TECHNICAL REPORT
70-57-AD

VARIATIONS IN THE CRUSHING STRENGTH OF PAPER HONEYCOMB

by

E. A. Ripperger

The University of Texas at Austin
Austin, Texas

Contract No. DAAG17-67-C-0189

December 1969

UNITED STATES ARMY
NATICK LABORATORIES
Natick, Massachusetts 01760

U.S. ARMY MATERIEL COMMAND

AIRDROP ENGINEERING LABORATORY

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Airdrop Engineering Laboratory
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Foreword

This work was performed during the period August 1967 through December 1969 under U. S. Army Natick Laboratories Contract No. DAAG-17-67-C-0189 for the Department of the Army Project No. 1M121401D195 entitled "Exploratory Development of Airdrop Systems" Task 13 - Impact Phenomena. The program is a part of continuing investigation directed toward obtaining improved energy dissipater materials for airdrop landing shock mitigation and a better understanding of the response of airdroppable material to airdrop impact phenomena.

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ABSTRACT

To determine why paper honeycomb pads, in which variables such as paper weight, cell size, cell shape, and glue line widths are ostensibly constant, sometimes vary rather widely in crushing strength, thirty one precisely controlled samples were fabricated in the laboratory and crushed under dynamic loading. Results of these tests show a wider variation than corresponding results of tests of commercial honeycomb. It appears that crushing failure is governed by random processes having to do with buckling patterns, and "blowout". Further study of the problem is recommended.

Studies are also reported of the air pressure developed in the cells during crushing, the effect on crushing strength of specimen size, the ratio of crushing area to total specimen area, and the crushing strength at very low crushing rates. Measurements indicate that air pressure may account for as much as 40% of the total observed crushing strength, but the low crushing rate tests cast some doubt on this. Specimen area has a significant effect on crushing strength which is believed to be a function of the ratio of the area of the outside cell row to the total crushing area.

VARIATIONS IN THE CRUSHING STRENGTH OF PAPER HONEYCOMB

1. Introduction

a. Gray Areas

Despite the fact that paper honeycomb has now been in use as a crushable cushioning material for nearly fifteen years, there are still certain aspects of its behavior on which little or no information has been published. These thin spots in available data are referred to here as gray areas. The primary objective of this investigation has been to fill in and elucidate some of these areas.

b. Plan of Presentation

Five problem areas have been investigated and are reported here. These areas are tabulated as follows:

(1) The effects of fabrication variables
(2) The contribution of the air pressure within the cells to the crushing characteristics of the honeycomb.
(3) The effects of variations in the area of the crushing stack.
(4) The effects of the geometry of the crushing body.
(5) The effects of crushing velocity in the low rate range.

One section of the report which follows will be devoted to each of these problem areas. In this section the current thinking on the problem will be discussed, the nature of the investigation undertaken will be described, and the results will be presented.

2. The effects of Fabrication Variables

a. The Problem

It has long been recognized that paper honeycomb samples made to the same specifications, and so far as could be ascertained by visual inspection, identical in form and detail, may, and usually do vary widely in crushing strength. In fact, samples fabricated by different manufacturers, but to the same specification so far as paper weight and glue line width are concerned have been known to differ from each other in crushing strength by as much as two to one. These extreme variations led to a change in U.S. Army specifications for honeycomb. Specifications were formerly based on paper weight, cell size and glue line width, whereas the specifications now are based on average crushing strength to 70% strain. It was found, however, that tolerances on the specified crushing strength had to be rather large if the cost of the honeycomb was to be kept to a reasonable level since the manufacturers could not, apparently, stay within tighter tolerances without incurring high additional costs. Wide tolerances in crushing strength also make it impossible to design optimum cushioning systems. By using the nominal crushing strength, the cushion designer on the one hand runs the risk of overstressing the cushioned system because the G loading would be too high for a strong honeycomb, and on the other hand, the item might be overstressed because a weak honeycomb would allow the item to "bottom" during the impact. These considerations indicate the desirability of tighter tolerances on the crushing strength of the honeycomb. Rational decisions on how to make tighter tolerances feasible from an economic standpoint have not been made because data concerning the effects on crushing strength of the different variables in the geometry of paper honeycomb have not been available.

b. <u>Systemic Investigation</u>

To pinpoint the sensitive parameters it was apparent that a systematic investigation would be required, of those parameters which are subject to rather loose control in the present fabrication techniques. Two parameters in particular, cell geometry and glue line quality, are suspect. To determine the sensitivity of crushing strength to variations in these parameters, it is necessary to produce honeycomb samples in which these parameters are tightly controlled. Furthermore, the fabrication technique must be flexible enough to allow changes in these parameters whenever changes are desired. When attempts to locate fabricators using techniques that incorporate these desirable qualities proved fruitless, it became obvious that a laboratory facility would have to be set up to produce a precision honeycomb. Such a facility was devised and constructed. A detailed description of it and its operation is given Schroeder[1]. The essential details of the technique are described in the next section.

As the first step in the program after the fabrication technique was developed, the variation in crushing strengths of apparently identical specimens was investigated. For reasons which will become obvious later the investigation never progressed beyond this phase.

c. Honeycomb Fabrication

After several variations on the idea of preshaping the cell walls by pressing the paper in dies of various types had been tried without success, it became apparent that an automated procedure was needed for creasing the paper at the appropriate points one step at a time. The machine that was designed and built for this purpose by Schroeder[1] is shown in Fig. 1. A three to five inch wide strip of paper is advanced through the device one step at a time by a solenoid actuated table. Each time the strip advances it is clamped and then crimped in the appropriate direction so it comes out as seen in the photograph. The action of the solenoids which move the different parts is controlled by the timer at the right. The width of the paper is determined by the thickness of the honeycomb pad that is to be made. Regular hexagonal cells or distorted shapes can be formed with limitations on dimensions as shown in Fig. 2.

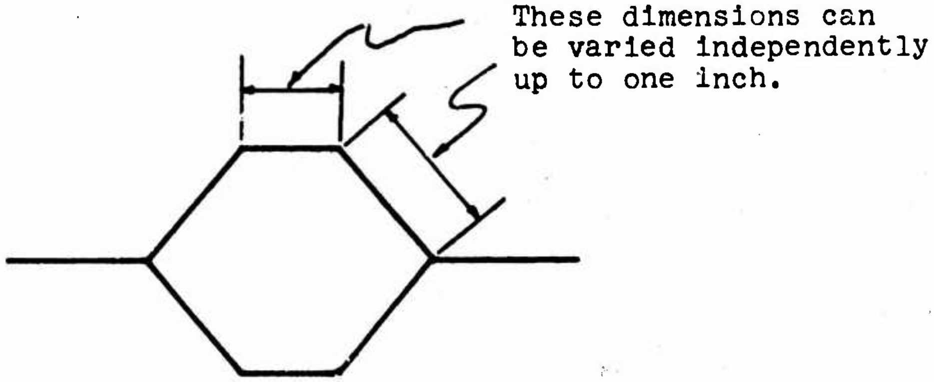
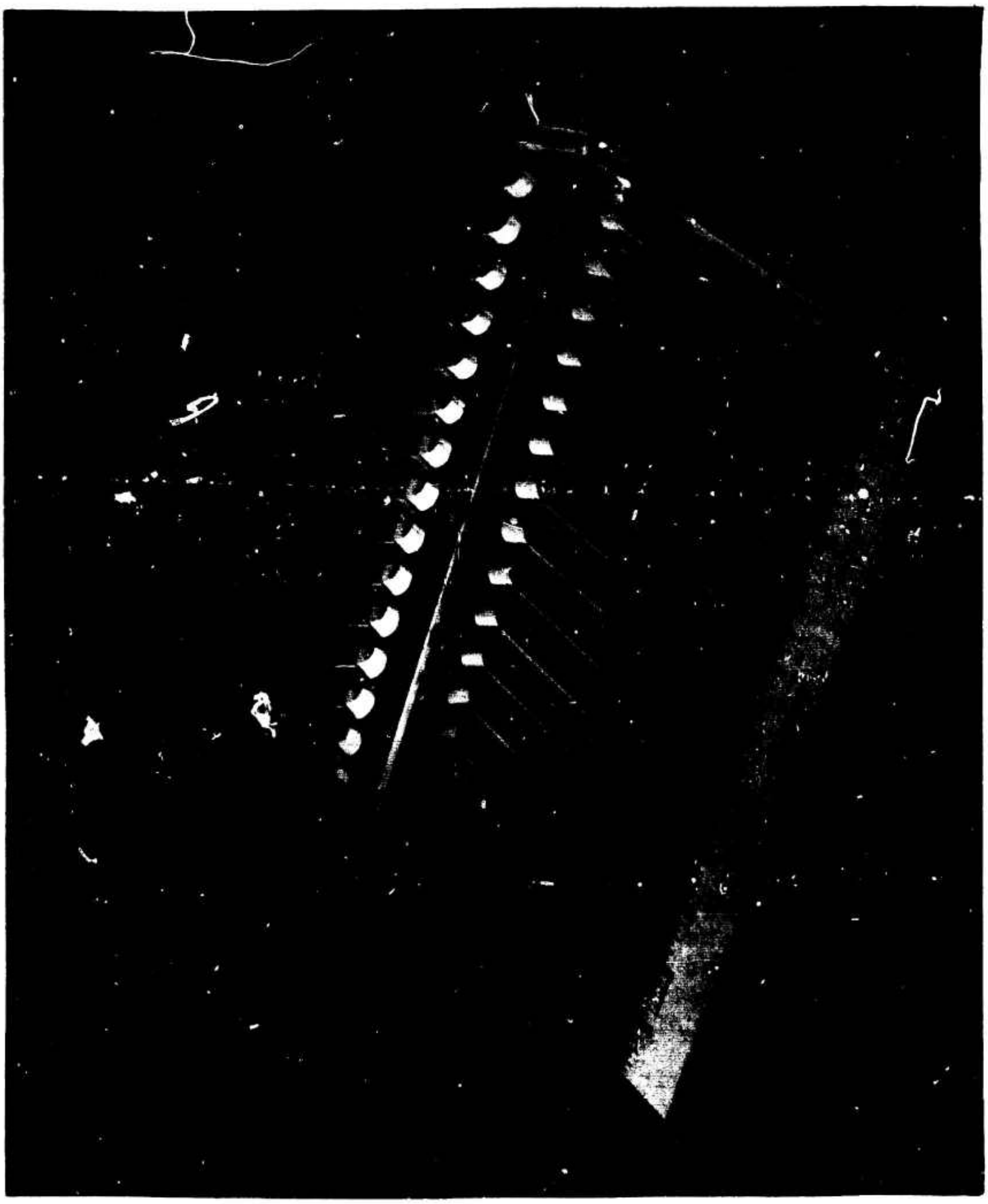


Fig. 2 Honeycomb Cell Dimensions

After the paper is bent as described it is glued together using a jig made up of a series of fingers as shown in Fig. 3. This jig holds the paper in shape and provides clamping surfaces for the glue lines. The gluing procedure is illustrated in Fig. 4. The two operations alternate and are repeated until a sample of the desired size is formed. Glue line width is controlled by the width of the bends in the paper.



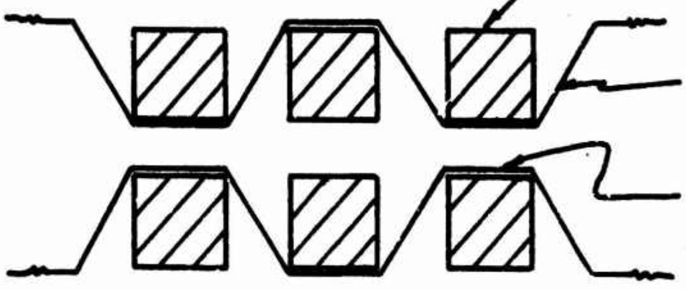
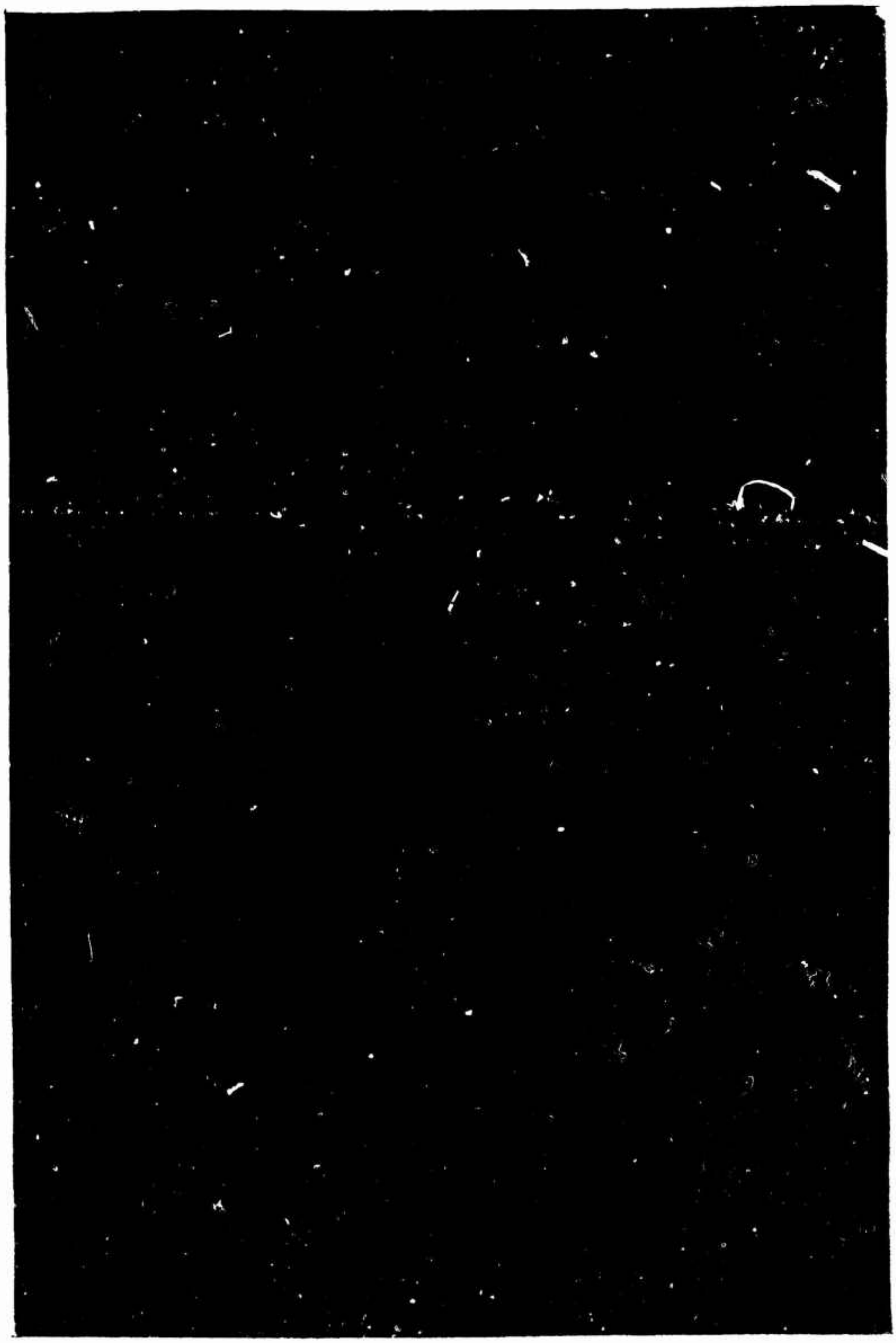


Fig. 4 Gluing Procedure

After the desired sample size has been formed, the cells are collapsed and the sample is clamped in a jig and trimmed with a bandsaw to make all the cells exactly the same height. This is necessary since exact heights cannot be maintained during the gluing operation. After trimming is completed the sample is unclamped and re-expanded by placing it in another jig which is used for holding the sample while the facing is applied. The collapse and subsequent re-expansion of the cells appears to have no adverse effects. When the facing has been applied to both sides of the sample it is ready for testing. A finished sample is shown in Fig. 5. Note the uniformity of cell size and shape.

As might be imagined the fabrication of honeycomb by this technique is a slow and tedious process. To reduce the time required for fabrication it was decided at the beginning of the investigation that only 12 in. x 12 in. x 3 in. specimens would be used. The laboratory dynamic tester[2] has been designed for testing specimens with an area of two square feet. To modify the tester for one square foot specimens and still retain all of its favorable characteristics, the 560 lb steel mass was replaced by a solid 220 lb aluminum mass.



d. Test Results

Initially four samples were prepared and tested. Data for those four samples are shown in Table I.

Table I

Precision Honeycomb

12 in. x 12 in. x 3 in. Samples - Impact Velocity 20.3 fps
80 lb Paper   3/16 in. Glue Line   Adhesive F

Sample	Density lb/ft^3	Energy $ft\text{-}lb/ft^3$ to 70% Strain	Average Stress lb/ft^2 to 70% Strain
S-1	1.90	4230	6050
S-2	1.87	4100	5860
S-3	1.90	3990	5710
S-5	1.90	4190	5990
Average		4130	5900

The maximum deviation from the average is 190 lb/ft^2 or slightly over 3%. A variation of that magnitude can be accounted for by errors in the determination of the area under the stress strain curve, and in the measurements which must be made for calibrations on the oscilloscope records. These results can be compared to those shown in Table II for an ordinary commercial honeycomb made with essentially the same paper weight and cell size as the precision honeycomb. The samples represented in this tabulation were selected at random from laboratory stock and tested in the same way as the precision honeycomb.

Table II

Commercial Honeycomb

12 in. x 12 in. x 3 in. Samples   80-0-1/2   Impact Velocity 20.3 fps

Sample	Density lb/ft^3	Energy Dissipated $ft\text{-}lb/ft^3$ 70% Strain	Average Stress lb/ft^2 70% Strain
C-1	1.97	4020	5740
C-2	-	4050	5780
C-3	-	4610	6500
C-4	-	4310	6150
Average		4240	6070

The maximum variation from the average for this group is 8.4% and the mean variation is 4.98%.

These results imply that quality control in fabrication is the all important factor and that with good quality control it should be possible to keep variations in average crushing strength within a ±5% range. However, results obtained in tests subsequent to those shown in Table I do not support this conclusion. These results, shown in Table III, represent fabrication and testing over a period of about one year. Several operators were involved in the fabrication but the same slow careful procedure was followed by each operator. Testing of all samples was performed by the same team that did the testing for the results in Table I. Some samples were precrushed to minimize the ringing in the records but this seemed to have no significant effect on strength. As may be noted there were some differences in the adhesive, glueline widths, and paper weights. It was necessary in the course of these tests to change from 80 lb to 70 lb paper due to the unavailability of the former. The effect of the change in paper weight on the average density of the samples seems to be almost negligible, 2.02 compared to 1.97 lb/ft^3. There was also an inadvertent change in the type of adhesive used for some of the specimens. This is indicated in Table III by the notation F or E. Both are commercial adhesives. The exact formulations are unknown but adhesive F is described as a vinyl acetate resin emulsion, and adhesive E as a polyvinyl acetate. There is no correlation in the data in Table III between average compressive stress and any of the variables which might possibly be associated with strength. If the data are grouped by paper weight and type of adhesive, variations from the average within the groups are as high as 28%.

e. Discussion of Results

If it can be assumed that these samples were made with the same careful quality control as those listed in Table I it must be concluded that these results completely destroy the original hypothesis that subtle differences in such factors as glue line width, cell shape and cell size cause the variations which are observed in crushing strength. It is now hypothesized that these variations are a result of random collapse and blowout patterns. Some examples of the type of blowout observed in the precision honeycomb are shown in Fig. 6. The general impression obtained from observing crushed samples of the precision honeycomb is that frequently the blowout is much worse than any observed in commercial honeycomb. It is difficult to put this factor into any quantitative terms but it has been observed on occasion that the cell walls are ruptured at least three inches in from the edges of the specimen.

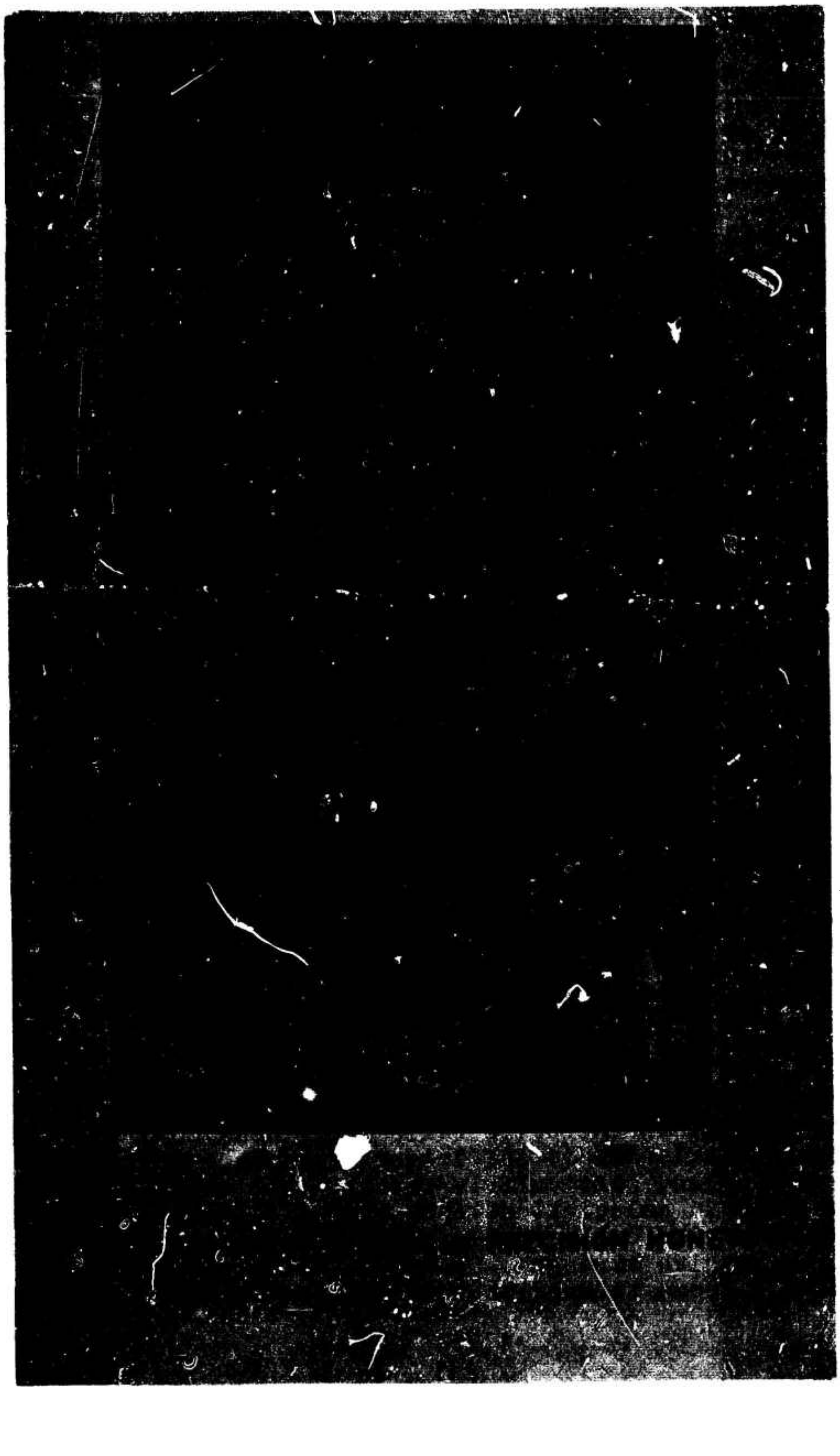
Table III

Precision Honeycomb

12 in. x 12 in. x 3 in. Samples   1/2 in. Cells
1/4 in. glue line   Impact Velocity 20.1 fps   70% Strain

Sample	Adhesive	Density lb/ft^3	Paper lb	Energy Dissipated ft-lb/ft^3	Average Stress lb/ft^2
p-1	E	-	80	2160	3100
p-2	E	-	80	3200	4570
[a]p-3	E	2.10	80	2790	3990
p-4	E	2.13	80	3.20	4460
[b]p-5	E	2.13	80	3660	5240
[b]p-6	E	1.96	80	2920	4170
p-7	E	1.97	80	3180	4550
p-8	E	1.95	80	2480	3540
[c]p-9	E	1.98	80	3320	4740
[c]p-10	E	1.93	80	2480	3540
p-11	E	2.09	80	2580	3690
[d]p-12	F	1.91	70	3500	5000
[d]p-13	F	1.91	70	1900--50% Strain-	3980
[d]p-14	E	2.00	80	3060	4370
[d]p-15	E	2.06	80	3540	5060
[d]p-16	E	1.94	80	3760	5380
[d]p-17	F	1.99	80	3950	5650
[d]p-18	F	2.10	80	3760	5380
[d]p-19	F	1.90	70	3320	4740
[d]p-20	F	1.91	70	3330	4760
N-1	F	2.03	70	3380	4830
N-2	F	2.02	70	2925	4180
N-3	F	1.87	70	2560	3570
N-4	F	2.05	70	2190	3130
N-5	F	1.86	70	2820	4030
N-6	F	2.03	70	2790	3980
N-7	F	2.02	70	2980	4260

a - record almost illegible
b - precrimped with a 1 in. drop
c - precrimped with a 3 in. drop
d - precrimped with a 6 in. drop



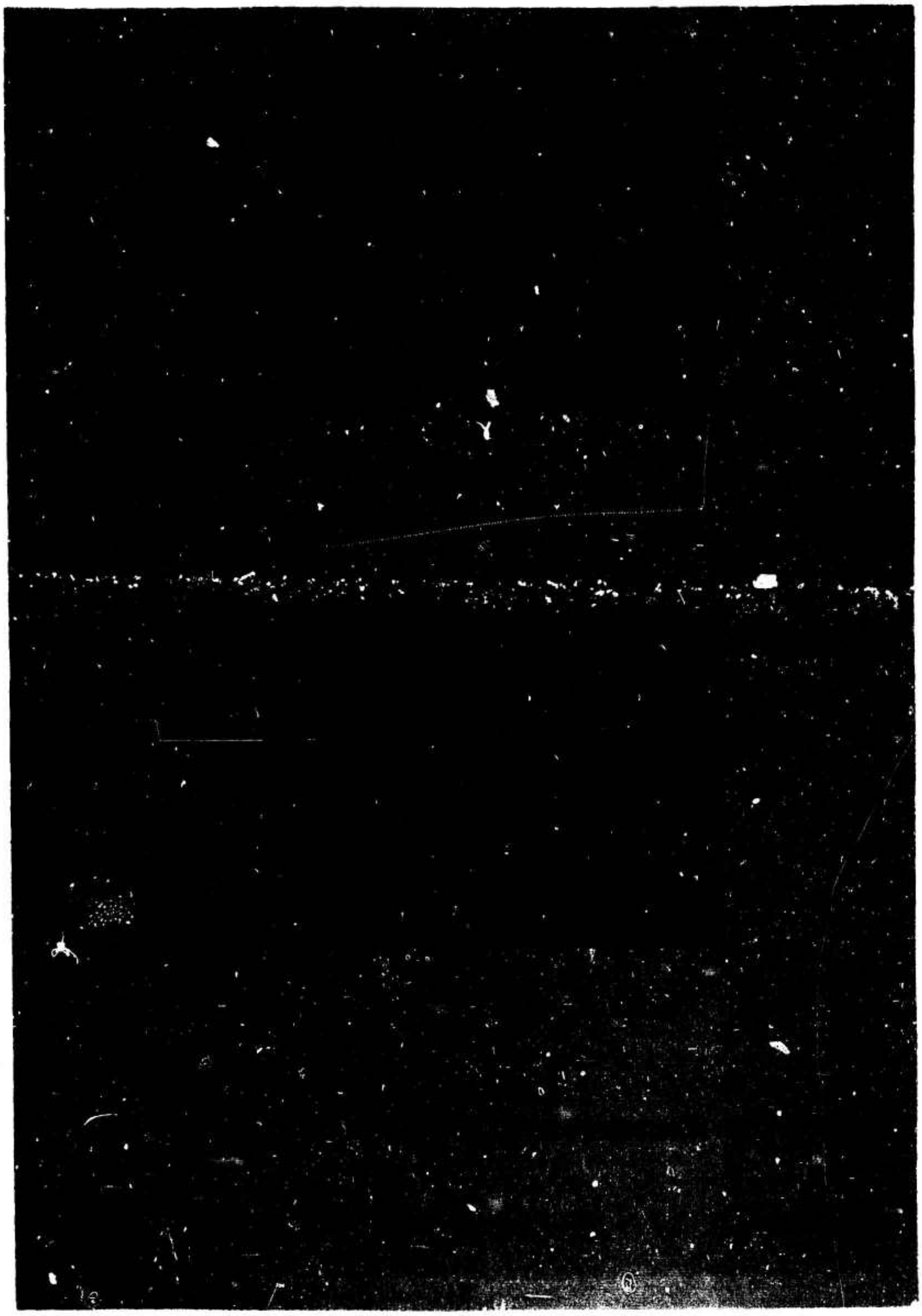
The air pressure built up within the cells may have an effect on crushing strength, whether blowout does or does not occur. As an example, consider a sample 12 in. x 12 in. in which no blowout occurs and there is no leakage of air out of the cells. At 50% strain the air pressure within the cells would be close to double atmospheric. This means a contribution to the crushing strength, by air pressure, of about 2,000 psf. This is 40% of the nominal average crushing strength of honeycomb, a not insignificant contribution. If three inches of blowout occurs around the edges the contribution of the air pressure to the crushing strength will be reduced from 2,000 to 500. This would mean a reduction in apparent crushing strength of 30%. Thus it is quite apparent that variations in the amount of rupturing of cell walls can have a significant effect on crushing strength. Air pressure can also affect crushing strength even when no rupturing occurs, by preventing the normal buckling of the cell walls and forcing variations in the buckling patterns to occur.

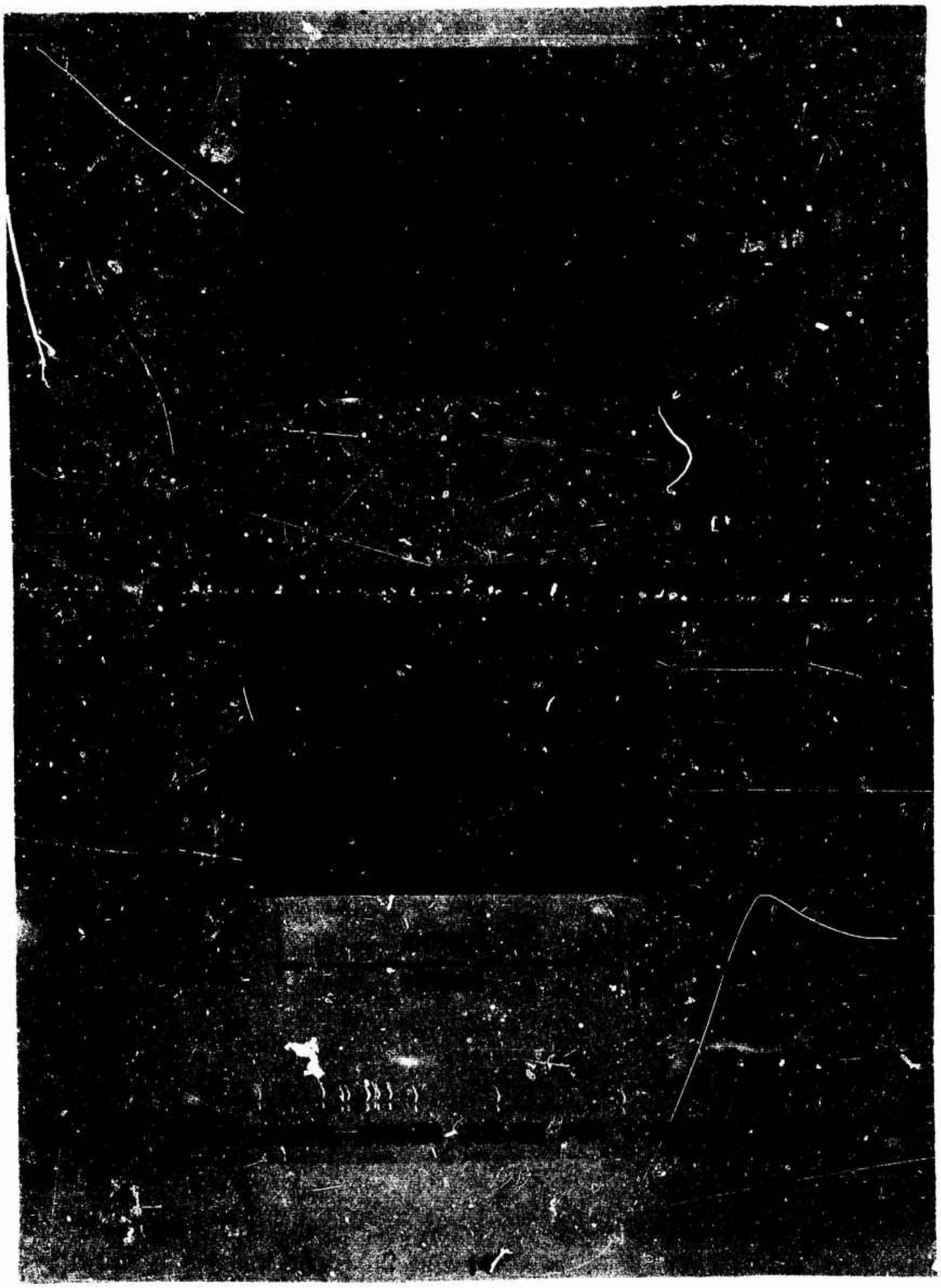
Typical stress strain curves for the precision honeycomb are shown in Fig. 7a, b and for commercial honeycomb in Fig. 7c, d. There appears to be some correlation between the shapes of these curves and the adhesive which was used. However, a few of the curves for specimens glued with adhesive F also exhibit the rising characteristic of the specimens glued with adhesive E. There is no obvious explanation for the difference in the curves but there are some noticeable differences between the two adhesives. Adhesive E for example, does not appear to penetrate the paper, dries more slowly and is somewhat brittle when dry. Adhesive F dries quickly, penetrates into the paper and is not brittle when dry. These characteristics do not, however, appear to provide any explanation of the differences in the stress-strain curves.

3. <u>Air Pressure within the Crushing Cells</u>

a. <u>Purpose of the Study</u>

As indicated in the previous discussion the air pressure developed within the cells while paper honeycomb is being crushed dynamically is sufficient to rupture some of the cell walls, particularly those in the outside rows. Furthermore, calculations show that if the air does not escape from the cells it should contribute significantly to the compressive strength. Indeed, the little evidence available seems to suggest that perhaps the air pressure





helps make paper honeycomb the effective energy dissipating material it is. To clarify the role which the air pressure plays in cushioning with a crushable material with a closed cellular structure some measurements have been made of the pressure during the crushing process. These measurements are described as follows.

b. Experimental Technique

To measure the pressure in the cells as accurately and as simply as possible a plywood base was prepared and a pressure transducer was mounted in this base, with the diaphragm of the transducer just slightly below the surface of the plywood. The facing paper over the cell in which pressure is to be measured is removed. To seal the cell-transducer system and prevent any air leakage at the interface between the cushion and the base, a ring of self vulcanizing silicone rubber is laid around the transducer. Then the honeycomb is placed on the base with the open end of the cell directly over the transducer. A weight is then placed on top of the pad and left there until the rubber has partially cured. The whole assembly is then placed in the stress-strain curve generator and crushed. Pressure is recorded as a function of strain, and at the same time the stress is recorded as a function of strain.

The pressure transducer used for these measurements is a Kistler Model 703L which has a diameter of 0.218 in. and a natural frequency of 500,000 Hertz. The high natural frequency enables the transducer to respond accurately to the rapid changes in pressure which might occur during the impact, and the small diameter makes it possible to measure the pressure in a single cell. One minor disadvantage of the transducer is in its sensitivity to acceleration. When the mass first strikes the sample it sends a stress wave through the cushion and into the base before any changes in pressure can develop. This stress wave accelerates the transducer and causes an output signal of significant amplitude. Fortunately this signal is oscillatory in nature and it occurs very early before any air pressure begins to develop.

In this test series a small piece of 70 lb paper is glued to the facing paper over the lower end of the cell before that end of the cell is opened. This paper is added as reinforcing and to facilitate making the seal. The entire arrangement is shown in Fig. 8 just before the sample is put in place on the base. A schematic drawing of the measurement system is shown in Fig. 9.

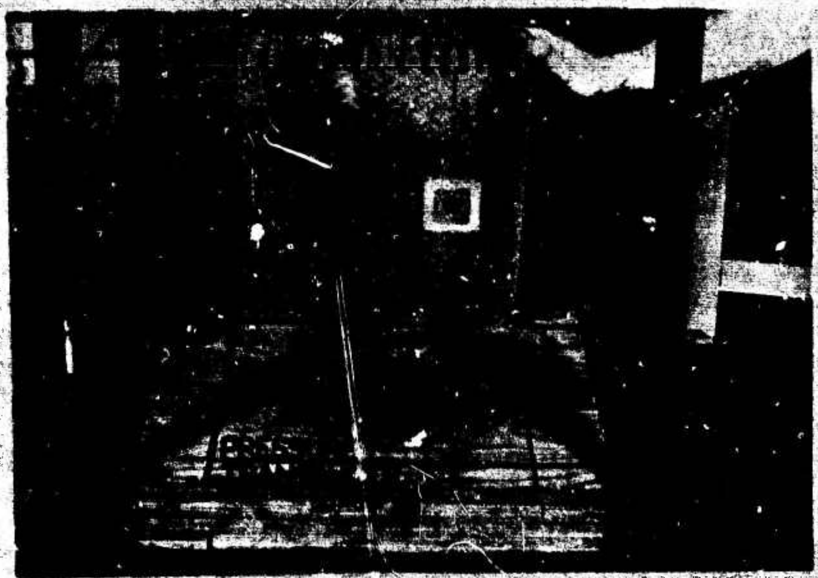


FIG. 8 PRESSURE TRANSDUCER ARRANGEMENT

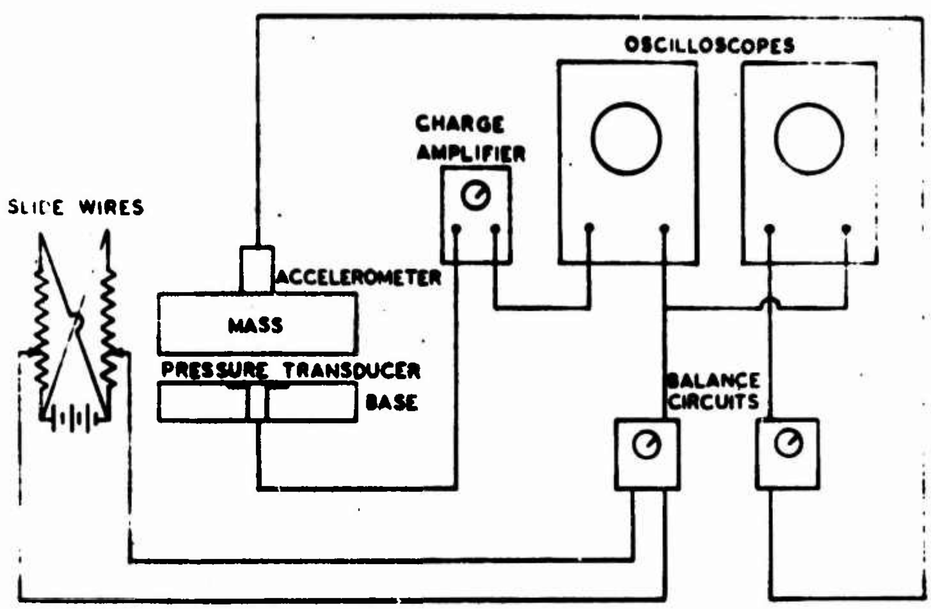


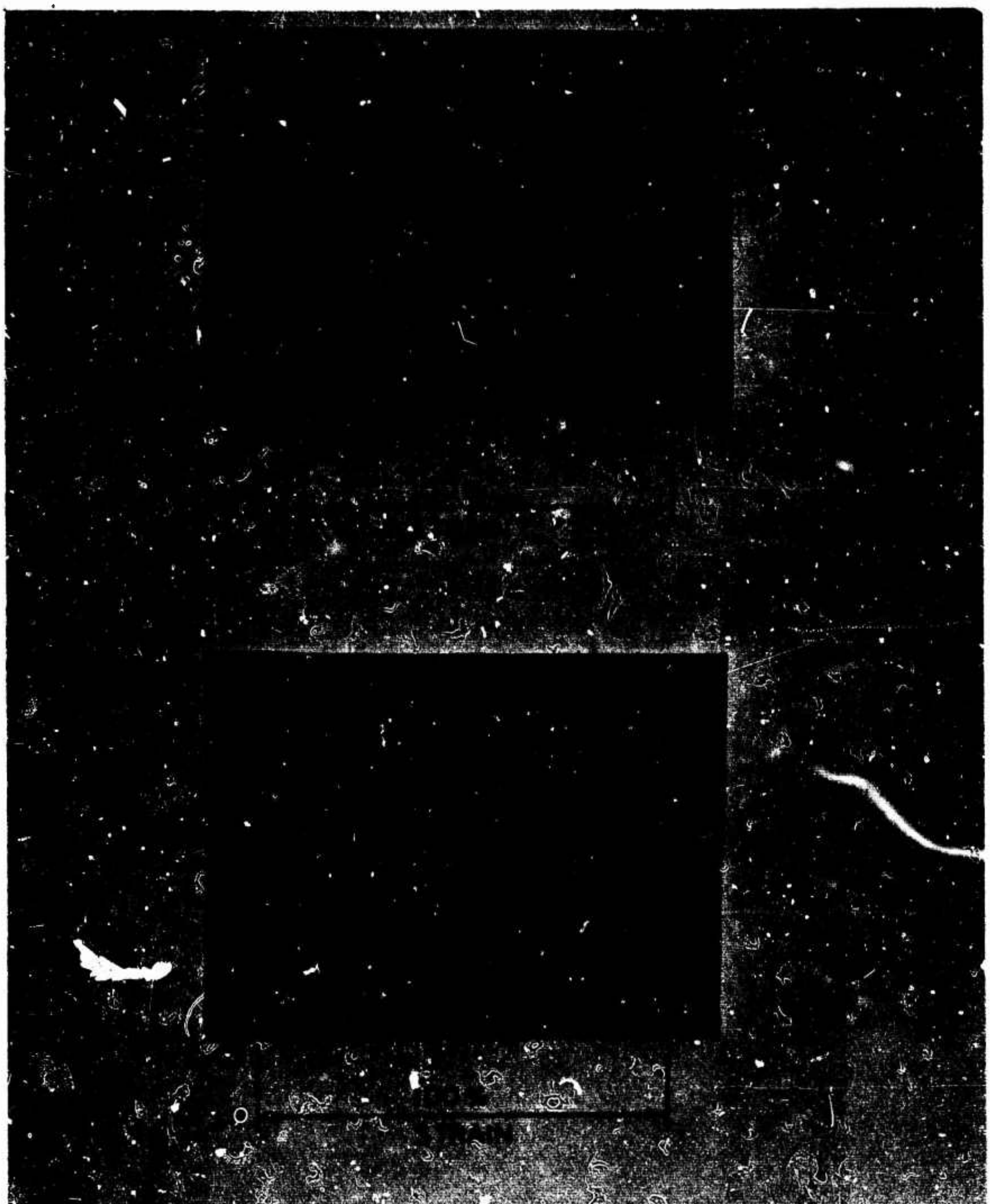
FIG. 9 SCHEMATIC OF PRESSURE AND ACCELERATION RECORDING SYSTEM

c. Experimental Results

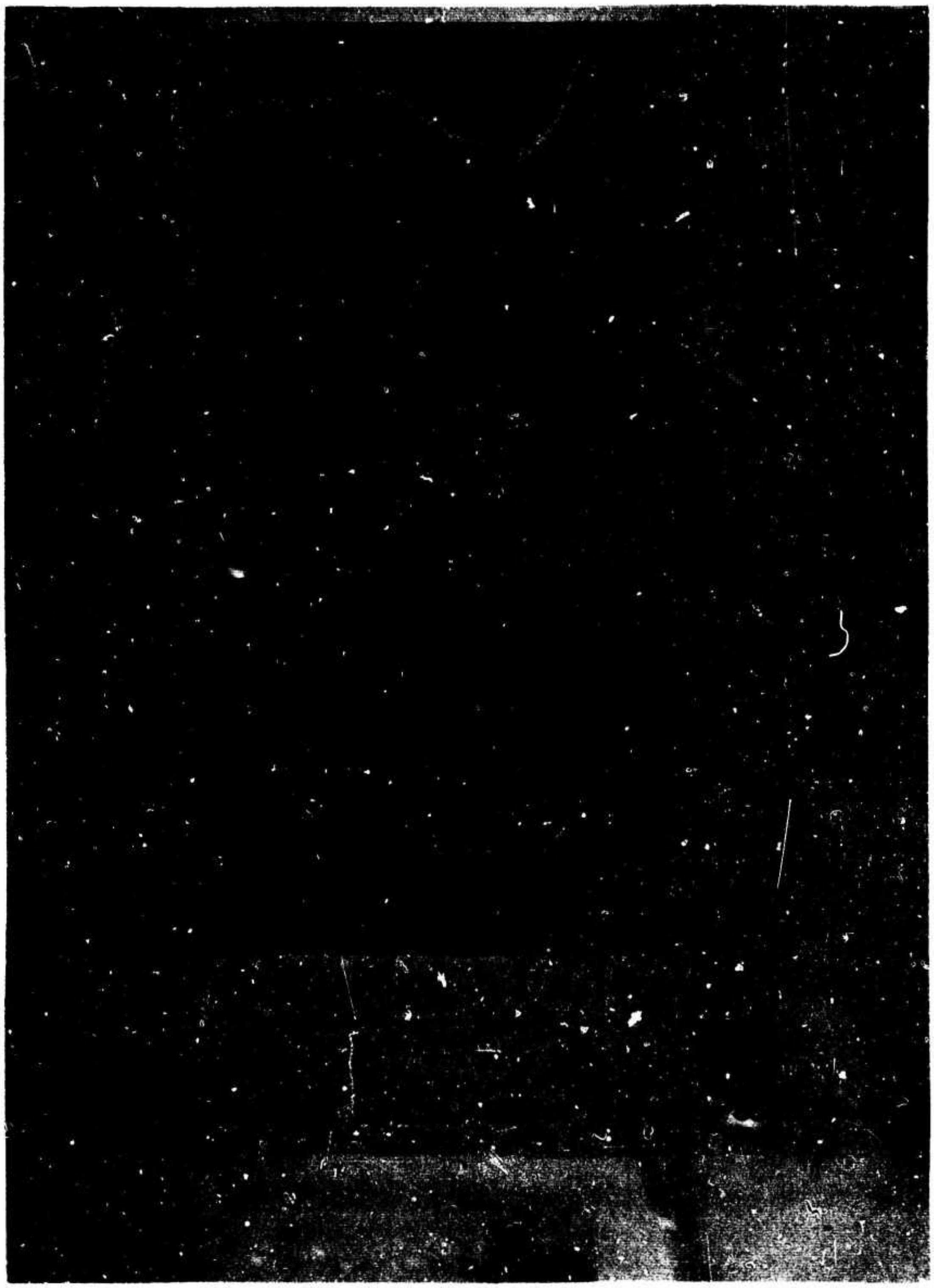
Pressure measurements were made in the cell at the center of a pad, in a cell midway between the center and outside of the pad, and in a cell in the outside row. Specimens were 12 in. x 12 in. x 3 in. pads cut from 3 ft. x 8 ft. panels of 80-0-1/2 commercial honeycomb. Impacts were produced by dropping a 220 lb mass on the cushion from a height of 8 ft-0 in., for an impact velocity of 22 fps.

Typical experimental results for the three different cell locations are shown, in Figs. 10, 11 and 12. For the center cell the compressive stress at 70% strain has dropped off to 5450 psf (the average stress to 70% strain is 6570 psf) while the air pressure has reached 32 psi in that particular cell. This is almost exactly the pressure change which would take place if the volume of a quantity of air at atmospheric pressure is reduced to 30% of its initial volume. If the pressure in all cells had reached that value the air pressure would be contributing 4600 psf to the crushing strength of the honeycomb. Not every cell contributes that much but it appears quite likely that, as the crushing proceeds, more and more resistance is offered by the compressed air until well over half the resistance to crushing may be coming from the entrapped air. Were it not for this entrapped air the apparent crushing stress would drop to a very low value in this particular honeycomb at 70% strain. The oscillations at the beginning of the pressure record are due to the acceleration of the transducer by stress waves coming through the cushion as previously discussed. Pressure does not become negative during the rebound as might be inferred from these records. This feature of the curve is typical of a piezoelectric transducer such as the Model 703L and the charge amplifer used with it.

The pressure in the midway cell, shown in Fig. 11, increases as crushing proceeds at about the same rate as the pressure in the center cell, until a strain of about 50% is reached. The plateau which the curve develops at that point is probably due to leakage from the cell, but it could also be due to the cell walls collapsing in such a way as to produce very little decrease in volume. There is no evidence available other than the curve itself on which to base a conclusion. It should be noted however that the average air pressure to 70% strain is essentially the same in the center and midway cells.



[illegible] AND STRESS STRAIN CURVES CENTER-CELL



In Fig. 12 the pressure in the side cell is obviously considerably less than that in either the center cell or the midway cell. This is undoubtedly due to leakage of air from the cell. One might expect however, that the pressure in the cell would increase until rupture occurs, and then it would drop suddenly. Since this does not happen it appears that the cell walls rupture almost immediately after the impact. However, in some preliminary experiments in which an attempt was made to build up a quasi-static pressure in the cells without collapsing them, it was found that air escapes readily from the outside cells. It was almost impossible to develop a measurable pressure inside the cells by coupling them to an air compresser. The air leaks out through both the paper and through the glued joints. Leakage from the inner cells is undoubtedly inhibited by the longer path the air must follow to escape.

It is clear that if the pressure in all outside cells is represented by this record in Fig. 12, the outside cells cannot contribute anything of significance to the crushing strength as a consequence of the build-up of air pressure in the cells.

Average crushing stresses indicated by acceleration measurements, and average air pressures in the different cells, up to 70% strain are shown in Table IV. If an average pressure of 15 psi is assumed in all except the outside cells, air pressure accounts for 1815 psf of the average crushing strength which is about 6800 psf.

These measurements show that air pressure within the cells can contribute significantly to the crushing strength of paper honeycomb at the higher strain levels. At low strains the crushing stress is determined by the structural characteristics of the honeycomb but at strains between 40% and 70% the crushing strength may be largely determined by the air pressure. The contribution of the air pressure will depend on the air tight integrity of the cells and this may be a highly variable quantity. Further investigation of that property is needed.

4. Variations in the Area of the Specimen

a. Purpose

It has long been recognized that the crushing strength of paper honeycomb is related to the area of the sample. A brief study of this relation was made by Karnes, et al. and

Table IV

Average Air Pressures and Crushing Forces

12 in. x 12 in. x 3 in. Specimens   70% Strain

Test No.	Cell	Average Pressure psi	Average Crushing Stress lb/ft^2
696	Center	10.3	5700
700	Center	12.0	5290
*703	Center	11.8	7320
705	Center	8.0	7130
706	Center	12.0	7700
707	Center	15.6	6570
708	Center	11.3	6860
709	Center	16.7	7230
710	Center	19.4	6840
716	Outside	7.9	6730
717	Outside	6.7	6090
719	Outside	4.7	6220
720	Midway	16.8	7150
722	Midway	18.6	6400
724	Midway	25.9	7230

*All tests from 703 on were made with the same type of honeycomb, but obtained from a different source.

reported in 1959[3]. The question is raised again here because of the evidence in the previous section of a significant contribution by the air compressed in the cells, to the apparent crushing strength. Also it is very obvious from inspection of crushed samples that the outer cell walls have been ruptured. The extent to which the outside cells rupture, in terms of distance from the edge, is not easily determined by inspection. A series of crushing tests on different areas has therefore been made to determine how serious the rupturing of cell walls is, so far as crushing strength is concerned.

b. Experimental Program

The specimen sizes included in this study are shown in Table V.

Table V

Test Specimens for Area Variations Study

80-0-1/2 Honeycomb

Drop Height-ft	Pad Dimensions-in.	No. of Pads/Test	Total Area $in.^2$
7-0	4 x 4 x 3	9	144
7-0	6 x 6 x 3	4	144
6-6	8 x 8 x 3	2	128
6-0	10 x 10 x 3	1	100
7-0	12 x 12 x 3	1	144
9-4 1/2	14 x 16 x 3	1	224

The arrangements of the specimens on the base of the stress-strain curve generator are shown in Fig. 13.

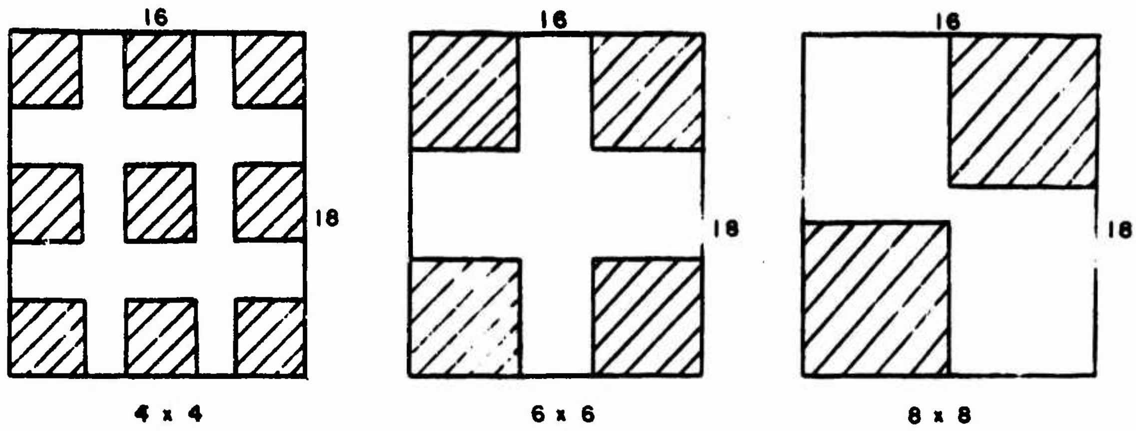


Fig. 13 Pad Arrangements for Impact Tests on Samples Smaller than 10 in. x 10 in.

c. Experimental Results

Average stresses, energy dissipated, and densities for all the samples are shown in Table VI.

Table VI

Average Crushing Strength

80-0-1/2 Commercial Honeycomb
70% Strain

No. Pads	Specimen Dimensions-in.	No. of Tests	Density lb/ft³	Energy Absorbed ft-lb/ft³	Average Stress lb/ft²
9	4 x 4 x 3	3	2.26	3804	5425
4	6 x 6 x 3	3	2.25	3945	5633
2	8 x 8 x 3	4	2.29	4262	6091
1	10 x 10 x 3	2	2.28	4335	6200
1	12 x 12 x 3	2	2.25	4505	6435
*1	14 x 16 x 3	2	2.23	3590	5985

* 60 % Strain

The increase in crushing strength with area indicates that there is a reduction in strength due to the inability of the outer cells to carry a full share of the load. As the specimen size increases the area of the outermost row of cells becomes a smaller and smaller percentage of the total area; therefore, the overall crushing strength of the sample increases with increasing area so long as the shape of the pad is square. It is not possible to determine from these results the exact extent of cell rupturing. However if it is assumed that a ruptured cell carries no load it can be seen that the complete rupturing of the outside row of cells reduces the apparent crushing strength of a 4 in. x 4 in. pad by about 44%. If two rows crush the strength would be reduced by 75%. The measured average crushing strength is 5425 psf. If this value represents 25% of the true crushing strength then that strength would be 4 x 5425 or 21700 psf. Since there is no evidence to suggest that paper honeycomb has an inherent strength of that magnitude it must be concluded that even with the small (4 in. x 4 in.) samples cell rupturing is limited to less than two rows. If crushed specimens such as those shown in Fig. 14 are examined it is seen that cells are ruptured farther in than the first row in places, but not every cell in the first row is ruptured. The rupturing does not appear to follow any definite pattern. If it is, as it appears, a random process, then the crushing strength should be expected to vary in a random fashion.

The stress-strain curves in Figs. 15 and 16 show that the crushing strength up to between 25 and 40% strain is essentially independent of specimen size. This must mean that all cells, regardless of specimen size, contribute equally to crushing strength until a strain of about 40% is reached. It also indicates that the crushing strength of a very large specimen should be about 7000 psf, the observed value in the 0-40% strain range. The dip in the stress-strain curves which begins at about 40% strain is a characteristic of paper honeycomb dynamic stress-strain curves. It is believed to be associated with cell rupturing.

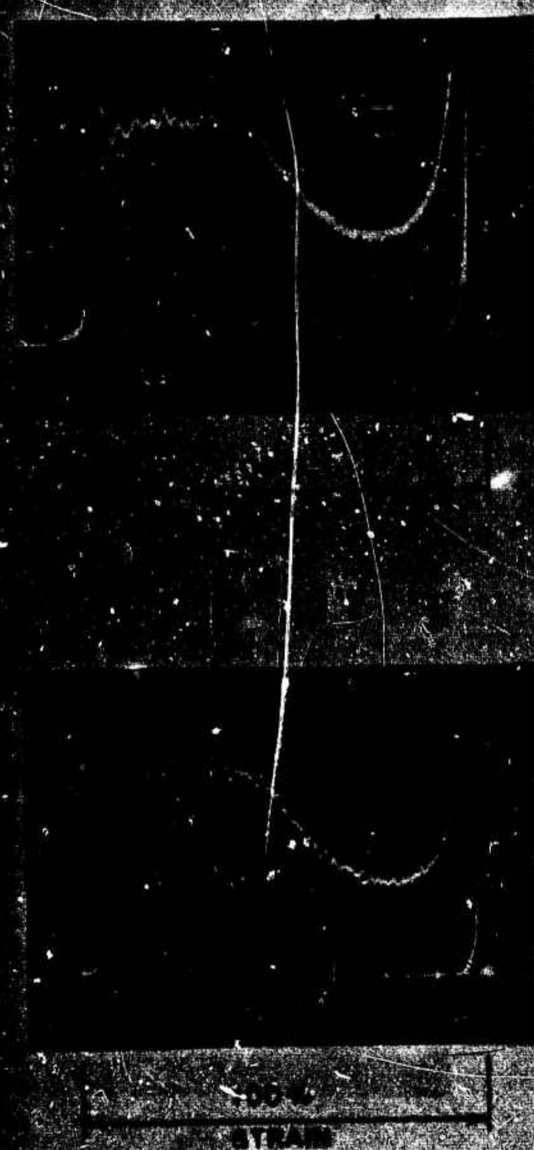
5. Low Velocity Crushing

a. Impact Velocity Effects

Studies conducted at the University of Texas in the past have all indicated that the crushing strength of paper honeycomb is independent of impact velocity in the range between 20 and 90 fps[4]. However, very early test results

VIEW PARALLEL TO [illegible]

FIG. 14 CRUSHED [illegible]



... CURVES FOR SAMPLES WITH SMALL AREAS

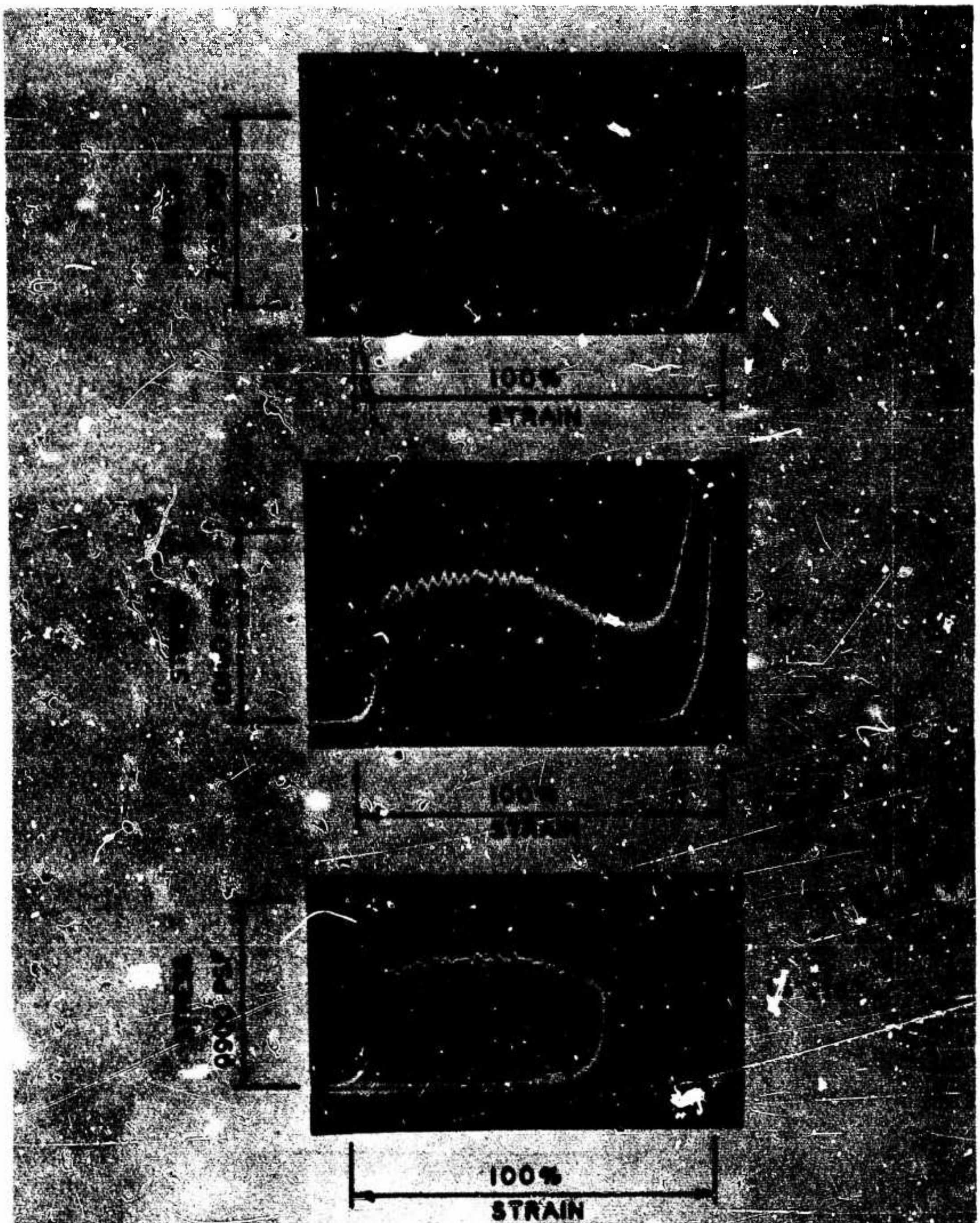


FIG. [illegible] STRESS - STRAIN CURVES FOR SAMPLES OF [illegible] show that the average crushing strength obtained by quasi-static loading is lower than the dynamic crushing strength[5]. These observations are especially significant here because (1) they imply that crushing strength is a definite function of impact velocity in the range between 0 and 20 fps. If this is the case it is important that the nature of the relationship be determined. (2) Differences in crushing strengths at very low velocities, and at the higher velocities may be directly connected to the air pressure in the cells. Therefore, additional light may be thrown on the role played by the air entrapped in the cells, by studies of quasi-static crushing.

b. Experimental Program

Quasi-static loading of 12 in. x 12 in. x 3 in. commercial honeycomb pads was accomplished with an Instron testing machine using the arrangement shown in Fig. 17. This machine has a head speed range from 0.002 in./min to 20 in./min. With another arrangement in which a hydraulic loading system was used a head speed of about 43 in./min was reached. Even this highest head speed is very low compared to 20 fps. (14,400 in./min). Consequently the experiments performed still leave a big gap in the data. It is very difficult, however, to obtain a device which will provide a constant crushing rate in the range between 43 in./min and 20 fps. In view of the cost and time involved, the decision was made to omit that range of crushing velocities from the program.

For the tests using the Instron machine, stresses were measured with a load cell and recorded as a function of time on a strip chart recorder. Deformations of the specimens were not recorded directly. Instead the constancy of the head speed and the paper speed of the recorder were relied upon for the deformation data. In the hydraulic load tests both force and deformation were recorded.

c. Test Results

Typical stress-strain curves for selected head speeds are shown in Fig. 18 compared to a dynamic stress-strain curve. This curve is taken from the record shown in Fig. 7c. The differences between the curves for the low velocity crushing are not considered significant. It might be noted here that at a head speed of 2 in./min, slightly over

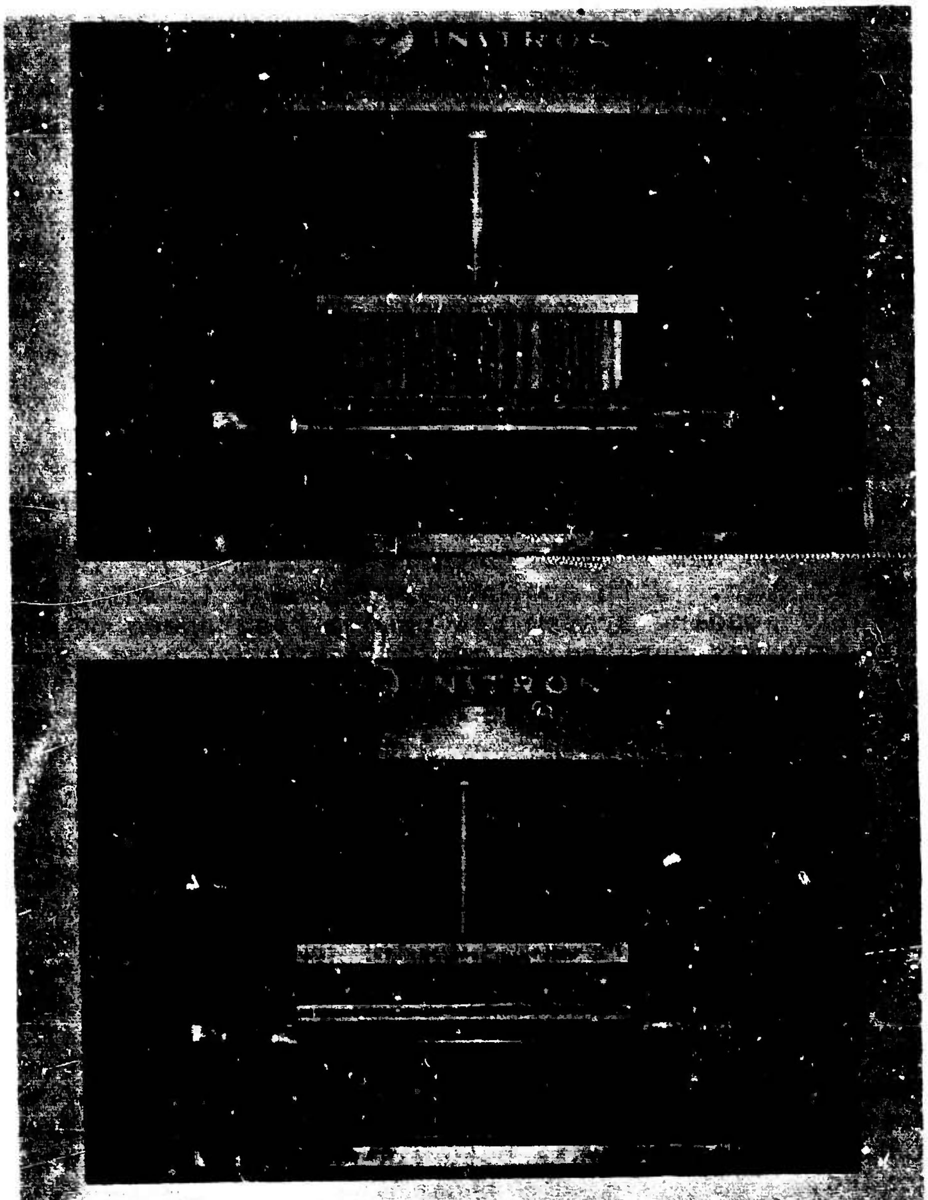


FIG. 17 STATIC TESTING ARRANGEMENT

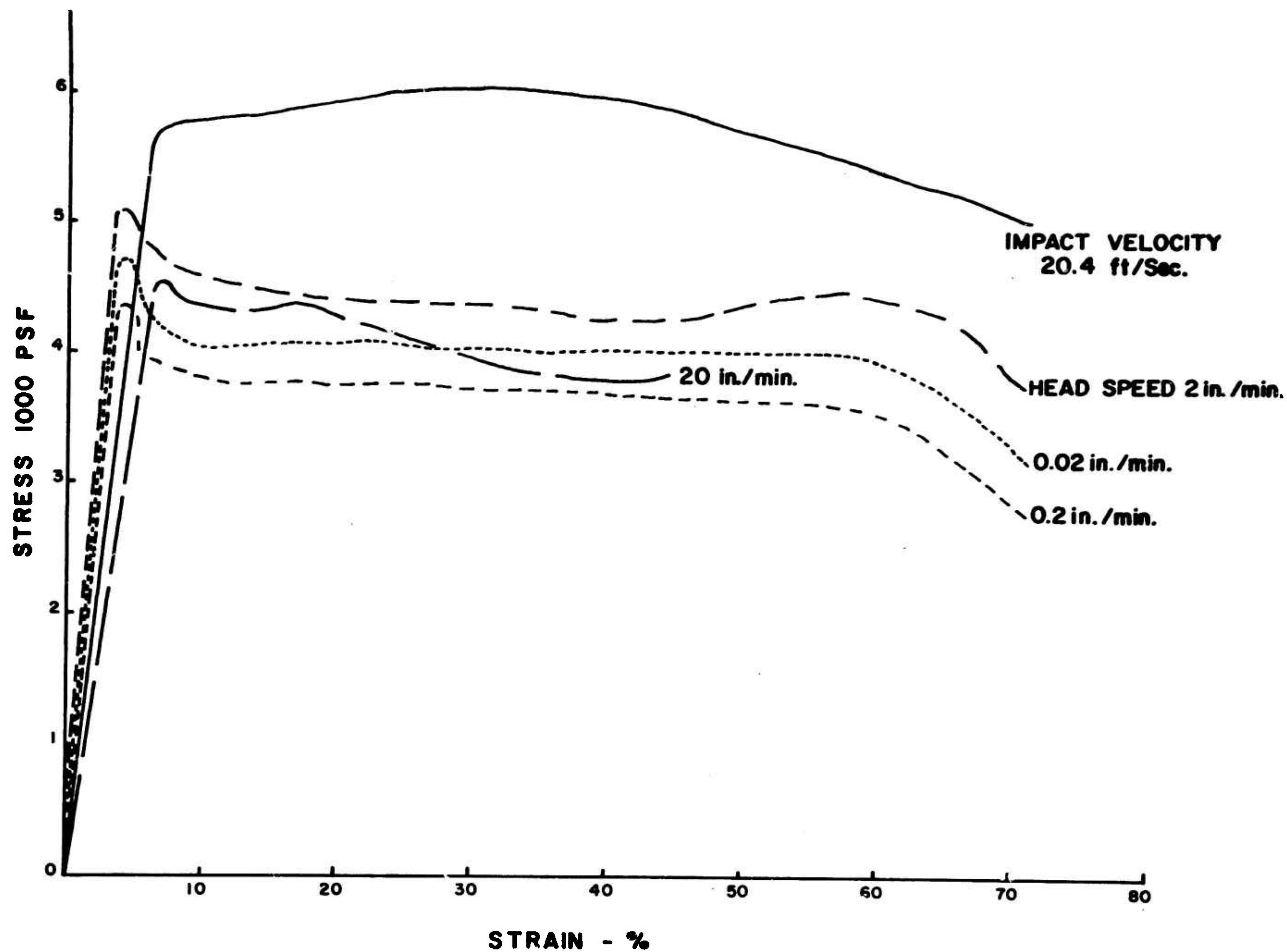


FIG. 18 STRESS-STRAIN CURVES FOR LOW LOADING RATES

2 minutes are required to reach 70% strain in a specimen 3 in. thick, and for a head speed of 0.02 in./min, a little more than 200 minutes are required to reach the same strain. It is not likely that any significant air pressure could build up in the cells at these low loading rates. Consequently, the stresses represented in Fig. 18 for the quasi-static loading rates should indicate the actual strength of the honeycomb. If this is accepted then the difference between the quasi-static curves and the dynamic curve must represent more than just the effect of entrapped air. If this were not the case the curves would be more or less identical at the low strains. Then as strain increases and air is compressed in the cells in the dynamic tests the crushing stress would rise above that indicated in the quasi-static tests. The increase in stress up to about 35% strain, in the dynamic loading, probably is due to compression of the air but the increase is only about 300 psf if a constant crushing strength in the absence of an air pressure is assumed, whereas, without any leakage the increase should have been more like 1,000 psf. The initial peaks in the quasi-static curves are not produced by air pressure since the possible air pressure at that point is insignificant. This initial peak is a characteristic of the way a buckling structure fails. It is also present in the dynamic stress-strain curves if the specimen has not been precrushed slightly. The decrease in the dynamic stress after 35% strain is reached is probably a result of cells rupturing and releasing pressures. The sharp drop which begins at about 60% strain in the quasi-static curve probably signifies the completion of the buckling pattern in the cell walls. If so, it might reasonably be expected that the same effect would appear in the dynamic curve. Since the dynamic curve is apparently not decreasing as sharply as the quasi-static curve it may be that the air trapped in the cells is still exerting some influence on the curve.

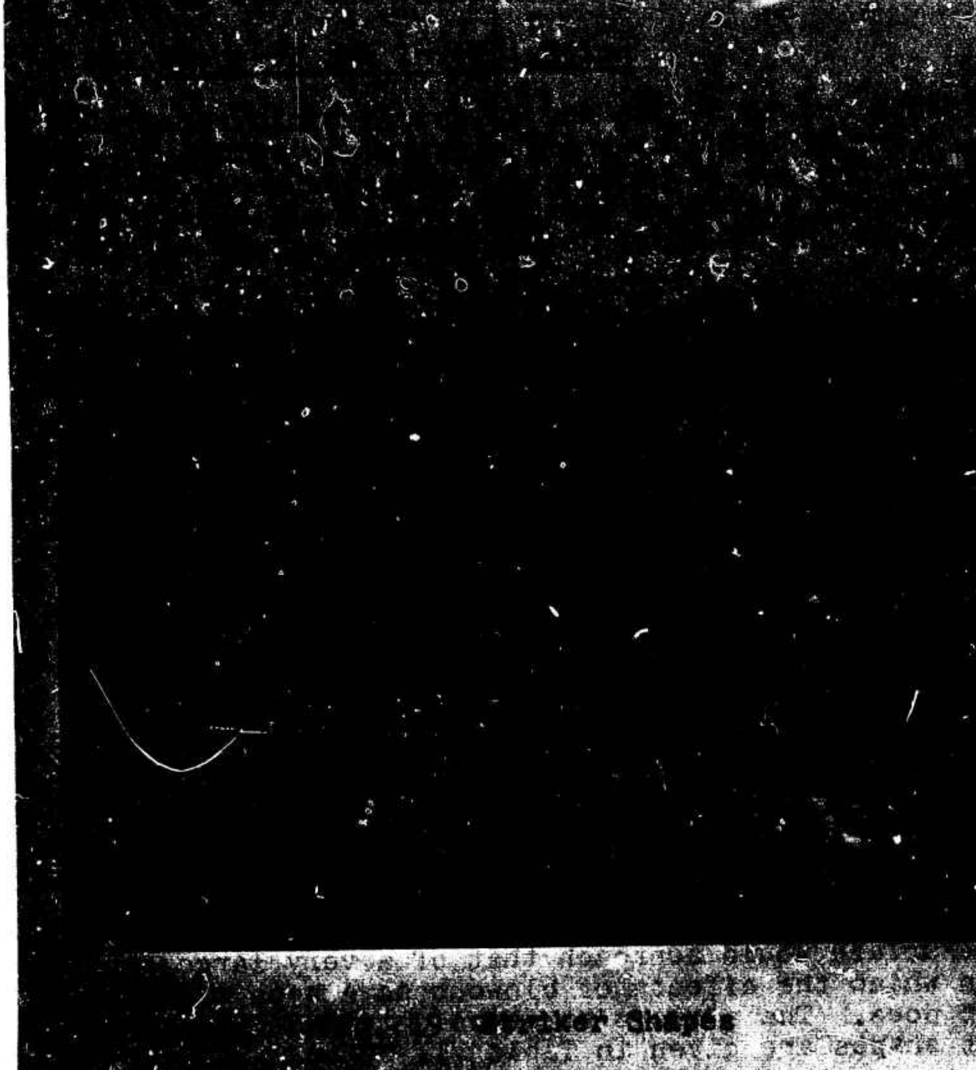
It must be concluded from these results that there is a strain-rate effect which is independent of the trapping of air in the cells, but it is not possible to determine from these measurements what the relative effects of the air entrapment and the strain rate are.

These results also suggest that the fabricators of paper honeycomb may be able to use a static loading test in lieu of a dynamic test for quality control checks. This might be attractive since the static test is simpler than the dynamic to perform, and the equipment required is less expensive.

Variation of Crushing Shape

a. **Objective**

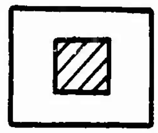
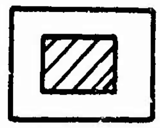
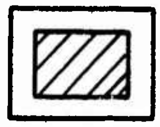
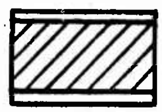
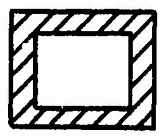
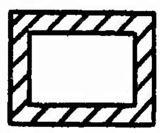
Oftentimes it is inconvenient or perhaps unwise to [illegible] a load spreader between a cushion and its point of bearing on a structure. For example, a cushion designer would understandably be hesitant to subject a transmission [illegible] differential to the concentrated force that would be [illegible] by a cushion covered with a load spreader. [illegible] would probably prefer to have the transmission [illegible] directly on the honeycomb so that it would [illegible] during the impact. In that case [illegible] crushing force should be used [illegible] related to the penetration [illegible]



[illegible] Striker Shapes

Table VI

Crushing Areas and Shapes

Striker	Figure*	Area
8 in. x 8 in. x 2 1/4 in. Solid		0.44 ft^2
10.4 in. x 10.4 in. x 2 1/4 in. Solid		0.75 ft^2
12 in. x 12 in. x 2 1/4 in. Solid		1.0 ft^2
16 in. x 16 in. x 2 1/4 in. Solid		1.78 ft^2
12 in. x 12 in. x 2 1/4 in. Solid		1.0 ft^2
14 in. x 14 in. x 2 1/4 in. Open		0.64 ft^2
12 in. dia. x 16 in. long	Hemicylinder	
12 in. dia.	Hemisphere	

* Cross hatching identifies the crushing area. All specimens 16 in. x 18 in.

c. Experimental Results

The crushing patterns produced by each of the 4 shapes are shown in Fig. 20. In general these photographs show that the honeycomb outside the area of actual contact is relatively unaffected. It might be expected therefore that the average crushing stress, say for an 8 in. x 8 in. solid surface would approach that of a very large specimen in which the effects of blowout have been minimized, and it does. The average stresses obtained for the different shapes are given in Table VII below.

Fig. 20a Sample [illegible] Hemispherical Striker

12" x 12" OPEN

FIG. 20b SAMPLES CRUSHED WITH DIFFERENT SHAPED STRIKERS

8" x 8" SOLID

12" x 12" SOLID

FIG. 20b SAMPLES CRUSHED WITH 8" x 8" AND 12" x 12" SOLID STRIKERS

If these average crushing stresses are plotted as a function of the ratio of the area of the striker to the area of the pad the best fit for the points appears to be a straight line with the lowest point on the curve coming from the striker with the largest area. Also it should be noted that the striker with the smallest area gives a crushing stress of 6710 psf, which is very close to the 7000 psf theoretical strength of a very large specimen, i.e., one for which the effects of exterior cell walls is minimized (see section 4). The material used in this series of tests came from a different source than that used in the tests of section 4 for area effects. For that honeycomb, the crushing strength of 12 in. x 12 in. specimens is 6435 psf, whereas the honeycomb used to obtain the results in Table VII has a crushing strength of 6070 psf for 12 in. x 12 in. specimens. (See Table II, honeycomb from same source as that in Table VII). Thus it appears that the two extrapolations are in even better agreement than they first appeared to be. This in turn supports the hypothesis that the principle reason for differences between the crushing strengths in tests such as those described in Table VII is a variation in the extent to which the outside cells in the crushing area are supported.

It would be unwise to set up any definite rules for determining from these data the design crushing stress for honeycomb stacks that are going to be crushed only over a portion of the cross section. However, a rough rule of thumb might be given based on the maximum and minimum crushing stress values. If the crushing strength of a very large specimen is known, along with the crushing strength of a 16 x 18 inch specimen one could interpolate linearly between those two values using the ratio of the crushed portion to the total area of the stack as a guide.

Not much can be said with regard to the two curved strikers other than to point out that the average crushing force for the hemicylinder is about 75% of the average crushing force for a 12 in. x 12 in. striking area (a 1:2 ratio of crushing area to total area) and for the hemisphere the average force is about 50% of that for the 12 in. x 12 in. area.

Typical stress-strain, or force deformation curves for some of the crushing surfaces of Table VII are shown in Fig. 21. The curves for the hemicylinder and hemisphere indicate that the resisting force provided by the honeycomb continues to increase as the cushion is crushed until a limiting value is approached. This limiting value probably is reached when the maximum diameter of the shape is in contact with the cushion. The limiting value also appears to

... CURVES FOR DIFFERENT ...

be approximately equal to the product of the projected area of the shape and the nominal crushing strength of the honeycomb. Designers can use these features of the crushing force - displacement relationship in deciding on the adequacy of a given cushion which directly supports a spherical or cylindrical device.

7. Summary

Test results obtained to date indicate that variations in dynamic crushing strength are not controlled by carefully and precisely fabricating the honeycomb. If anything, variations in crushing strength of the precision honeycomb are more pronounced. No definite reason can be given for the greater variability but it might be related to imperfections in the geometry which facilitate formation of buckling patterns and thus reduce the randomness of performance of commercial honeycomb. The crushing force is believed to depend very critically on the type of buckling pattern that develops, and this pattern may be influenced by many factors, particularly the air pressure within the cells and the blowout that occurs.

Air pressure measurements within the cells during crushing indicate that air pressure is carrying a significant part of the load at strain levels above 50%. The maximum pressure is developed at the center of a pad. At the half way point between the center and outside of the pad the pressure is essentially the same as at the center, and at the outside row of cells the pressure developed is very low, due no doubt to cell rupturing and lateral expansion and leakage of air through the paper. The high pressure developed within the interior cells and the random blowout of the outside cells could conceivably contribute to the randomness of crushing strength test results.

The crushing strength of honeycomb is significantly affected by the area of the specimen used for making the test as might be expected if the outside cells blow out or for any other reason fail to carry a full share of the load. Crushing stress increases with the area almost linearly in the range between a 4 in. x 4 in. and a 12 in. x 12 in. sample. A study of the variation in strength indicates that the effective cell failure is limited to no more than the outer row of cells. However, not all cells in the outer row rupture and it has been observed that cells as many as 4 or 5 rows into the interior are ruptured. Consequently, the cell damage is merely expressed in terms of the outside cells, but in actuality is not limited to those cells.

Changes in crushing rates of several orders of magnitude have no appreciable effect on crushing strength in the very low rate range. However, there is a significant increase in crushing strength between the low (quasi static) rate range and an impact at 20 fps. This difference is believed to be due at least partially to the effect of the air within the cells. At very low crushing velocities the entrapped air can escape without much increase in pressure whereas at the higher rates, sufficient pressure is developed to rupture some of the cells. The evidence also indicates that the difference in strength is at least partially due to a genuine strain rate effect in the cell buckling process.

If the test sample is constant in size and shape, but the crushing area varies, the apparent crushing strength varies inversely as the area. This is believed to result from a reduction, as the area decreases, in the loss of affected cells. These losses normally occur in the outermost rows of cells which do not receive much support from adjacent cells.

8. Conclusions

a. The average crushing strength of paper honeycomb is not particularly sensitive to uniformity of cell size and shape, paper weight, and type of glue but depends rather on cell size, glue line width, and the amount of cell destruction by blowout.

b. The amount of cell destruction by blowout is a random function which seems subject to more extreme variations the more carefully the honeycomb is fabricated. This problem may be aggravated by variations in glue line strength which result from the method of application and curing used in the fabrication process.

c. The air pressure developed within the interior cells during crushing reaches sufficient magnitude to account for as much as 40% of the observed crushing strength at 60% strain. The contribution of the air pressure may depend very critically on the quality of the paper and the glued joints. It should not, therefore, be assumed that in all paper honeycombs air pressure is supplying an appreciable part of the crushing strength.

d. Crushing strength decreases significantly with the area of the sample. For example, the crushing strength of a 16 in. x 18 in. (2 square feet) sample may be 15% higher than the crushing strength of a 4 in. x 4 in. (0.11 square feet) sample. This decrease results from the fact that a greater percentage of the area of the small sample is made up of outer cells which blow out or collapse at lower loads because they have less lateral support than the inner cells.

e. There is a definite increase in the average crushing strength of paper honeycomb loaded dynamically with an impact velocity of 20 fps, over that of similar samples loaded at crushing rates of 20 in./min. This difference appears to be a rate effect rather than a result of air leaking out of the cells at the low loading rates and not having time to escape at the high loading rates.

f. The loading rate at which strain rate effects become evident is undetermined.

g. If a honeycomb sample is crushed by a rectangular surface which is small compared to the total area of the sample, the crushing strength observed approaches the strength of a very large sample. As the area of the crushing surface increases with respect to the area of the sample the apparent crushing strength decreases. The decrease depends upon the extent to which the outside cells lose support from adjacent cells, support which influences the buckling pattern and allows the cells to blowout due to air pressure inside the cells.

h. Curved surfaces such as a hemisphere, or a hemi-cylinder give a lower average crushing force but the final crushing force is approximately equal to the product of the projected area of the surface and the crushing strength of the honeycomb as determined by standard methods.

9. <u>Recommendations</u>

a. Air pressure developed during crushing should be studied further. In particular it is suggested that tests be made in which the honeycomb is evacuated. Results from such tests when compared with those from non-evacuated specimens ought to do much to clarify the role of the entrapped air in energy dissipation.

b. Further measurements should be made of the air pressure developed in the cells to clearly determine how the pressure varies with position in the body, and to determine more precisely how pressure varies with crushing deformation and crushing velocity. In that connection, the effects of perforating cell walls, especially the outside cells, on air pressure and crushing strength should be investigated.

c. Further studies of the effects of variations in paper thickness, cell size and glue line width on crushing strength should be made using laboratory produced honeycomb.

d. The nature of the crushing rate effect, on crushing strength should be investigated further, and the velocity range in which it begins to appear should be pin pointed.

e. The cushioning characteristics of paper honeycomb crushed with a velocity component normal to the cell direction as well as parallel to it should be studied.

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13. ABSTRACT

To determine why paper honeycomb pads, in which variables such as paper weight, cell size, cell shape, and glue line widths are ostensibly constant, sometimes vary rather widely in crushing strength, thirty one precisely controlled samples were fabricated in the laboratory and crushed under dynamic loading. Results of these tests ~~show a wider~~ variation ~~than~~ corresponding results of tests of commercial honeycomb. It appears that crushing failure is governed by random processes having to do with buckling patterns, and "blowout". ~~Further study of the problem is recommended.~~

Studies are also reported of the air pressure developed in the cells during crushing, the effect on crushing strength of specimen size and the ratio of crushing area to total specimen area, and the crushing strength at very low crushing rates. Measurements indicate that air pressure may account foras much as 40% of the total observed crushing strength, but the low crushing rate tests cast some doubt on this. Specimen area has a significant effect on crushing strength which is believed to be a function of the ratio of the area of the outside cell row to the total crushing area.

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