insignificant until the angle of inclination exceeds 10%. Recommendations are made for taking these various characteristics of paper honeycomb into consideration in the design of cushioning systems.

THE CRUSHING STRENGTH OF PAPER HONEYCOMB

1. Introduction

Many of the factors which influence the crushing strength and energy dissipation capacity of paper honeycomb have been studied in the past and reported on from time to time. It has been established in these previous studies that

a. The crushing strength is essentially independent of impact velocity in the range from 20 to 90 ft/sec.[1,2]

b. Crushing strength is not sensitive to uniformity of cell size, paper weight, or type of glue, but is directly related to the average density of the material.[3,4]

c. Crushing strength is not significantly affected by moisture content if the content is less than 12% of the dry weight of the material.[1,5]

d. Crushing strength is dependent on the horizontal cross sectional area of the test sample. It decreases as the area decreases.[4] This decrease appears to be related to the ratio of the area of the outside row of cells to the total sample area.

Although the question has been raised and studies have been made in the past, the role that air entrapped in the cells plays in the energy dissipating capacity of paper honeycomb has not been clarified. At one time it was concluded that the entrapped air was unimportant. However, elementary analysis, and subsequent measurements, although not conclusive, indicate that the air could have a significant effect on crushing strength and energy dissipation.[4] It has also been suggested that the entrapped air, in the process of producing cell blowout and glue line rupture, contributes to the variations in crushing strength that have been observed.[4] In this report the question of the effect of the entrapped air is considered again and test results are presented which indicate both the direct and the indirect effects of the entrapped air on the performance of paper honeycomb as a crushable cushioning material.

Another aspect of the crushing characteristics of paper honeycomb that has been largely ignored in past studies is the relationship between crushing strength and the orientation of the impact velocity vector with respect to the normal to the facing of the cushioning pad. It has long been recognized that cushioning which is adequate for a normal impact may not be adequate for impacts with velocity components both parallel to and perpendicular to the impact surface. However, no serious field problems in this regard have been reported. As a consequence, studies of paper honeycomb characteristics have been focused on other aspects. In this report some results are presented of an experimental study of the dynamic crushing strength of 80-0-1/2 paper honeycomb samples subjected to impacts in which the impact velocity vector was not along the normal to the surface of the sample.

2. Effects of Entrapped Air

a. Experimental Studies and Techniques

As indicated above, the purpose of this study was to determine the role which air entrapped in the honeycomb cells plays in the energy dissipation process. If the simple view is taken that the air is completely entrapped, and the force required to compress the air is merely added to the force required to crush honeycomb that contains no air, it is immediately seen that the compression of the air would be adding approximately 2120 psf. (1 atmosphere) to the crushing strength at 50% strain, and that this addition would vary inversely as the volume of the compressed air in the cells. Thus if honeycomb without air crushes at a constant stress, honeycomb with air would show a stress-strain curve with the rectangular hyperbolic shape characteristic of the pressure-volume relationship for a gas in isothermal compression. In general, the stress-strain curves for paper honeycomb do not have this appearance. Consequently one must conclude that the entrapped air plays no part, or the simple view as outlined above does not adequately describe the action. To answer first the question, does the air play an important role or does it not, would seem to require only that stress-strain curves for completely evacuated samples be compared to those for unevacuated samples. Thus, considerable time and effort were expended in trying to make tests of evacuated samples using a vacuum chamber, just slightly larger than the specimen, sealed with a flexible or an easily breakable membrane in combination, and separately. This membrane rested on top of the specimen and was attached at the edges to the chamber. The impact mass first made contact with the membrane and then crushed the specimen. If the breakable membrane (milar) was used it was cut almost immediately at impact. As soon as the membrane was cut, there was a rush of air into the chamber which caused an inward buckling of several rows of cells around the perimeter of the sample.

This buckling caused a significant loss of crushing strength. The flexible seal (rubber) eliminated the problems associated with the breakable seal but introduced some other difficulties. Because the flexible seal was difficult to stretch, a small 7 x 7 in. specimen size was required which introduced some indeterminable area effect factors when used as a control or comparison specimen. Also the seal offered some appreciable resistance to the crushing and therefore altered the apparent energy dissipation characteristics of the sample. These and other considerations indicated that the only way to properly conduct a test of a completely evacuated sample would be to place the entire drop facility and specimen in the vacuum chamber together. Although this could be accomplished it promised to be a time-consuming and expensive way to accomplish the objective. Consequently an attempt was made to devise an alternate method for accomplishing that objective.

If the air could be exhausted unimpeded from a specimen, during a crushing test, the contribution of the compressed air to the apparent compressive strength would be eliminated. Consequently this was the line of attack that was adopted. A test procedure was devised which is described as follows. The facing paper is removed from one face of a 12 x 12 in. honeycomb specimen so that each cell becomes in effect an open cell with direct access to the atmosphere. This specimen is then placed open face down on a platform constructed with an expanded metal mesh top. The mesh openings are diamond shaped approximately 1-1/2 in. across one pair of corners and 1/2 in. in the orthogonal direction. This mesh is supported by a wooden box around the perimeter and by five narrow plates uniformly spaced in the interior of the box. These details may be seen in Fig. 1. The platform supports the specimen during crushing but allows the air in the cells essentially an unimpeded exit. Control specimens with facing paper intact are also crushed on this platform to obtain results for comparison with the results from the open specimens. Some test results are shown in Table I. The comparison of average stresses shows that the open cell specimens crush to 70% strain with an average stress that is approximately 15% lower than that from comparable closed cell specimen tests. In contrast to the crushed closed cell specimens the crushed open cell specimens show no glue line rupture, and the buckling patterns are uniform throughout most of the specimens with no gross cell wall buckling at the perimeter. Some typical closed and open cell crushed specimens are shown in Fig. 1.

Open Cells

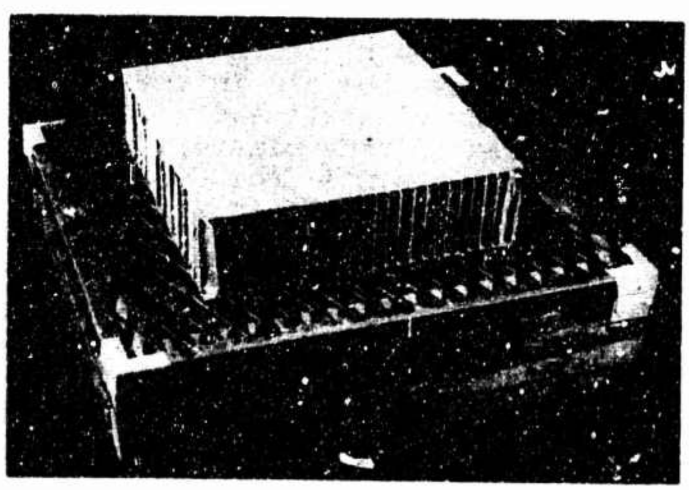
Closed Cells

(a) Crushed Open and Closed Cell Samples: Note the Absence of Blowout in the Open Cell Sample

Open Cells

Closed Cells

(b) Crushed Samples: Note the Uniform Crushing and the Absence of Glue Line Failures in the Open Cell Sample



(c) Grid Platform for Open Cell Tests

Fig. 1 Open and Closed Cell Testing

Table I

Honeycomb Test Results

Closed Cell

Specimen	Core Density* lb/ft^3	Crushing Strength Average to 70% Strain psf	Normalized** Crushing Strength psf
C-1	1.58	4030	3940
C-2	1.66	4590	4300
C-3	1.63	5000	4750
C-4	1.44	4125	4440
C-5	1.56	4690	4580
C-6	1.55	4400	4400
C-7	1.54	4370	4400
C-8	1.68	5400	4980
C-9	1.67	5240	4860
C-10	1.74	5250	4680
Average	1.61	4709	4533

Open Cell

Specimen	Core Density* lb/ft^3	Crushing Strength Average to 70% Strain psf	Normalized** Crushing Strength psf
O-1	1.61	3490	3360
O-2	1.63	3920	3730
O-3	1.93	4690	3770
O-4	1.52	3700	3770
O-5	1.57	3840	3800
O-6	1.45	3700	3960
O-7	1.42	3540	3860
O-8	1.62	4510	4310
O-9	1.64	4320	4080
O-10	1.67	4490	4170
Average	1.61	4020	3881

*"Core Density" is the density of the core stock with the facings removed.

**These strengths are obtained by multiplying the average crushing strength by the ratio of the core density to 1.55 which is an arbitrarily selected core density. Earlier test results show that around a core density of 1.50 lb/ft^3 the crushing strength varies almost linearly with density.[2]

The uniform manner in which the open cell specimens crush as compared to the crushing of the closed cell specimens indicates that air pressure gradients across the cell walls alter the buckling patterms. Closed cell specimens which have been crushed have the interior cell walls pushed in random directions and there is extensive rupturing (delamination) along the glue lines.

The open cell versus the closed cell tests show very definitely that the entrapped air has an effect on the crushing strength of honeycomb. This effect is a result of several different actions. One is, of course, simply the pressure increase in the air as it is compressed. Another is the change in buckling patterns produced by the internal pressure of the air. This latter effect suggests that although the 14% to 15% apparent increase in crushing strength of the closed cell specimens over that of the open cell specimens is accurate for a 12 x 12 in. specimen, it cannot be extrapolated to other sizes of specimens. To determine the extent to which the outward bulging of the cells along the periphery of closed cell samples affects crushing strength and also to gain insight into the directional characteristics of honeycomb, some further studies have been made. In these studies eight long, narrow specimens (4" x 24") were prepared as follows. One group of four specimens designated the "T" group was cut so the glue lines were transverse to the longitudinal axis or the long axis. The other group of four designated the "L" group was cut with the glue lines parallel to the long axis. This glue line orientation is illustrated in Fig. 2. These specimens were intended to simulate the edge regions of a honeycomb pad.

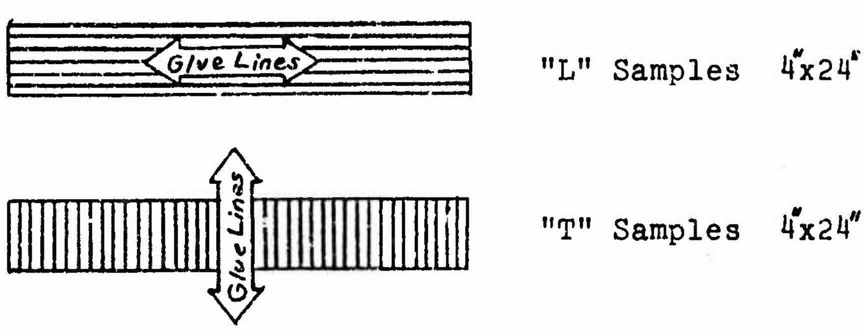
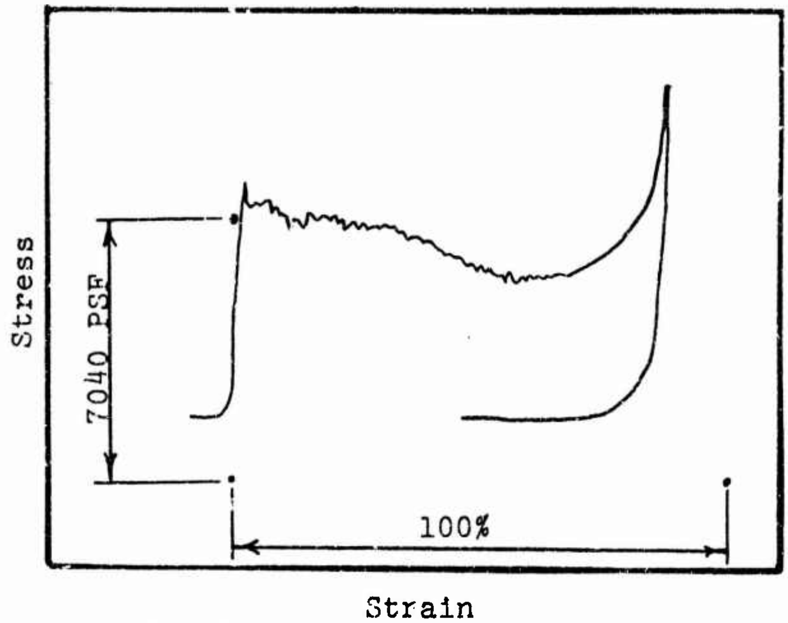
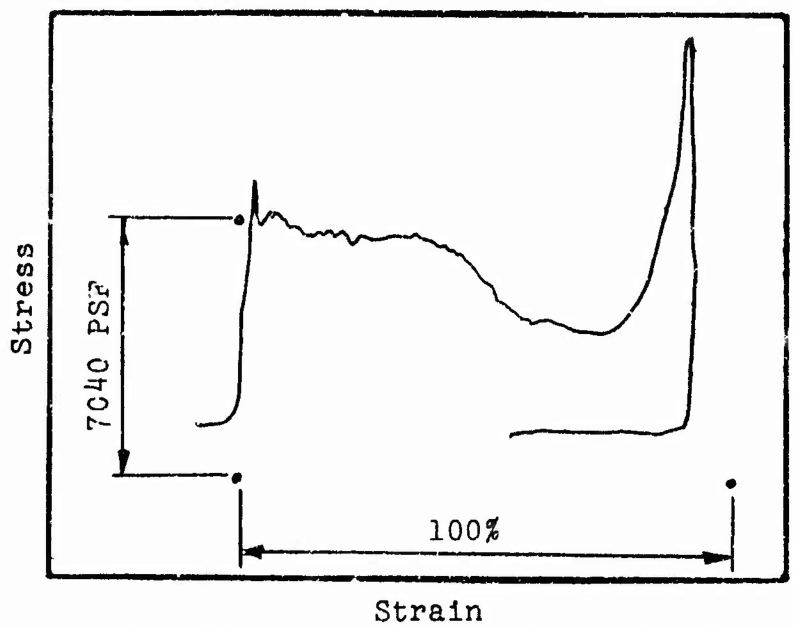


Fig. 2 Glue Line Alignment for Edge Simulation Tests (Top View)



Glue Lines Parallel to Long Axis



Glue Lines Transverse to Long Axis

Fig. 3 Stress-strain Curves - Edge Simulation Tests

Some typical stress-strain curves for each of the two groups are shown in Fig. 3 and the complete tests results are compiled in Table II. The stress-strain curves show very little difference up to 50% strain. Between 50% and 70% strain the curves for the "T" specimens decrease rapidly and those for the "L" group decrease but not to the same extent as the "T" specimens. This indicates that the air trapped and compressed in the "L" group of specimens contributes the slight difference in crushing strength. This contribution is more than enough to compensate for the reduction in strength caused by the severe buckling of the outer cell rows. The difference in crushing characteristics of the two types of specimens is clearly shown in Fig. 4a.

The loss of strength in the "T" specimen after 50% strain is passed is attributed to the rapid escape of air from the interior of the specimen. In these specimens the air has only a short distance to travel in comparison to the distance it must travel in escaping from the "L"

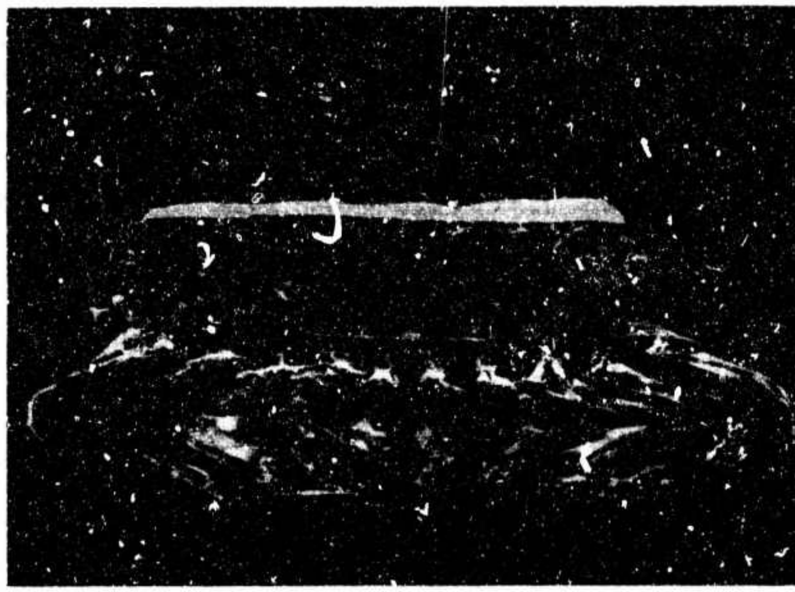
Table II

Edge Simulation Tests

4"x24"x3" Paper Honeycomb Samples

Specimen		Average Stress - psf
T-1		4330
T-2		4290
T-3		4240
T-4		4330
	Average	4300
L-1		4460
L-2		4480
L-3		4460
L-4		4440
	Average	4460

specimens. From these observations it has been hypothesized that if the two exposed glue line edges of a specimen (i.e., the two short edges of the "L" specimens) could be protected from the air pressure differential, glue line rupture could be prevented or delayed. Thus loss of strength due to rapid air escape would be reduced.



(a) End Views of Long, Narrow Samples Cut with Glue Lines Transverse to Long Axis (Top) and Parallel to the Long Axis (Bottom)

(b) Samples with Covered Glue Line Edges Paper Glued on Face and at Corners (Top), Taped with Two Lengths Two Inch Wide Tape (Center), Paper Glued on Face and Taped at Corners (Bottom)

Fig. 4 Air Compression Effects

To test this hypothesis some 12" x 12" specimens were prepared. The edges of these specimens were treated in different ways. Each method of preparation was intended to create a buffer pressure zone between atmospheric pressure and the internal pressure produced in the specimen. One specimen was placed in a plastic bag, sealed with tape so pressure would develop in the bag when the volume was decreased by compression of the specimen and the bag. Two specimens were prepared with facing paper glued to the exposed glue line edges of the sample. This paper facing was glued at the corners on one of the specimens and on the other it was taped at the corners. A fourth specimen was prepared by taping the exposed edges with two lengths of 2" wide tape. These methods of treating the edges of the samples are illustrated in Fig. 4b. Samples prepared in this way were crushed in the dynamic tester and dynamic stress-strain curves were obtained. The average stress for each of these special samples and for a control sample are shown in Table III. From the typical stress-strain curves shown in Figs. 5 & 6 for these specimens, one can see that there is a near constant stress maintained for the duration of the crushing. The maximum strain reached varies from 82% to 86%, whereas the control specimen (edges not covered) reached a maximum strain of 91%. The stress-strain curve for this specimen is shown in Fig. 6. An energy absorption comparison shows that the specimens with the covered edges absorbed almost 10% more energy up to the 70% strain level than the control specimen. This difference is attributed to the energy dissipation provided by the entrapped air. To dissipate energy the entrapped air must leak out while it is still under pressure. However, the cells need not rupture for leakage to occur. Air readily leaks through the paper but not so rapidly as to prevent pressure buildup when the sample is rapidly compressed. It seems very likely that this leakage took place in both the control specimen and in the specimens with covered edges, the essential difference being a higher pressure buildup before rupture and fewer rupture cells in the specimens with the covered edges. It is also possible that the buckling modes in the specimens with covered edges are more favorable to energy dissipation as a result of the decrease in the extent of glue line rupture, or delamination, in these specimens as compared to the control specimen.

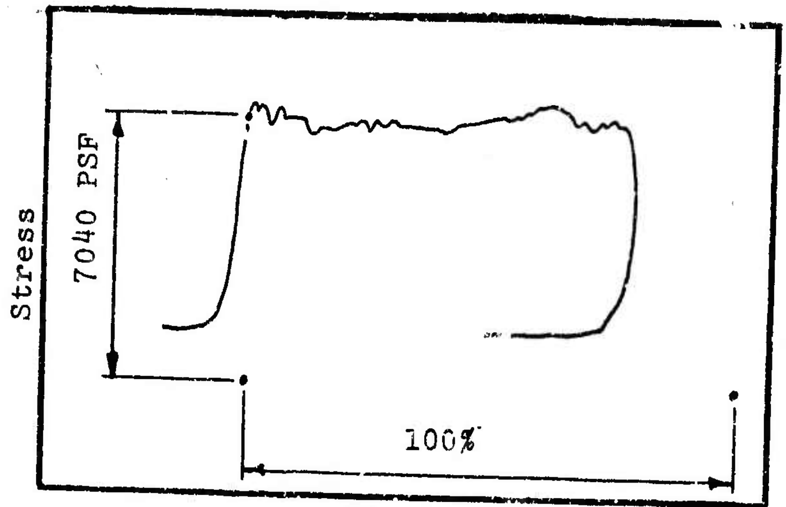
Another interesting result which should be noted is the very small range in the crushing strengths of the samples with covered edges. The variation among the samples was less than 1%. This suggests that the large variations

Table III

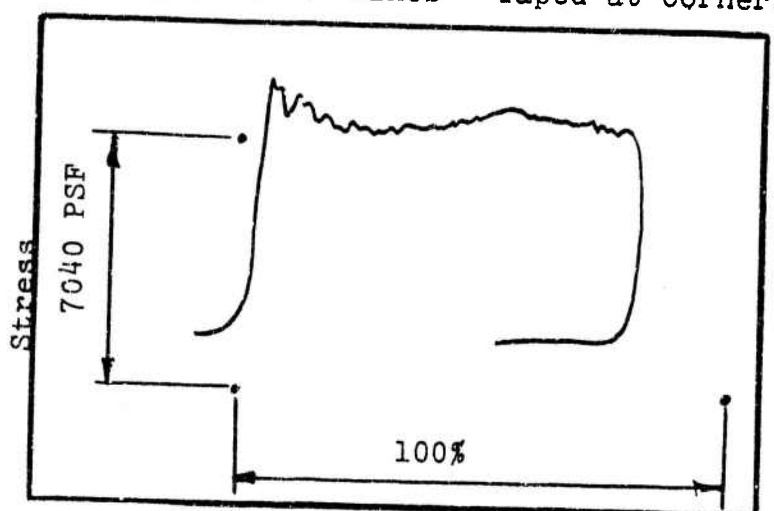
Edge Treatment and Air Compression Effects

Sample	Specimen weight (grams)	Total prepared weight (grams)	Mode of Preparation	Maximum strain (%)	Average stress to 70% ε psf	Average stress to 80% ε psf
AR-1 a	230	230	None (control)	91	4720	4370
AR-1 b	250	250	"	89	4840	4730
AR-1 c	247	247	"	87	4470	4380
AR-2	216	271	Inside plastic bag	86	5490	5225
AR-3	218	246	Glue line edges covered with paper glued top and bottom and taped at corners	82	5450	5350
AR-4	240	265	Glue line edges covered with paper glued top and bottom and at corners	81	5310	5280
AR-5	220	258	Glue line edges covered with two lengths of two inch wide adhesive tape	84	5430	5270

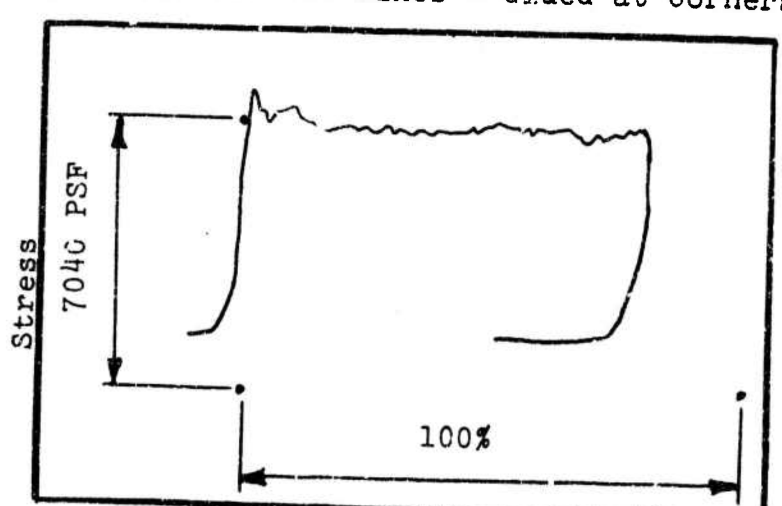
Average difference between control average and special samples = 13%
Maximum " " " " " " " = 15%
Minimum " " " " " " " = 12%



Strain
Paper Covered Glue Lines - Taped at Corners

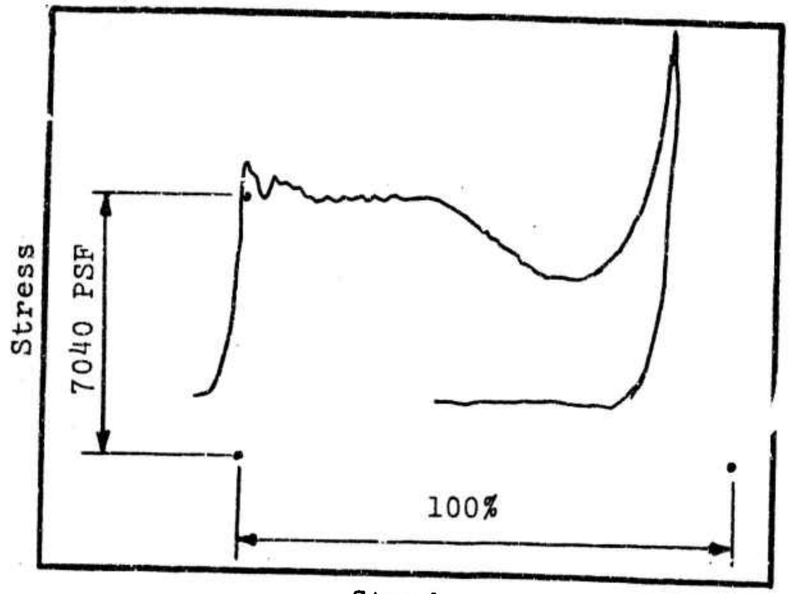


Strain
Paper Covered Glue Lines - Glued at Corners

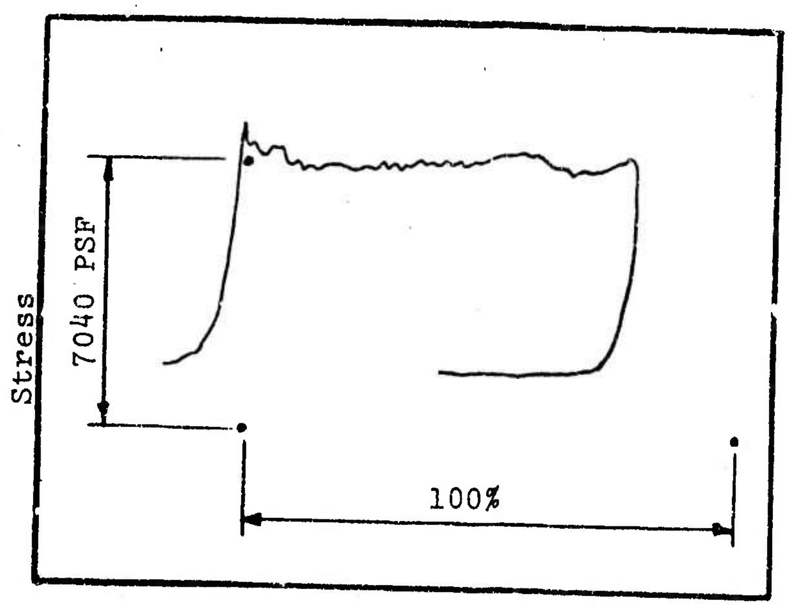


Strain
Taped Glue Lines

Fig. 5 Stress-strain Curves - Covered Glue Line Tests



Strain
Control Sample - No Glue Line Cover



Strain
Sample Inside Plastic Bag

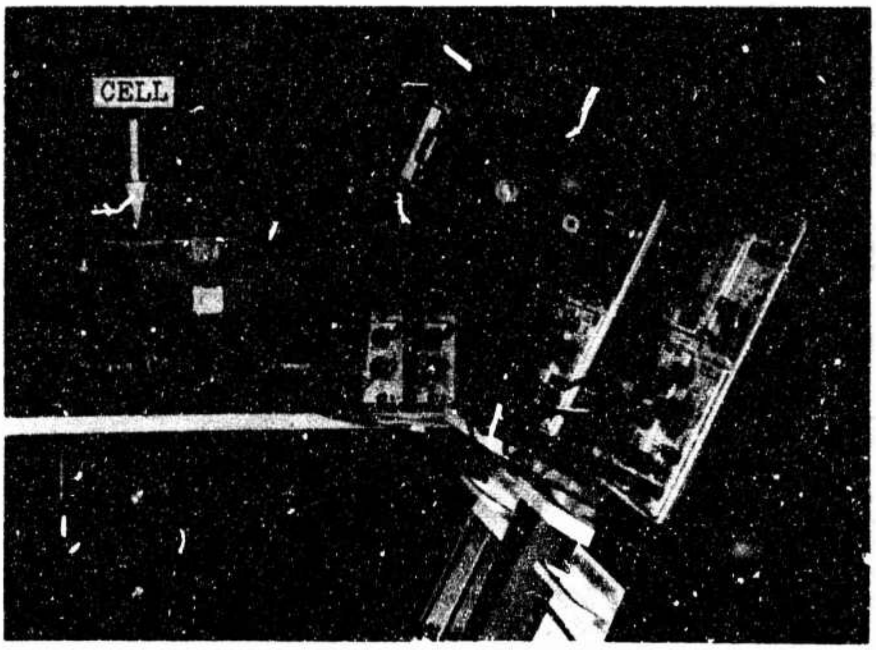
Fig. 6 Stress-strain Curves - Glue Line Effects in crushing strengths that generally seem to prevail in paper honeycomb tests may be due to random glue line delamination and the subsequent escape of air.

If the stress-strain curve for the control sample (untaped speciman) shown in Fig. 6 is examined it is seen that the low point on the curve occurs at or near 70% strain. At 80% strain the stress level is about the same as the average stress between 0 and 45% strain, and bottoming of the sample is beginning. Since bottoming occurs when the cells are essentially completely collapsed it should occur at the same strain in the taped and untaped specimens. Thus it appears that if the taped specimen had been crushed to 88-90% strain, instead of 80%,it also would have bottomed. Therefore the essential difference between the stress-strain curves for the two specimens occurs between 45 and 80% strain. It is the additional energy dissipated by the taped specimen in this range that kept it from bottoming. To crush the taped specimen to 88-90% strain more input energy is required than was available in this test.

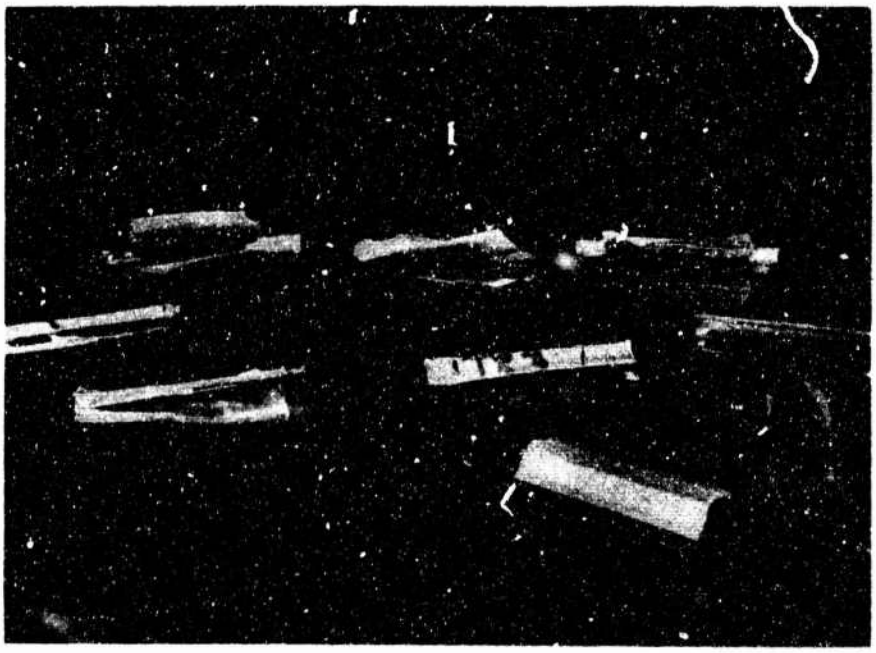
Originally 70% strain was selected as the maximum strain for design calculations because it was believed to be the strain at which bottoming begins, since the stress-strain curve begins to climb steeply at 70%, or slightly greater strain. Now our studies indicate that bottoming does not really begin until 80% strain is reached. Other test results selected at random from more than 1000 tests performed in the Engineering Mechanics Laboratory over the past two years all support this observation. Thus it appears that the maximum strain used in cushion design could be increased from 70% to 80%. Furthermore, if the edges of the cushions are taped, or otherwise treated so as to inhibit blowout, honeycomb cushioning will be utilized more efficiently and the total volume of cushioning material required can, in many cases, be reduced from the volume required under present design procedures.

b. Rupture Strengths of Single Cells

The manner in which a single paper honeycomb cell fails as a result of excessive internal pressure has been studied with the broad objective of learning what pressures produce rupture, and in general how the cells rupture, with the more specific objective of determining how variations in gluing techniques affect rupture strength. The apparatus used for the tests is shown in Fig. 7a. After the cell is clamped in place as shown, pressure is applied by activating the solenoid valve seen just below the specimen. This valve admits pressurized nitrogen to a copper tube which connects to the



(a) Equipment Used for Determining the Rupture Pressure as a Function of Time

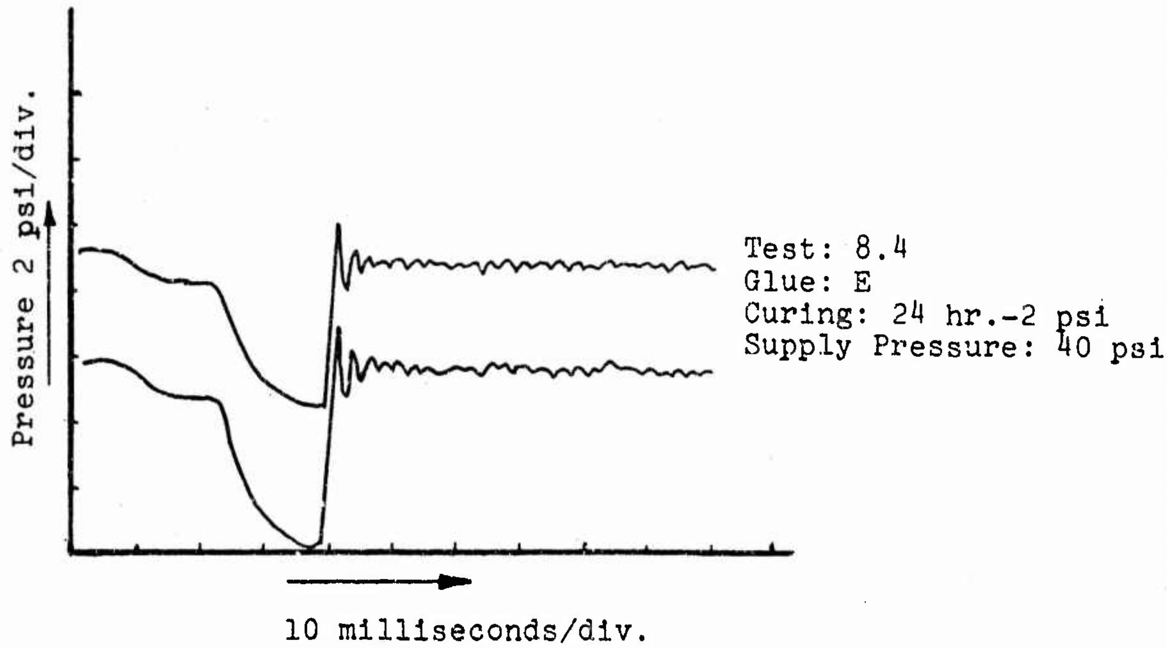


(b) Ruptured Cells: Note How All Failures Occurred at the Glue Lines

Fig. 7 Rupture Testing of Single Honeycomb Cells specimen. Two pressure transducers are used, one with the diaphragm normal to the direction of the in-flow of nitrogen and the other with its diaphragm parallel to the flow direction. These transducers can be seen at the right of the cell under test. Outputs from these transducers are recorded using the oscilloscope and camera seen at the right in the photograph. The oscilloscope sweep is triggered by the activation of the solenoid valve. The pressure transducers each have a natural frequency of 500,000 Hertz so they are fully capable of responding to any rates of pressure change that may occur in these tests. Some typical pressure-time records are shown in Fig. 8. The two curves are the outputs from the two transducers. As may be seen there is no significant difference between the two records. Consequently only one transducer is needed. The time at which rupture occurs is indicated by a sudden jump in the curve, followed by a rapidly damped oscillation. The shape of the curves prior to rupture is primarily due to the action of the solenoid valve. If a plastic tube which does not rupture is substituted for the paper honeycomb cell the pressure-time curve has essentially the same appearance as the curves in Fig. 8 before rupture occurs. Some typical cell failures which have been observed are shown in Fig. 7b. Although the paper is torn in some of these cells the failure was actually in the glued joint. The tearing of the paper occurred after the glued joint failed. Joints do not fail because the glue line ruptures. They fail by delamination of the paper at the glued joints.

To determine how the preparation of the glued joints might affect the rupture process a number of samples of single cells were prepared and tested. Ten sets of samples were prepared by properly crimping strips of 70 lb. paper. Glue lines were made 1/4 inch wide, and the cell size a nominal 1/2 inch. Glue was applied to one strip of paper using a silk screen technique. Then another strip of paper identical to the first is placed on top of the glue striped strip, in proper register to make hexagonal cells when the cells are expanded. Variables that were included in the preparation of the test cells are shown in Table IV.

It was intended that each set be tested at the end of a 24-hour curing period, but this was not accomplished in all cases. Some samples cured much longer than others after the initial period under pressure. Relative humidity in the laboratory during the fabrication and test period was maintained at 50 ± 5%.



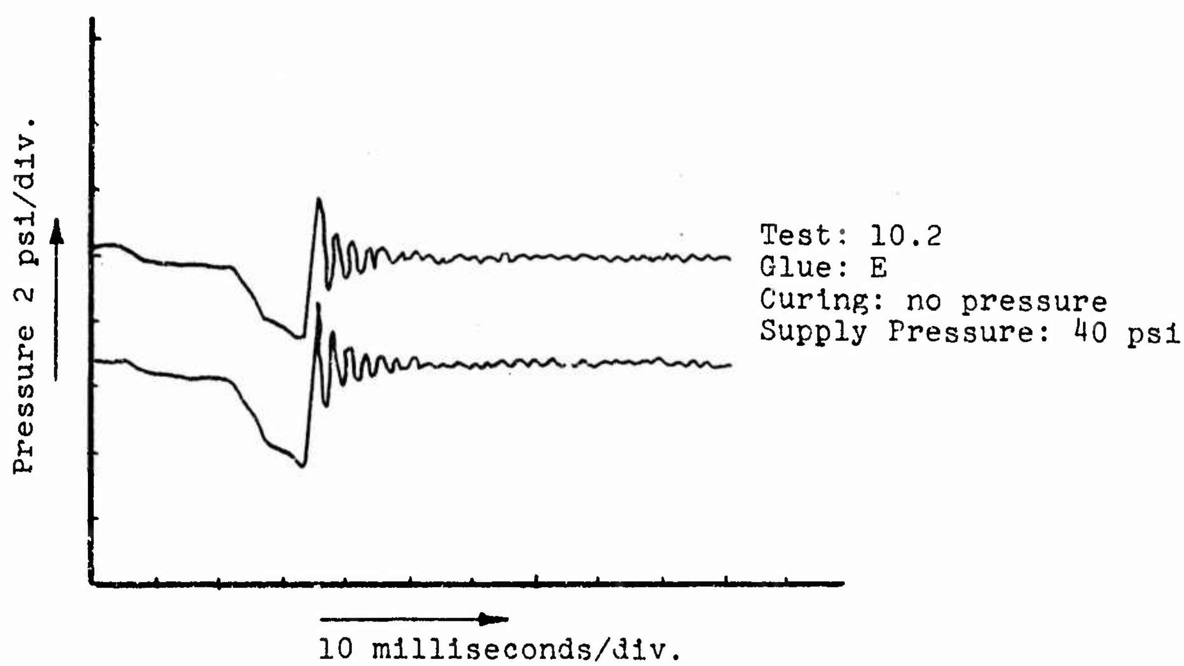


Fig. 8 Single Cell Pressure-Time Records

Table IV

Variables in Cell Preparation

Set No.	Glue	Curing pressure	Time under pressure	Time without pressure
1	F	1 psi	2 hrs.	22 hrs.
2	E	1 "	2 "	22 "
3	F	1 "	1 "	23 "
4	E	1 "	1 "	23 "
5	F	1 "	24 "	--
6	E	1 "	24 "	--
7	F	2 "	24 "	--
8	E	2 "	24 "	--
9	F	0	0	--
10	E	0	0	--

The most general conclusion, reached after some 40 tests, is that the nature of the failure is not affected by the curing procedure. Failure in all cases was by delamination of the glued joints. In no case did the cell walls rupture. Some representative pressures at rupture are given in Table V.

Table V

Single Cell Rupture Pressures

Set No.	Glue	Rupture pressure-psi
1	F	4.4
2	E	4.8
3	F	5.4
4	E	3.2
5	F	4.0
6	E	3.8
7	F	3.6
8	E	5.2
9	F	5.6
10	E	3.2

At least 3 cells were tested for each set but the values given in the table are not averages. They are results selected at random from the whole lot of tests for each set. Variations in the blowout pressure for a given set are, in many cases, as large as the variation between sets.

These results indicate that there is no significant variation in the blowout pressure that can be attributed to the glue type or the curing procedure. The insignificance of these variations can be seen from the following. Suppose every cell in a honeycomb pad ruptures when the internal pressure reaches 5 psi. In that event the increase in apparent crushing strength of the pad would be 5 x 144 or 720 psf. A variation of plus or minus 2 psi in the rupture pressure would cause a variation of plus or minus 288 psf in apparent crushing strength of the pad. For a 6000 psf honeycomb this would be a variation of less than 5%. However, when a honeycomb pad is crushed the interior cells support each other and there are, in theory at least, no pressure gradients. Consequently the cells cannot rupture. Only the outside cells are able to rupture at the pressures, and in the manner observed in the single cell tests. It may be assumed that not more than 25% of the total crushing area consists of outside cells. This means that the increase in apparent crushing strength attributable to the cells that blow out is 5 x 144 x 0.25 or 180 psf. Assuming again a plus or minus 2 psi in the rupture pressure the variation in apparent crushing strength due to that factor would be only 2 x 144 x 0.25 = 72 psf. Thus it must be concluded that variations in blowout, or rupture pressures, do not account for any significant part of the variations in crushing strength usually observed. If the glue and the curing techniques have any effect on the crushing strength that effect must be produced by some action other than blowout of peripheral cells.

3. Nonplanar Impacts

a. Honeycomb Crushing Strengths

Paper honeycomb clearly has a non-isotropic structure with a much higher resistance to crushing forces which act parallel to the cell walls, or normal to the pad faces, than to forces which act perpendicular to the cell walls. In normal usage as a cushioning material in air drop operations honeycomb pads are almost always subjected to impacts in which the impact velocity vector has components perpendicular to as well as parallel to the cell walls. Nevertheless it has been customary in the design of cushioning systems to consider only the component of velocity that is parallel to the cell walls. To provide some information on the crushing characteristics of paper honeycomb when both components of velocity are present an experimental study has been made. In these studies tests were made in which the angle between the impact velocity vector and the cell walls was 5°, 10°, 15° and 20°. To do this the laboratory

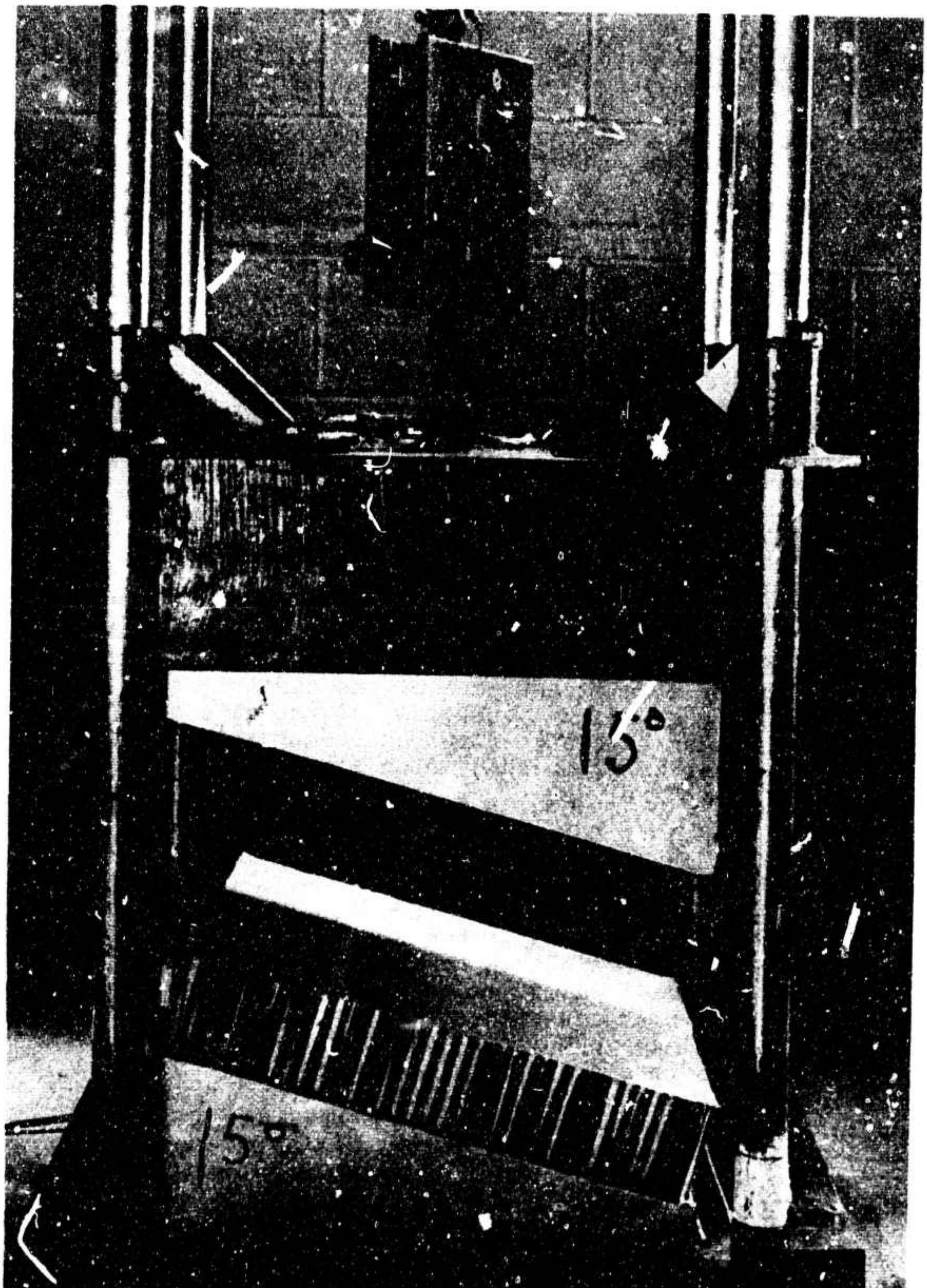


Fig. 9 Impacting a Honeycomb Sample with the Impact Velocity Vector Inclined to Normal to the Face of the Sample

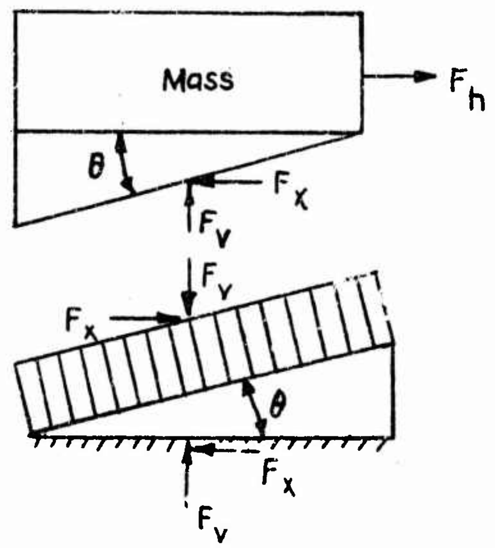


Fig. 10 Free Body Diagrams of the Mass and Cushion for an Inclined Impact

impact tester was modified as shown in Fig. 9. A set of wedges such as those shown in Fig. 9 were constructed for each of the 4 angles. The velocity vector (the velocity of the mass at impact) is always vertical. A component of velocity perpendicular to the cell walls is obtained by rotating the face of the sample with respect to the velocity vector. The impacting mass weighs 572 lbs. and the impact velocity varies from 16 to 19 fps. The test specimen was a single honeycomb pad 16 x 18 x 3 in.

To interpret the results of these tests it will be helpful to consider the free body diagrams of the crushing mass and the honeycomb shown in Fig. 10. All forces acting during the crushing can be resolved into components, as shown in Fig. 10, one normal and the other tangent to the surface of the specimen. The component F_v is measured by an accelerometer on the mass. This force is provided ultimately by the base of the testing machine. The horizontal component F_h is supplied by the columns that guide the mass. In a standard drop test with the velocity vector parallel to the cell walls there would be no F_h. Since there is no lateral acceleration of the mass $F_x = F_h$. There is no measurement of this force. However, since there is no lateral restraint on the specimen F_x must be less than the limiting friction force. It is estimated therefore to be less than 0.1 F_v. This estimation is based on the probable value of the coefficient of friction between wood and steel because the support structure for the honeycomb specimen is made of wood and rests on the steel base of the tester. Since F_x is unknown but believed to be small it is neglected in the analysis of test results. In that case the crushing force parallel to the cell walls is $F_v \cos \theta$ and the component normal to the cell walls is $F_v \sin \theta$. Results of these measurements are shown in Table VI.

Table VI

Crushing Strengths for Inclined Impact

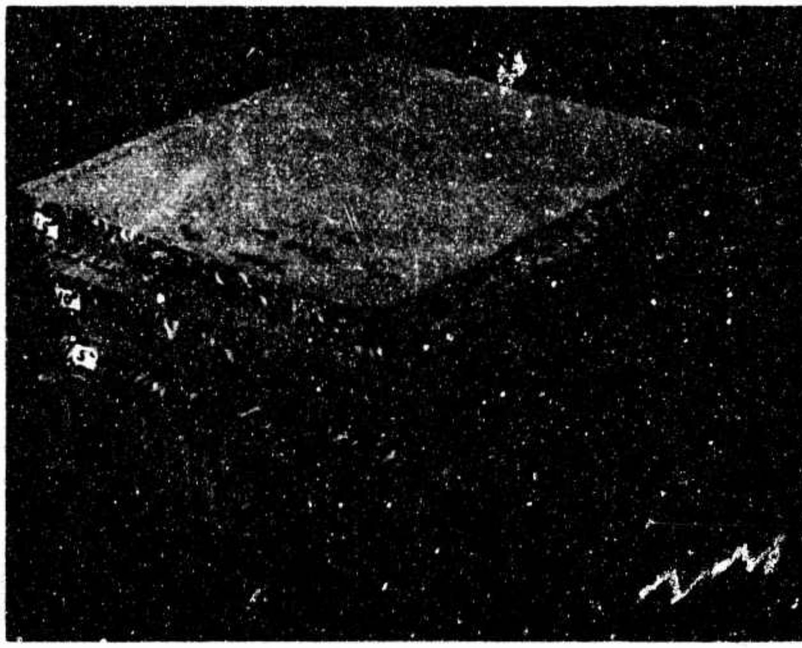
θ	F_v	$F_v \cos \theta$	$F_v \sin \theta$*
0	6300	6300	0
5	6240	6200	540
10	5882	5780	1025
15	5375	5200	1390
20	4580	4300	1570

*This force component acts transverse to glue lines

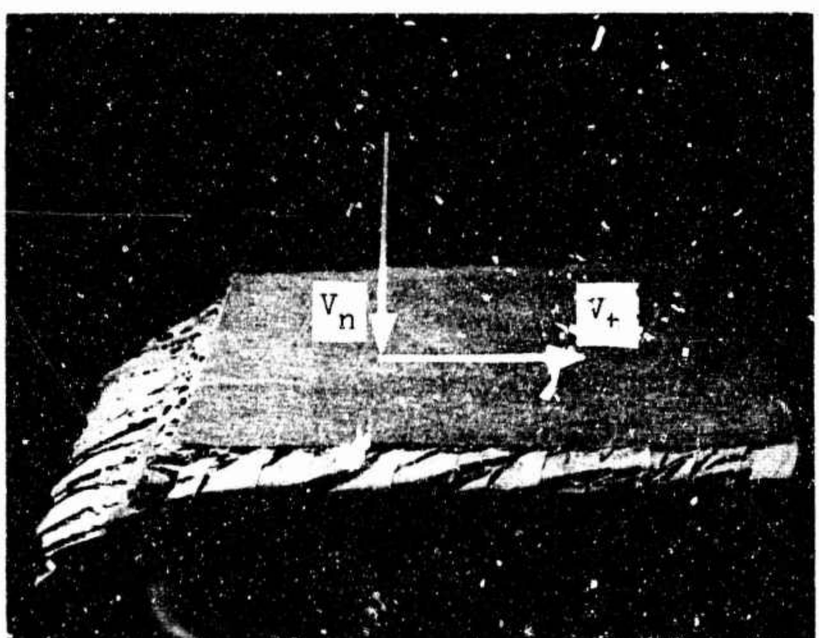
These results each represent an average of at least 5 tests. The effects on the honeycomb of the shearing stress that results from the force component $F_v \sin \theta$ are shown in Fig. 11. These photographs show that as the angle of impact increases the cell walls in the crushed specimen are skewed more and more until at $\theta = 15^\circ$ the skew angle is nearly 45°. It is not clearly evident in these photographs but inspection of the crushed samples shows that the cell walls are buckled, except for the skew, in essentially the same pattern for all values of θ.

b. Orientation of the Glue Line with Respect to the Tangential Velocity Vector

During the testing of these inclined specimens it was noted that the direction of the glue planes with respect to the velocity component along the face of the specimen had a significant influence on the crushing strength. This development was investigated by preparing and testing two groups of samples, one designated NP-P and the other NP-T. These designations indicate nonplanar-parallel and nonplanar-transverse. Parallel and transverse refers to the direction of the tangential velocity vector with respect to the glue line. This is indicated in Fig. 11b. The NP-P group of specimens crushed at an average value of F_v 6% greater than that for the NP-T group. The glue line apparently adds some



(a) Samples Impacted with the Velocity Vector Inclined 5, 10, and 15° to the Normal, and with the Velocity Component in the Plane of the Facing Transverse to the Glue Lines



(b) Samples Impacted with the Velocity Vector Inclined 20° from the Normal

V_t Parallel to Glue Lines (Top)

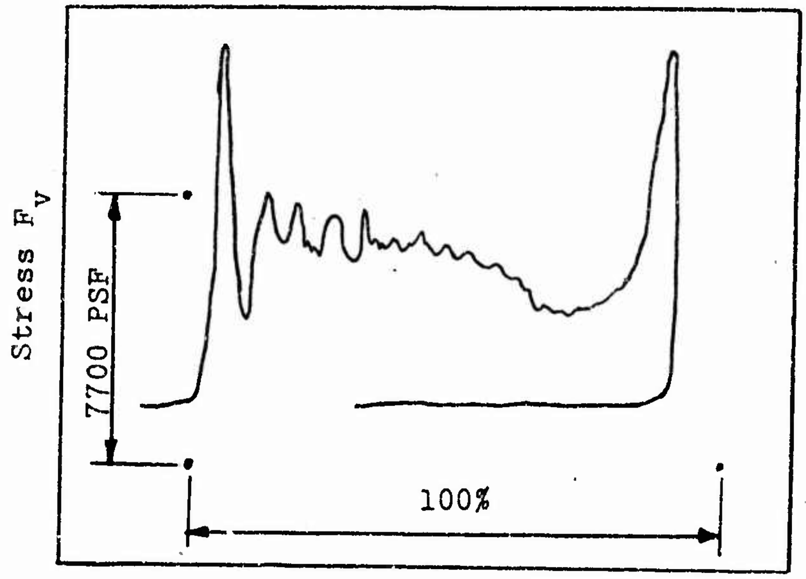
V_t Transverse to Glue Lines (Bottom)

Fig. 11 Samples Impacted with a Velocity Vector Inclined to the Normal to the Sample Face.

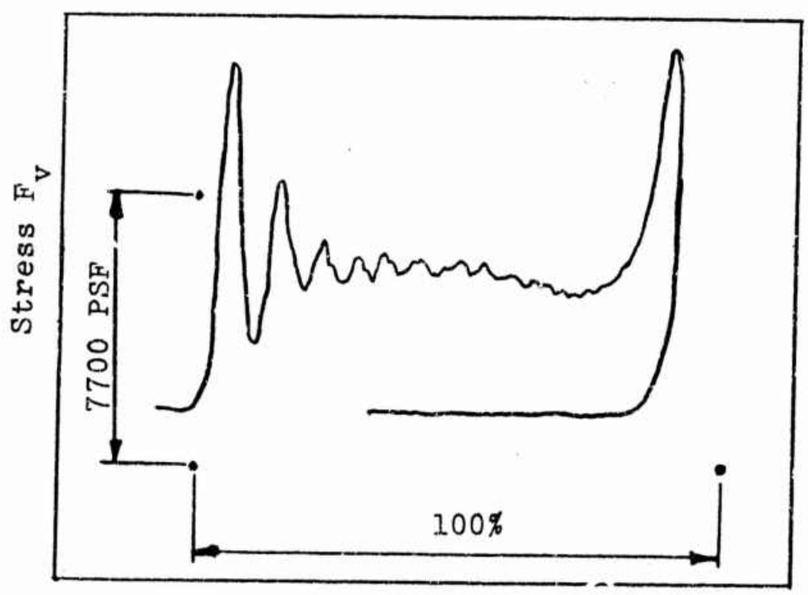
stiffness to the honeycomb against the skewing previously noted if the plane of the glue lines is parallel to the velocity vector V_T. Typical stress-strain curves for the two test configurations are shown in Fig. 12. The oscillations which appear in the early part of the records were caused by vibration of the wooden support for the test specimen. They are not characteristic of the material. Note that the NP-P specimens crush at a greater stress than the NP-T specimens up to 50% strain, but thereafter the stress drops rapidly. The NP-T specimens maintain a more constant stress with little decrease after 50% strain is passed. These differences are believed to result from dissimilar glue line failures in the two configurations. The NP-P specimens show a rippled or twisted appearance parallel to the glue line. This rippling of the paper sheared the glue lines and allowed more air to escape thus decreasing the crushing strength. The NP-T specimens crushed in a simple buckling mode transverse to the glue line, fewer glue lines ruptured, thus allowing the entrapped air to play a more effective role.

These results indicate that whenever it is possible to do so honeycomb cushioning that is to be used in an inclined velocity vector situation should be oriented with the glue lines parallel to the direction of the expected velocity component.

The alignment of the glue lines is also important for other reasons. In a typical cushioning configuration for a vehicle crushing stacks on one side of the vehicle almost invariably have a complementary stack due to symmetry on the opposite side. If these complementary stacks are not square a difference in the direction of the glue lines with respect to the long side of the stacks would mean that one stack would provide less cushioning than the other. This would cause the vehicle to tip toward the weaker side and in some cases might cause crushing stacks in other areas of the vehicle to buckle, and in general reduce the effectiveness of the cushioning. If the glue line edges of the pads are taped as suggested previously, this problem is minimized or eliminated. As indicated above, it also makes a difference in cushioning performance if the glue lines are not aligned parallel to the direction of the horizontal component of velocity. It is suggested that the honeycomb pads be cut so as to align the glue lines parallel to the long axis of the platform since that is the most likely direction for a horizontal component of velocity.



Strain
V_t Parallel to Glue Lines NP-P



Strain
V_t Transverse to Glue Lines NP-T

Fig. 12 Stress-strain Curves -
20^{o} Inclined Velocity Vector Tests

4. Conclusions

a. The air entrapped in honeycomb cells has a very definite effect on the crushing strength but the magnitude of the effect is dependent on a number of factors such as the size of the test sample and the orientation of the glue line planes with respect to the long edge of the sample if the sample is not square. For 12 x 12 in. samples the entrapped air produces an increase in apparent crushing strength of 14% to 15%. Since the magnitude of this effect is dependent on specimen size it cannot be extrapolated to the 16 x 18 in. specimens used for standard testing.

b. By treating the edges of test samples so as to reduce the blowout of cells, e.g., by taping, the increase in apparent crushing strength by the compressed air can be made more nearly independent of sample dimensions.

c. If glue lines are normal to the long edges of rectangular specimens blowout is facilitated and the crushing strength is reduced from that obtained using samples with the glue line planes parallel to the long edges of the sample.

d. Single cells when subjected to an increasing internal pressure fail by delamination of the glue joints. The paper does not rupture. Failure of the joints occurs at an internal pressure of approximately 5 psi.

e. Paper honeycomb samples that are subjected to impacts with the crushing velocity vector inclined to the direction of the cell walls crush at stresses that are reduced as the angle of inclination increases. However, the reduction is not significant until the angle of inclination exceeds 10°. At an angle of 20° the crushing stress, normal to the face of the sample, is approximately 80% of the crushing strength for an impact in which the velocity vector is parallel to the direction of the cell walls (normal to the face of the sample).

If an air-dropped item protected by a cushioning system designed for an impact normal to the face of the cushioning is subjected to an inclined impact it will be exposed to a g-loading of less than the design load but unless an excess of cushioning volume, over the design volume, is provided damage may result from severe bottoming of the cushioning.

f. The orientation of the glue lines with respect to the direction of the impact velocity component has an appreciable effect on the crushing strength. For a 20° inclination the difference in average crushing strengths of

12" x 12" specimens is about 5% between the specimens with glue lines parallel to the velocity vector and those with glue lines perpendicular to the velocity vector. Specimens with the glue lines parallel to the velocity vector are stronger.

g. Greater uniformity in crushing strengths are obtained in open cell testing and when edge treatments to reduce blowout are provided. Thus it appears that randomness and irregularity in blowout patterns is one of the factors that contributes significantly to variations in the apparent crushing strengths of apparently identical honeycomb samples.

5. Recommendations

a. The crushing strength of paper honeycomb can be made almost independent of cushioning pad size, and also more uniform from sample to sample by reducing, or controlling cell blowout. To do this one must somehow reinforce, or seal, the cut edges of the sample that are perpendicular to the glue line planes. These advantages should be weighed against the difficulties and the cost of providing the necessary edge treatment. It may be that the costs are so high that the treatment can only be justified in certain critical cushioning situations. In any event an operational decision is required.

b. Even if no edge treatment is used the crushing strengths of long narrow pads can be increased by requiring the pads to be cut with the long edge parallel to the glue lines.

c. To provide an extra margin of protection for airdropped items which may land with a horizontal component of velocity as well as a vertical component it is suggested that the cushioning system be designed for the vertical component of velocity and that cushioning volume required in the design be increased by some factor which will depend on such considerations as the estimated magnitude of the horizontal component of velocity, the ruggedness of the cushioned item, the resulting height of the cushioning (for stability considerations) and the nature of the terrain on which the drop is to be made. An increase of 25% in the volume, achieved by increasing the height, not the areas of the cushioning pads, should provide an ample margin of safety. Probably 1/2 that much would be sufficient but this is a decision that can be made only after careful consideration of the factors enumerated above.

d. Cushioning pads should be oriented, if possible, with the glue lines parallel to the expected direction of the horizontal component of velocity. It is suggested that the pads be cut and arranged on the platforms so the glue lines are parallel to the fore and aft direction of the platform.

e. In routine testing of honeycomb samples for average crushing strength samples should be cut so the glue lines are parallel to the long edge of the sample. It is not so important that the glue lines be parallel to the long edge. The important requirement is that all samples be cut the same way.

f. No further research on the characteristics of paper honeycomb appears to be needed at this time. If any significant changes in production techniques occur this recommendation should be reconsidered.

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