ON THE EFFECT OF MOISTURE CONTENT ON THE SHOCK TRANSMISSION PROPERTIES OF HONEYCOMB CUSHIONING

By

Punnapa Asvanit

A THESIS

Submitted to

Michigan State University

in partial fulfillment of the requirements

for the degree of

MASTER OF SCIENCE

School of Packaging

1988

ABSTRACT

ON THE EFFECT OF MOISTURE CONTENT ON THE
SHOCK TRANSMISSION PROPERTIES OF
HONEYCOMB CUSHIONING

By

Punnapa Asvanit

The effect of moisture content on the cushion curves for Honeycomb was investigated and a mathematical approach aimed at the development of a model to predict the peak acceleration was attempted. Two different cell sizes of Honeycomb having various moisture contents were used to determine static crushing strengths and dynamic shock transmission values for three different drop heights at seven different static stresses. The two mathematical models attempted were the adiabatic air compression model and an energy approach based on a dynamic extension of the static stress strain curve. Because of the complicated structure of Honeycomb, neither model provided accurate results and it was therefore concluded that modelling was impractical. A curve fitting approach which resulted in a high degree of correlation with the experimental data was used instead.

Dedicated to my parents, Sermsuph and Sutham Asvanit

ACKNOWLEDGMENTS

I would like to express my sincere thanks to Dr. Gary J. Burgess as my advisor for his understanding, guidance, and time. There are no words that can express my appreciation.

I would also like to thank Dr. Paul S. Singh for his thoughtfulness, support, and advice as a member of my committee.

I would also thank to Dr. George E. Mase for his time and support as a committee member.

Also, special thanks to Mr. Mark Jacobson, Director of Marketing for International Honeycomb Corporation, for providing the materials and funds for this research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

P_o initial pressure before compression, (14.7 psi.)

P final pressure at any instant during compression, (psi.)

V_o initial volume before compression, ($inch^3$)

V final volume at any instant during compression, ($inch^3$)

k ratio of specific heats, (1.4 for air)

W drop weight, (lb)

h drop height, (inches)

x deflection, (inches)

A load bearing area, ($inch^2$)

t cushion thickness, (inches)

σ_b buckling stress, (psi.)

ϵ maximum strain, (inches/inch)

σ static stress, (psi.)

G peak acceleration, (g's)

G_c calculated peak acceleration, (g's)

G_{exp} experimental peak acceleration, (g's)

Var variance

$\sum$ sum

N number of data

a,b,c,d,e,f,g,p,q,r coefficients

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

During the period from 1953 to 1959, the Structural Mechanical Research Laboratories at the University of Texas in Austin,Texas, under contract with the Delivery Quartermaster Research and Development command [1,2], had investigated many kinds of cushion materials to determine the best available material suitable for single drop aerial delivery. Specifically, the dynamic stress strain curves were investigated to provide information about the energy absorption characteristics of the material from which the cushion properties of the material could be determined. Honeycomb cushioning was determined to be the cushion most suited for this particular use. The structure of Honeycomb is a core consisting of oval cells bounded on both sides by curved panels as shown in Figure 1. The entire structure is made from unbleached Kraft linerboard paper. The oval core structure is constructed from Kraft paper with a 33 pound basis weight and the face panel from 69 pound basis weight linerboard. Following the selection of Honeycomb as the most practical cushioning material for aerial drops, the many factors which affect the dynamic stress strain curve such as density, moisture content, impact velocity, and temperature were investigated. Hopf [3] studied the effect of moisture content on the static stress strain curve of Honeycomb cushion and found that the stresses and consequently the energy absorption capabilities decrease as the moisture content increases. Later, Ripperger [4] published a paper on the energy

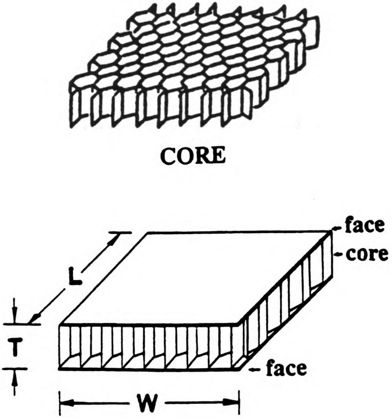


Figure 1 : Crossection of a Honeycomb cushion

absorption characteristics of paper Honeycomb based on research conducted at the University of Texas in Austin. In 1983, cushion curves for Honeycomb were experimentally developed by Singh [5] under standard lab conditions of 72°F & 50% RH. To date, this body of knowledge constitutes virtually all that is known about the cushioning properties of honeycomb. Still, some very important behavioral characteristics of Honeycomb came out of these analyses. The most important of these are brought out in the static stress strain curve.

A typical static stress strain curve for a Honeycomb cushion is shown in Figure 2. The various parts of the curve correspond to three distinct types of behavior during compression. During the first stages of compression, the stress builds up very rapidly in a nearly linear fashion. The material compresses elastically with no visible change in shape until a point is reached where the Honeycomb core starts to buckle. Buckling continues under a nearly constant reduced stress until the cushion reaches a strain of about 65%. At this point, all of the the Honeycomb cells have completely collapsed and the Honeycomb cushion acts like a solid block of paper under compaction. Therefore, the stress builds up rapidly again and exceeds the initial peak stress as the applied load increases.

The energy absorbed per unit volume of cushion during compression is just the area under the stress strain curve up to the point of compression. This includes energy which is dissipated and stored energy which is recoverable. The amount of recoverable elastic energy is typically very small compared to the total energy absorbed during impact

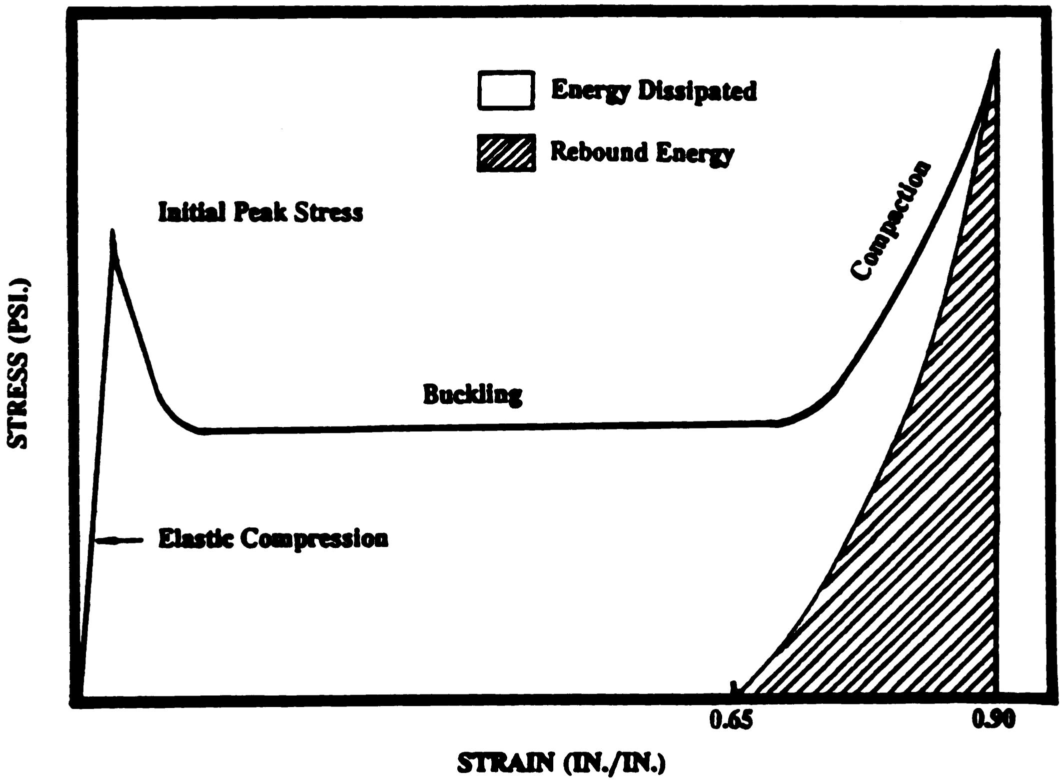


Figure 2 : A typical stress strain curve for Honeycomb

since buckling of the Honeycomb cell walls is irreversible. The stress strain curve during unloading from the compaction stage is also shown in Figure 2. The area under this curve is the elastic energy recovered during the rebound stage of an impact and corresponds to the rebound energy per unit volume of cushion given back to the impacting object. The ratio of this rebound energy to the energy dissipated is called the ' Resilience ' [4] which is considered to be a fundamental dynamic material property related shock absorption ability. Since an excessive amount of rebound energy given back to an impacting object is potentially damaging to this object simply because this subjects the object to repeated impacts, a cushion with a high resilience is not considered to provide adequate protection. Honeycomb cushions typically have very low resilience values which are essentially constant up to compaction and therefore are considered to be very good dissipaters of impact energy. Consequently, Honeycomb is an excellent cushion material for single drop use. The resilience however rises when the cushion is compressed to a strain of around 70% to 75% [2] since this is the point at which compaction dominates. After this point, the stress increases rapidly which results in large decelerations. Ideally, the cushion designer would like to operate in the low stress region (flat part) of the static stress strain curve since this results in the smallest deceleration. For this reason, Witting [6] recommends a precompression of 0.2 inches before using it as a cushion in order to overcome the initial peak (bulking) stress. However, if complete crushing of the pad is expected, precompression is not nesessary. In general, the larger cell size cushion is less resilient than the smaller cell size cushion. Also, resilience tends to decrease when the impact velocity increases.

The dynamic stress strain curves obtained from five grades of Honeycomb material produced results which were similar in shape to the static curves except that the dynamic stresses were higher [2]. The grade of Honeycomb cushion is simply a measure of its overall density due to cell size, different combinations of paper basis weights and percent resin impregnation. The percent difference between the static and dynamic stress for a given strain depends on the cell size ,the cushion density, and processing. Karnes et al [2] tested five untreated Honeycomb grades and showed that for a core density range of 1.0 lb/ft^3 to 2.6 lb/ft^3, the average dynamic energy absorption is about 44% higher than the static value. The maximum strain under dynamic test conditions at the point of bottoming out (compaction) was about 2 to 5 percent higher than the static maximum strain value.

The effect of density on peak stress was also studied [2]. Cushions with densities ranging from 1.0 lb/ft^3 to 3.0 lb/ft^3 were used and the peak (buckling) stresses were found to range from 1400 lb/ft^2 to 10,000 lb/ft^2. The effect of cushion density on dynamic energy absorption by changing the strain from 70% to 80% was also studied. It was found that the increase in energy absorption of the 1.0 lb/ft^3 density cushion was 15% and for the 3 lb/ft^3 density cushion, 22%. But the variation in density among two hundred 3/4 inch cell size Honeycomb samples made from paper with a basis weight of 99 lb. was found to be 35% and the variation in maximum crushing stress was 25% [2]. Therefore, even though density seems to influence the energy absorption ability of Honeycomb material, variations in density among samples from the same lot obscure the relationship between the two. Other factors however also effect the crushing strength. Among these are cell size, the thickness of glue line, processing, moisture and temperature.

When Honeycomb is subjected to different relative humidity environments, it normally takes about 14 days for it to reach equilibrium although 90% of the equilibrium moisture content is absorbed or desorbed within the first 48 hours [3]. The size of the specimen is of course the major factor that determines the time it takes for the sample to reach its equilibrium moisture content. For Honeycomb with a low moisture content, the static stress strain curve shows a dramatic reduction in stress after the initial peak stress is reached because of the brittle nature of the structure. For Honeycomb with a high moisture content, resistance to buckling is diminished so this reduction is not as pronouced. Moisture content nevertheless affects the static stress strain curve significantly and the effects are different depending on % moisture content and cell size. On the average, Honeycomb shows a decrease in energy absorption of around 60% when the moisture content is increased from 6% (dry) to 20% (wet). In the dynamic stress strain curve case, for the 3/4 inch cell size, an increase in moisture content did not effect the initial peak stress until the moisture content was more than 12% and the decrease in average stress was found to be around 45 percent when a moisture of 17% was reached [1]. For the 1/2 inch cell size, the average stress decreased gradually to about 25% when the moisture content was increased from 10% to 24%. For light grade Honeycomb with a 1 inch cell size, there is no significant difference in stress due to moisture content. It was very interesting to find that after exposing Honeycomb to the weather for 30 days during which 4.5 inches of rain fell and then drying the sample in sunlight for 3 days, no change in the crushing strength was detected over unweathered samples.

Impact velocity and temperature are two additional factors which were studied. The effect of impact velocity on energy absorption characteristics of Honeycomb was found to be insignificant for impact velocities up to 90 fps [2]. Temperature seems to be a factor that affects the crushing strengh of Honeycomb only through its effect on moisture content. There is only a slight difference in average crushing strength between 0°F and 85°F for low moisture contents [4]. An increase in the moisture content at 0°F has the net effect of raising the crushing strength due to freezing.

The final factor which affects Honeycomb cushion performance is the perimeter to load bearing area ratio. A high perimeter to area ratio causes ' blowout ' of the cell walls along the edges which then reduces its resistance to compression. This blow out occurs as a result of an unbalanced pressure from the air trapped in cell during compression. Lighter density Honeycomb is more vulnerable to blow out. By keeping this ratio small and the impact velocity less than 60 fps, this factor is not a serious problem.

The research performed by Singh et al [5] on standard Honeycomb was aimed at evaluating the effects of cell size, cushion thickness and drop height on the shock transmitted. All of the samples used in this study were stored at standard conditions of 72°F and 50% RH and the drop testing was done under the same conditions. Honeycomb was found to yield the typical concave cushion curves except at the bottoming out point where the peak acceleration increased rapidly. The purpose of this study is to extend this work to include the effects of moisture content.

CHAPTER 2

MATERIALS AND TEST METHODS

2.1 MATERIALS AND STORAGE CONDITIONS

The Kraft Honeycomb cushions used in this research were manufactured by International Honeycomb at University Park Illinois. In this study, two different cell configurations, 1/2 and 3/4 inch, were tested. Samples measuring 8"×8" were carefully cut from 3" thick Honeycomb stock and separated into 1/2" and 3/4" cell groups. The specimens were further divided into four groups and placed in four different temperature and humidity conditions for at least 2 weeks in order to achieve equilibrium with the ambient atmosphere. The four conditions were :

a) 100±2°F & 32±3 % R.H.

b) 99±1°F & 83±3%R.H.

c) 41±2°F & 88±3 % R.H.

d) Freezer @ 5°F

which represent various combinations of equilibrium moisture contents within the samples. To achieve these conditions, humidity chambers were used. The temperature and humidity of the chambers containing the samples stored in conditions (b) and (c) were automatically controlled. For the others, only the temperature was automatically controlled and the relative humidity was left dependent on the temperature. The humidity chambers remained closed except for opening and closing so that the variation in relative humidity was taken to be that characteristic for this equipment, ±3%. A psychrometer was periodically used to verify the temperatures and humidities for the first three conditions. Since no reliable estimates of relative humidity could be made inside the freezer, the moisture content for the last case was left undetermined but is expected to be low.

2.2 DETERMINATION OF THE MOISTURE CONTENT

Method: The ASTM D644-55 method [7] which is the standard for determining moisture content of paper material by oven drying was followed with the exception than an airtight weighing container was not used to transfer the specimen from the vacuum oven to the balance. Instead, some of the specimens were transfered from the conditioning chamber to the balance by wrapping them in a polyethylene bag to prevent moisture loss to the atmosphere during transfer. The remaining samples were left in the chambers for drop testing later. The specimens were weighed as quickly as possible after removal from the bag. The initial weight was recorded and the specimens were placed in a vacuum oven for 6 hours at 90°F. The oven used was a Vacuum Oven Model No. 5831 manufactured by National Appliance Company and the scale was an Analytical Balance Model AE 160 manufactured by Mettler Company. After 6 hours, the vacuum oven was flushed with nitrogen and the specimens were immediately transfered to a glass desiccator filled with anhydrous $CaSO_4$ and allowed to cool to room temperature for at least 45 minutes. They were then weighed to determine the dry weight. Each weighing was done in duplicate. The moisture content on a percent dry basis was then determined by

$$\text{Percent Moisture} = [\ (W_1 - W_2)/W_2\ ] \times 100$$

where W_1 = original weight of the moist specimen and

W_2 = weight of specimen after vacuum oven drying

The percent moisture contents of the specimens were determined after seven and fourteen days of storage.

2.3 STATIC COMPRESSION TEST

Materials: The two different cell sizes of Kraft Honeycomb cushions measuring 8"×8" were conditioned at the 4 different conditions for two weeks.

Apparatus: A Lansmont Model 76-5K compression tester with a capacity of 6000 pounds was then used to perform the compression test. The output of the load cell was coupled to an Allen Datagraph Incorporated series 715 plotter which recorded the entire force versus deflection curve during compression with the tolerance of ±0.3% on force.

Method: Each specimen was enclosed in a polyethylene bag to prevent any change in moisture content during the test. A 50 pound preload was applied and the force was increased until the strain reached 90%. Using the force versus deflection curves obtained from the plotter, the peak compression force and corresponding deflection were recorded for five identical specimens at each moisture condition and cell size. The stress versus strain curve was obtained by dividing the force by the load bearing area and the deflection by the cushion thickness respectively.

2.4 DROP TEST

Materials: Specimen sizes varied depending on the desired static stress (pounds per square inch) because of practical load limitations imposed by the drop tester:

a. A specimen size of 8"×8" was used for static stresses ranging from 0.3 to 2.3 psi.

b. A specimen size of 6"×6" was used for static stresses ranging from 2.49 to 4.09 psi.

c. A specimen size of 4"×4" was used for static stresses ranging from 4.4 to 5 psi.

Some of specimens were cut to the required size using a bandsaw before placing them in the controlled condition chambers.

Apparatus: The equipment used for the drop test consisted of:

1. A Lansmont Corporation Model 23 cushion tester with a flat dropping head onto which ballast weights could be loaded, a lifting mechanism, and rebound break trigger switch.

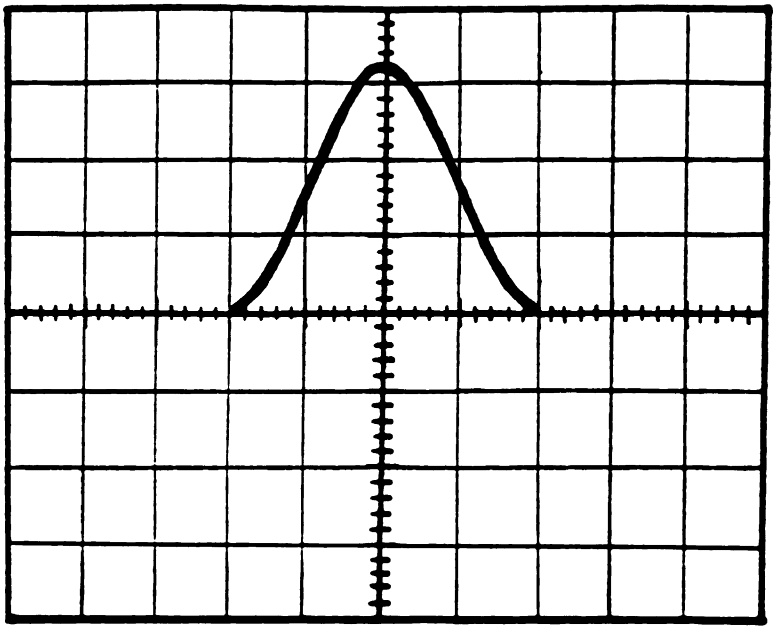
2. A Dytran Model 3030A piezoeletric accelerometer with a output characteristic of 10 mV/g's and a tolerance of ±2% was mounted on the droping head of the drop tester.

3. A Kistler Model 5116 AC piezotron coupler with a tolerance of ±5% was used to amplify the output of the accelerometer.

4. A Kikusui 20 MHz series 5020-ST storage ocilloscope with a tolerance of ±3% received the signal from the coupler and displayed the shock pulse from the accelerometer. The accelerometer mounted on the free falling dropping head responds to the shock incurred by the dropping head contacting the cushion and sends a signal though the coupler for amplification. The enhanced signal is then sent to the

oscilloscope where the shock pulse is displayed and stored on the screen. A typical shock pulse recorded on the oscilloscope is shown in Figure 3. The peak acceleration and the shock duration was determined using the oscilloscope settings and the accelerometer output characteristic. For example, in Figure 3, the height of the shock pulse on the oscilloscope screen is 3.2 div. Therefore, the output of the accelerometer is 3.2 div × 100 mV/div = 320 mV and the peak acceleration is 320 mV/10mV/g = 32 g's. The width of the shock pulse is 4 div and therefore the shock duration is 4 div × 5 ms/div or 20 ms. In reading the peak acceleration on the oscilloscope, an error can occur due to the thickness of the trace which is typically 0.1 division. The percent error depends on the vertical sensitivity and the peak acceleration values. Since in this research 3 different vertical sensitivities were used, the percent error is based on the maximum value which is 6.25%. For example, using a vertical sensitivity of 100 mV/div to record a 16 g peak acceleration, the error can be 0.1 div/1.6 div. or 6.25%.

Method: The ASTM 1596-78a method [8] for determining the Shock Absorption Characteristics of Package Cushioning Materials was followed with the exception that only one drop was performed since Honeycomb does not recover after the first impact. Duplicate samples were used for each static stress. Each specimen was wrapped in a polyethylene bag while tranfering from the conditioning chamber to the testing lab since the testing lab is kept at standard conditions of 73±3.5°F and 50±2%RH. Three different drop heights (24,30,and 36 inches) and seven different static stresses for each drop height were used for each storage condition and cell size. Only the peak acceleration was recorded.



Vertical Sensitivity = 100 mV/div.

Sweep Rate = 5 ms/div.

Figure 3 : A typical shock pulse recorded on the oscilloscope

CHAPTER 3

RESULTS

The equilibrium moisture contents for both cell sizes after 14 days of storage are shown in Table 1. Note that the percent moisture contents for the 1/2" and 3/4" cell sizes differ by only 1%. Since the moisture content for the freezer condition turned out to be as high as that for the 99°F & 83%RH environment, only the first three moisture content conditions will be used in the remainder of this analysis. Specifically, the three different moisture contents for the 1/2 inch cell size were taken as 5.56%, 14.65%, and 18.28%. and for the 3/4 inch cell size, as 5.26%, 14.34, and 19.23% The raw data from which these values were determined are presented in Appendix A.

The static compression test results for the different cell sizes and moisture conditions are shown in Table 2. The initial peak stress for the 1/2 inch cell size was about twice as much as that for the 3/4 inch cell size for each moisture condition. The strains corresponding to these initial peaks ranged from 2.8% to 4.75%. Note that the initial peak stress decreases as the moisture content increases. At 19% moisture content, this stress is half that for a moisture content of 5%, which agrees with Hopf [3]. Details are presented in Appendix A.

Table 1 Equilibrium moisture content for the 1/2 inch and 3/4 inch cell sizes at the 4 moisture conditions after 14 days of storage.

Condition	%MC for 1/2 in. ± s.d. cell size	%MC for 3/4 in. ± s.d. cell size
100°F & 32%RH	5.56 ± 0.092	5.26 ± 0.158
99°F & 83%RH.	14.65 ± 0.003	14.34 ± 0.100
41°F & 88%RH.	18.28 ± 0.013	19.23 ± 0.134
Freezer(5°F)	15.86 ± 0.099	15.64 ± 0.465

Table 2 The initial peak stress and strain for the 1/2 inch and 3/4 inch cell sizes at the 4 moisture conditions

Cell size (inch)	Condition	Stress ± s.d. (psi.)	Strain ± s.d. (in./in.)
1/2	100°F&32%RH.	51.93 ± 1.410	0.048 ± 0.0053
	99°F&83%RH.	32.29 ± 1.190	0.038 ± 0.0030
	41°F&88%RH.	24.65 ± 0.954	0.034 ± 0.0017
	Freezer(5°F)	29.73 ± 1.320	0.039 ± 0.0050
3/4	100°F&32%RH.	24.44 ± 0.522	0.045 ± 0.0032
	99°F&83%RH.	14.33 ± 0.500	0.028 ± 0.0018
	41°F&88%RH.	13.20 ± 0.513	0.029 ± 0.0028
	Freezer(5°F)	14.02 ± 0.734	0.039 ± 0.0797

The experimental data for the shock transmission values G for the 1/2" and 3/4" cell size specimens at the four moisture conditions are shown in Tables 5.A through 6.C in Appendix A. When plotted against static stress to obtain the cushion curves, the result was not a smooth curve. This can be explained in part by the small number of repetitions used during testing and by inherent errors associated with measuring G. Note that in general, the peak accelerations are higher for lower moisture contents than for high moisture contents. This result was expected since for both cell sizes, the low moisture content samples could withstand more static stress than high moisture content samples. The lowest peak acceleration values on the cushion curves are in the range of 20 to 30 g's depending on cell size, drop height, and moisture content. For the both the 1/2 inch and 3/4 inch cell size, the bottoming out point for high moisture contents occured at lower static stresses than for low moisture contents.

CHAPTER 4

ANALYSIS OF DATA

In this analysis, the development of a mathematical model to predict the shock transmission characteristics of honeycomb during the contact phase is considered, the purpose of which is to eliminate the need for cushion curves. But the model must be able to predict the shock transmission values using only basic information with good accuracy and must also be practical for use.

4.1 ADIABATIC MODEL

Starting with a model for a semi-rigid paper structure enclosing trapped air in the form of a rectangular cushion, two resisting forces must be considered. The first is the paper structure itself. The stress required to buckle the honeycomb columns depends on the stiffness of the paper, the cell size, the thickness of the sample and the moisture content in the paper. The buckling stress may be determined from theoretical considerations but is better obtained from the static stress strain curve as the initial peak stress. The second force comes from the compressed air trapped in the cells. If compression is assumed to be adiabatic then

$$PV^k = P_oV_o^{\ k} \tag{1}$$

where k is the ratio of specific heats for air, taken to be 1.4.
P and V are the pressure and the volume of specimen at any instant during compression.
P_o and V_o are the initial pressure (14.7 psi.) and volume of specimen.

The mechanical work required to compress the air from volume V_o to V is

$$\text{Work} = -\int_{V_o}^{V} PdV = \frac{P_oV_o^{\ k}}{k-1}\left[\frac{1}{V^{k-1}} - \frac{1}{V_o^{\ k-1}}\right] \tag{2}$$

The final compressed volume of the cushion may be obtained from an energy balance in which the potential energy of the falling weight goes into compressing the trapped air and buckling the paper structure. The potential energy is the weight multiplied by the drop height and the work done by the outside atmosphere is just the atmospheric pressure multiplied by the change in volume. The work required to buckle the paper is the buckling stress multiplied by the change in volume and the work to compress the trapped air inside is given in equation (2). The energy balance from release of the weight to maximum cushion compression then is

$$W(h+x) + P_oAx = \frac{P_oV_o^{\ k}}{k-1}\left[\frac{1}{V^{k-1}} - \frac{1}{V_o^{\ k-1}}\right] + \sigma_bAx \tag{3}$$

where x is the maximum compression, σ_b is the buckling stress, h is the drop height, W is the weight, and A is the loading bearing area.

Setting $$x/t = \epsilon \text{ (maximum strain)}, \tag{4}$$

where t is the cushion thickness, the initial and deformed cushion volumes become,

$$Vo = At \text{ and } V = Vo(1-\epsilon) \tag{5}$$

and the energy balance in equation (3) is

$$W(h+\epsilon t) + P_oV_o\epsilon = \frac{P_oV_o^{\,k}}{k-1}\left[\frac{1}{V_o^{\,k-1}}\right]\left[\frac{1}{(1-\epsilon)^{k-1}} - 1\right] + \sigma_b V_o \epsilon \tag{6}$$

Setting $$W/A = \sigma = \text{static loading}, \tag{7}$$

$$\frac{\sigma}{P_o}\left[\frac{h}{t} + \epsilon\right] + \left[1 - \frac{\sigma_b}{P_o}\right]\epsilon = \frac{1}{k-1}\left[\frac{1}{(1-\epsilon)^{k-1}} - 1\right] \tag{8}$$

From equation (8) the maximum strain ϵ may be determined for each static loading σ and drop height h once the buckling stress σ_b is known from the static compression test. This value may then be used to find the peak acceleration using Newton's Law. Equating the unbalanced force from Figure 4 to mass times acceleration gives

$$(P + \sigma_b)A - P_oA - W = \text{mass} \times \text{acceleration} = WG$$

Where G is the peak acceleration in g's. Using equations (1),(5),and (7) gives

$$G = \frac{P_o}{\sigma}\left[\frac{1}{(1-\epsilon)^k} - 1\right] + \frac{\sigma_b}{\sigma} - 1 \tag{9}$$

where ϵ is the solution to equation (8).

Unfortunately, the cushion curves generated by equations (8) and (9) by using various drop heights, static loadings and thicknesses do not fit the experiment data. This suggests that the model is inadequate and must be elaborated on. The sources of error in the model are most likely due to the fact that the air inside the cells is not truly trapped during compression since the buckling of the Honeycomb cells causes the paper

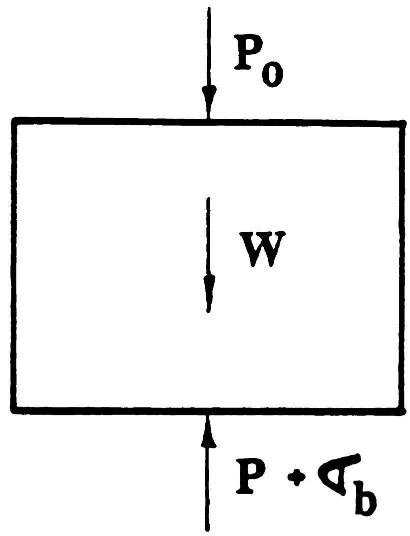


Figure 4 : Free body diagram of a Honeycomb cushion at maximum compression in a drop

to tear allowing air to flow thoughout the Honeycomb network, similar to what happens in an open cell foam. Since the original model already produces equations which are difficult to use, it is expected that a more elaborate model will produce even more complicated results and so the modelling approach will be abandoned in favor of a more practical approach. This approach uses the static compression stress strain curve to predict shock transmission values in the belief that all of the relevant resisting forces left out in the previous model are accounted for in the stress strain curve. The only obvious force which will not show up in the static compression test results is the viscoelastic or strain rate dependent term. This approach will be discussed next.

4.2 STATIC STRESS STRAIN CURVE MODEL

The research conducted at The University of Texas [1,2] was aimed at using the dynamic stress strain curve to predict the peak acceleration in a drop. An example of the calculation of peak acceleration was given but no verification that the calculated results agreed with the experimental ones was demonstrated. Since the dynamic stress-strain curve is very difficult to obtain experimentally due to the need for a high strain rate compression tester, the approach which uses the dynamic stress strain curve to predict shock level will be carried out by assuming that the dynamic stress is a constant multiple of the static stress for each value of strain. This multiple will then be determined by requiring that the predicted shock levels match the experimental ones as closely as possible in an overall sense. The expected size of this value is 1.4 corresponding to earlier research [2] which found that the dynamic energy absorption is about 1.4 times the static energy absorption.

An energy balance requires that the potential energy of the impacting mass in the drop is absorbed by the cushion material in the form of stored and dissipated energy. Since the sum of these energies is just the area under the dynamic stress stain curve multipled by the volume of cushion and the potential energy is just weight times drop height,

$$At \int_0^{\epsilon_m} \sigma d\epsilon = WH$$

which leads to

$$\int_0^{\epsilon_m} \sigma d\epsilon = \frac{\sigma H}{t} \qquad (10)$$

Equation (10) gives the maximum cushion strain ϵ_m for a given drop height H and cushion thickness t in terms of the static loading σ. Starting with Newton's law,

$$F - W = WG$$

where F is the peak cushion force exerted on the object and rearranging,

$$G = \frac{F}{W} - 1 = \frac{\sigma_m}{\sigma} - 1 \qquad (11)$$

where σ_m = F/A
and σ = W/A = static loading.

The general procedure then is to calculate the maximum strain ϵ_m from equation (10) for a given drop height, static loading, and thickness using the dynamic stress strain curve. The peak stress σ_m corresponding to this value of ϵ_m is also found from the assumed dynamic stress strain curve and this result is then substituted into equation (11) to get the peak acceleration. Starting with the experimentally determined static stress-strain curve shown in Figure 2, the assumed dynamic stress strain curve was taken to be :

$$\text{dynamic } \sigma = C \times \text{static } \sigma \tag{12}$$

where C is a constant. Investigating various values for C ranging from 1.1 to 3 in steps of 0.1, the above procedure to determine G was carried out and compared to experimental values for G. The correct value for C was taken to be the constant which gave the least variance between the calculated and experimental data.

Unfortunately, no single constant factor was found which gave acceptable results. Therefore, the static stress strain curve cannot be used as such to predict the peak acceleration. This is a result which is specific to Honeycomb since for most plastic foam cushions such as Ethafoam 220®, the static stress strain curve can be used to predict the peak acceleration with good accuracy [9]. The main reason for the failure of this approach is that there are many factors involved in the dynamic compression of honeycomb which must be considered. Some of these are the buckling of the paper cells, the post-buckling compaction of the paper which may lead to tearing and rupture and the resultant flow and compression of air thoughout the cell network. All these factors are influenced by the strain rate and therefore do not show up in the static stress strain curve used as the basis for this model. Having attemped several models with limited success, it was determined that the most practical approach was to fit the data base to a descriptive equation which takes into account all of the Honeycomb cushion parameters such as cell size, thickness, and moisture content as well as drop parameters such as drop height and static loading.

4.3 CURVE FITTING APPROACH

This approach begins with the assumption that there exists some function which relates peak acceleration G to the static stress σ for a given cell size, moisture content and drop height, in the form,

$$G = f(\sigma)$$

which presumably has a Maclaurin series expansion [10],

$$f(\sigma) = a + b\sigma + c\sigma^2 + d\sigma^3 + e\sigma^4 + f\sigma^5 + \ldots \qquad (13)$$

Since the function $f(\sigma)$ is not known beforehand, the usual approach cannot be used to find the coefficients ,a,b,c,d,.... The series will therefore be truncated and fitted to the experimental data. The choice of the degree of the polynomial left after truncation must be based on the fact that it should be able to produce a curve with a variable curvature and yet be able to smooth out any fluctuations in experimental data that would lead to oscillatory behavior. For these reasons, a cubic polynomial was chosen since this allows the curvature to change linearly with the static stress,

$$G_c = a + b\sigma + c\sigma^2 + d\sigma^3 \qquad (14)$$

The first derivitive of this is the slope and the second derivitive is the rate of change of slope or the curvature : $f'' = 2c + 6d\sigma$. At this point, there are four unknown coefficients (a,b,c,d) which must be determined for each data set (drop height, moisture content and cell size). Since there are seven data points for each data set, the cubic equation will obviously not fit the experimental data exactly. The procedure for fitting the cubic to the experimental data will therefore be based on a least squares approach which involves minimizing the variance between the predicted (cubic) and the actual (experimental) data. The variance is defined as the sum of the squares of the differences between the experimental data the cubic predictions,

$$\mathrm{Var} = \sum_{i=1}^{N} (Gc_i - Gexp_i)^2 \tag{15}$$

where Var = variance
N = number of data = 7
Gc_i = cubic prediction values from $i = 1$ to N
$Gexp_i$ = experimental data from $i = 1$ to N

Substituting Gc from eqution (14) into equation (15) gives

$$\mathrm{Var} = \sum_{i=1}^{N} (a + b\sigma_i + c\sigma_i^2 + d\sigma_i^3 - Gexp_i)^2 \tag{16}$$

The coefficients a, b, c, and d are determined by requiring the variance to be a minimum. This in turn requires that the partial derivitives of the variance with respect to each unknown coefficient a, b, c, and d be equal to zero which leads to the system of linear equations shown below in matrix form,

$$\begin{bmatrix} N & \sum\sigma & \sum\sigma^2 & \sum\sigma^3 \\ \sum\sigma & \sum\sigma^2 & \sum\sigma^3 & \sum\sigma^4 \\ \sum\sigma^2 & \sum\sigma^3 & \sum\sigma^4 & \sum\sigma^5 \\ \sum\sigma^3 & \sum\sigma^4 & \sum\sigma^5 & \sum\sigma^6 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = \begin{bmatrix} \sum Gexp_i \\ \sum\sigma Gexp_i \\ \sum\sigma^2 Gexp_i \\ \sum\sigma^3 Gexp_i \end{bmatrix} \tag{17}$$

The sums in the 4x4 matrix on the left are pure numbers related only to the static loadings used and the sums in the 4x1 vector on the right are pure numbers related to both static loading and the shock levels obtained experimentally. The coefficients a, b, c, and d obtained from the solution to the system of linear equations in equation (17) are then substituted back into equation (14) to predict the peak acceleration as a function of static stress. At this point, the cubic obtained applies only to the data set corresponding to the N data $(\sigma_i, Gexp_i)$ used in equation (17) and this data set is for a particular drop height, cell size, and moisture condition.

Having obtained the cubics for the three different drop heights with the same cell size and moisture content, the next step is to combine the three different cubic equations for these drop heights into one equation which will be valid for a given cell size and moisture content. To do this, the coefficients a, b, c, and d for the three different drop heights of 24, 30, 36 inches, will be replaced by functions a(h), b(h), c(h), and d(h). Again, using the fact that every function has a polynomial series representation, the new coefficient a(h) will be taken as a quadratic in h,

$$a(h) = e + fh + gh^2 \tag{18}$$

with similar expressions for b(h), c(h), and d(h). The three new sub-coefficients, e, f, and g are chosen so that equation (18) produces the correct value for 'a' in the cubic equation (14) when the associated drop height is used. More specifically, starting with the cubic fit equations for the three drop heights h_1, h_2, and h_3,

$$h_1 \; ; \quad G = a_1 + b_1\sigma + c_1\sigma^2 + d_1\sigma^3 \tag{19}$$

$$h_2 \ ; \quad G = a_2 + b_2\sigma + c_2\sigma^2 + d_2\sigma^3 \qquad (20)$$

$$h_3 \ ; \quad G = a_3 + b_3\sigma + c_3\sigma^2 + d_3\sigma^3 \qquad (21)$$

with all a's, b's, c's, and d's known, the coefficients e,f and g in equation (18) must satisfy

$$a_1 = e + fh_1 + gh_1^2 \qquad (22)$$

$$a_2 = e + fh_2 + gh_2^2 \qquad (23)$$

$$a_3 = e + fh_3 + gh_3^2 \qquad (24)$$

Equations (22), (23), and (24) can be written in matrix form as

$$\begin{bmatrix} 1 & h_1 & h_1^2 \\ 1 & h_2 & h_2^2 \\ 1 & h_3 & h_3^2 \end{bmatrix} \begin{bmatrix} e \\ f \\ g \end{bmatrix} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \qquad (25)$$

The solution to this equation will reproduce the original coefficients in the cubics exactly since there are precicely three conditions for three unknowns. Similar procedures hold for b(h), c(h) and d(h). Now the new equation for the peak acceleration G as a function of static stress and drop height is

$$G = (e_1 + f_1h + g_1h^2) + (e_2 + f_2h + g_2h^2)\sigma + (e_3 + f_3h + g_3h^2)\sigma^2 + (e_4 + f_4h + g_4h^2)\sigma^3 \qquad (26)$$

Equation (26) represents the cushion curves for a given cell size and moisture condition. The next and final step is to modify this equation to account for moisture content. Since there were only three moisture contents studied in this research, the procedure used to incorporate moisture content into equation (26) is the same as that used for the three different drop heights. Each of the coefficients e,f,and g in equation (26) is represented by a quadratic equation in the moisture content. For example,

$$e(mc) = p + q(mc) + r(mc^2) \qquad (27)$$

For each of the three different moisture contents, the coefficients p, q, and r are chosen so that the appropriate values of e are obtained. Having done this, a total of 36 coefficients per cell size are needed to generate the Honeycomb cushion curves for the peak acceleration G versus static stress σ as a function of drop height and moisture content. Since these 36 coefficients were determined from 63 total data points, it may be argued that a significant reduction in data set to a simpler form has not been achieved. The true advantage in going to a polynomial fit such as this however is that the resulting equation can be used to interpolate and hopefully extrapolate the original data.

Therefore equation (26) with the e's, f's, and g's replaced by the approprite quadratics in moisture content can be said to represent the cushion curves for each cell size in the range of drop heights from 24 to 36 inches and moisture contents from 5% to 20%. The results of the curve fitting procedure for the 36 coefficients for the 1/2" and 3/4" cell are shown below.

1/2" cell size :

$$\begin{aligned} G = \; & [\; (2141.7 - 586.6335mc + 28.23396mc^2) \\ & + (-131.0519 + 40.1117mc - 1.95597mc^2)h \\ & + (2.187297 - 0.67702mc + 0.033222mc^2)h^2 \;] \\ & + [\; (-5921.151 + 1592.872mc - 74.80475mc^2) \\ & + (403.0712 - 111.7416mc + 5.2735mc^2)h \\ & + (-6.738682 + 1.887945mc - 0.089581mc^2)h^2 \;]\sigma + \ldots \end{aligned}$$

$$
\begin{aligned}
&+ [\ (4278.041 - 1102.514mc + 50.79702mc^2) \\
&\quad + (-296.6764 + 77.60213mc - 3.587287mc^2)h \\
&\quad + (4.973702 - 1.314057mc + 0.0610037mc^2)h^2\ ]\sigma^2 \\
&+ [\ (-869.4235 + 217.7587mc - 9.8961mc^2) \\
&\quad + (60.77629 - 15.36812mc - 0.699846mc^2)h \\
&\quad + (-1.02519 + 0.261585mc - 0.0119425mc^2)h^2\ ]\sigma^3 \qquad (28)
\end{aligned}
$$

3/4" cell size :

$$
\begin{aligned}
G = &\ [\ (3696.99 - 784.0774mc + 37.36841mc^2) \\
&\quad + (-235.6423 - 49.61091mc - 2.393295mc^2)h \\
&\quad + (3.84767 - 0.77626mc + 0.375613mc^2)h^2\ ] \\
&+ [\ (-12776.91 + 2769.62mc - 132.8082mc^2) \\
&\quad + (848.1788 - 179.4374mc + 8.65857mc^2)h \\
&\quad + (-13.97149 + 2.85055mc - 0.13741mc^2)h^2\ ]\sigma \\
&+ [\ (12907.01 - 2889.705mc + 141.7144mc^2) \\
&\quad + (-868.3288 + 189.815mc - 9.344711mc^2)h \\
&\quad + (14.31966 - 3.04068mc + 0.14913mc^2)h^2\ ]\sigma^2 \\
&+ [\ (-4056.462 + 943.0456mc - 47.34888mc^2) \\
&\quad + (273.6282 - 62.48795mc + 3.14268mc^2)h \\
&\quad + (-4.474995 + 1.00335mc - 0.050125mc^2)h^2\ ]\sigma^3 \qquad (29)
\end{aligned}
$$

The predictions of equations (28) and (29) are compared to the experimental data in Figures 5 through 10. Visually, the fit appears to be very good. A quantitative measure of fit is provided by the correlation coefficient [11],

$$R = \sqrt{\frac{\sum[\ Gc - \bar{G}\ ]^2}{\sum[\ Gexp - \bar{G}\ ]^2}} \qquad (30)$$

with

$$\bar{G} = \frac{\sum Gexp}{N} \qquad (31)$$

where N is the total number of data (N = 63 for each cell size), G_{exp} are the experimentally determined shock levels and G_c are the predicted values from the fitted curves. Using the data in Appendix B, the correlation coefficient for the 1/2" cell size was found to be R = 0.9670 and for the 3/4" cell size, R = 0.9927, both of which are considered to be very good [11].

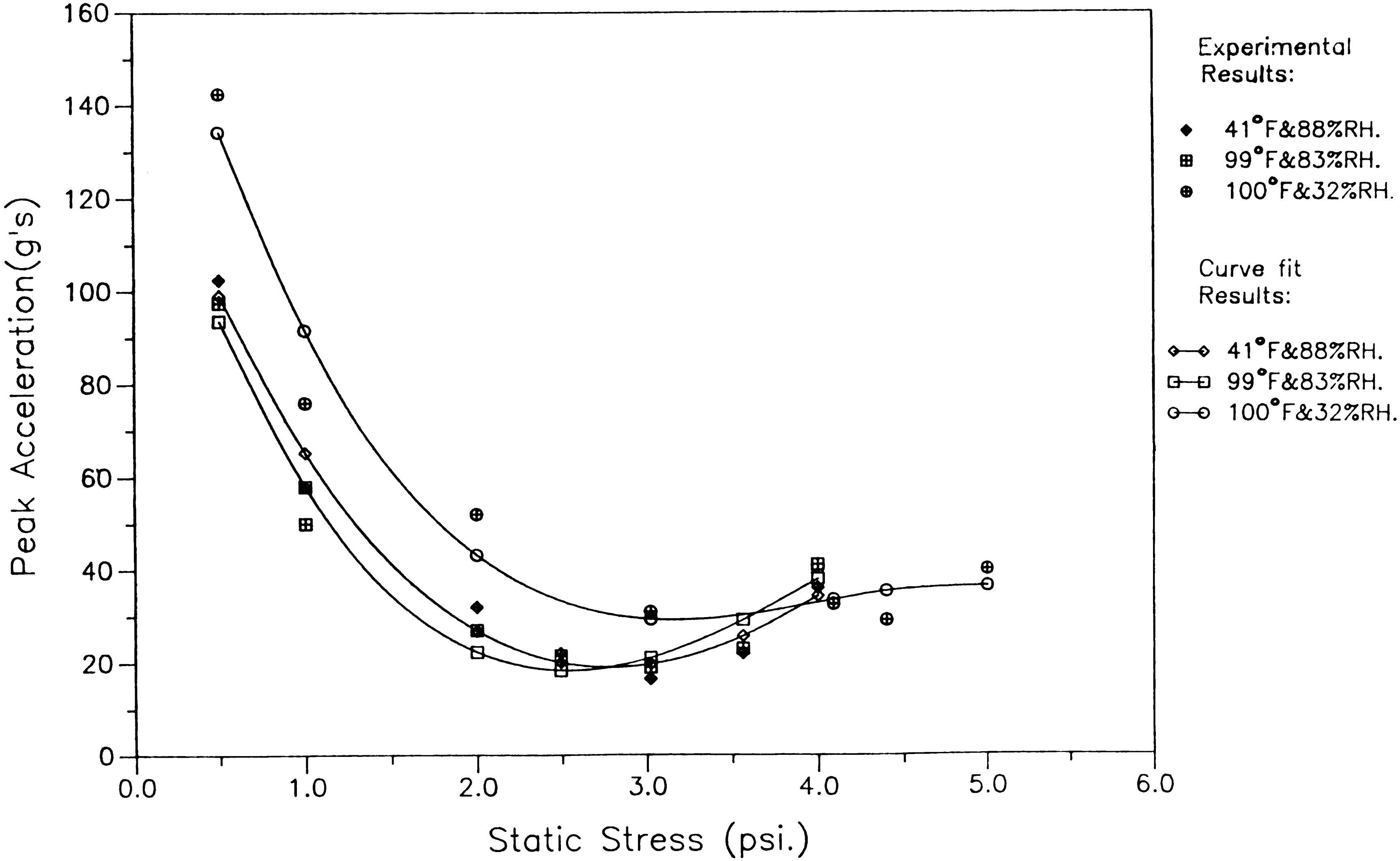


Figure 5 : Comparison between the curve fit and experimental results for the 1/2 inch cell size for a 24 inch drop height at 3 moisture conditions

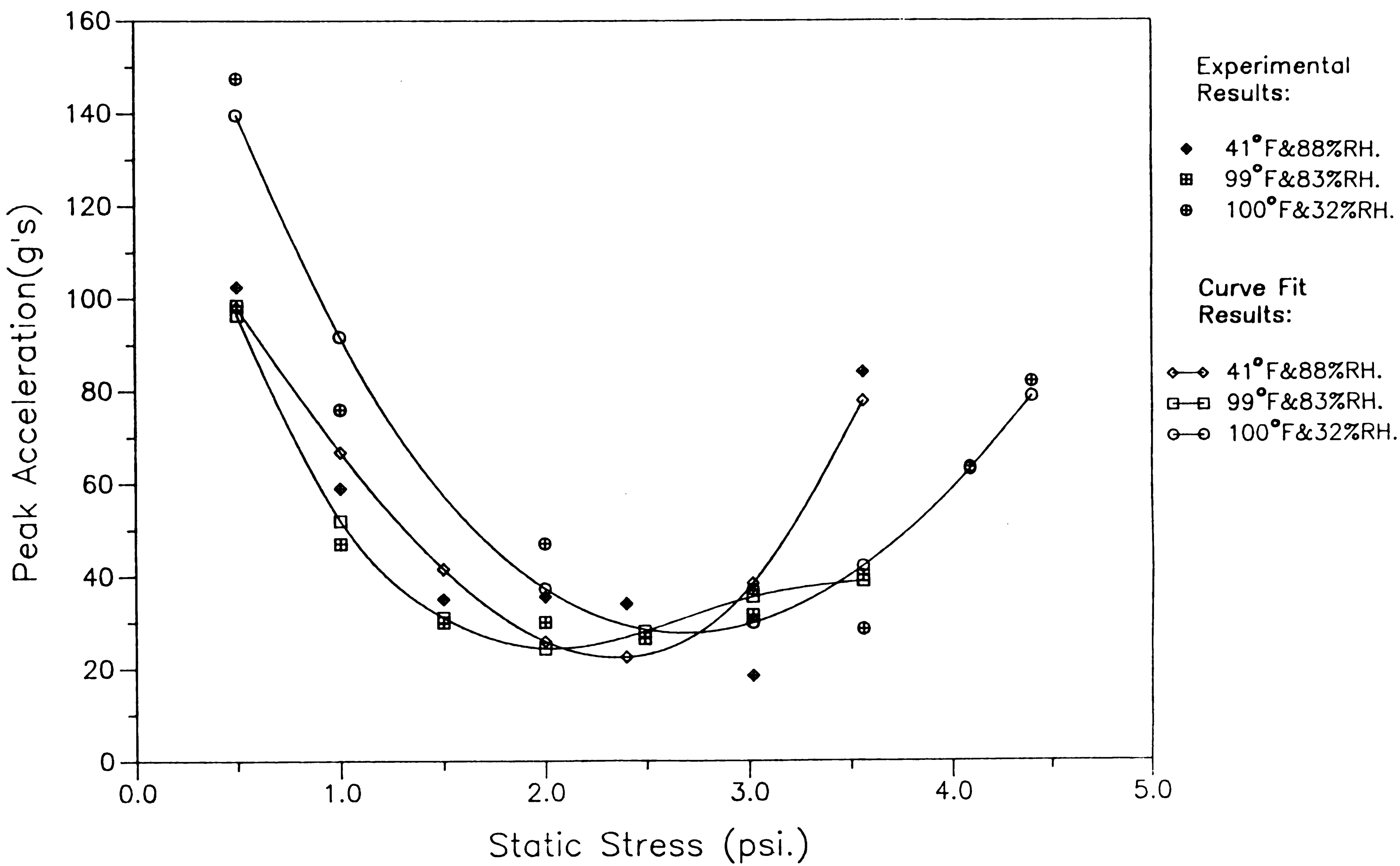


Figure 6 : Comparison between the curve fit and experimental results for the 1/2 inch cell size for a 30 inch drop height at 3 moisture conditions

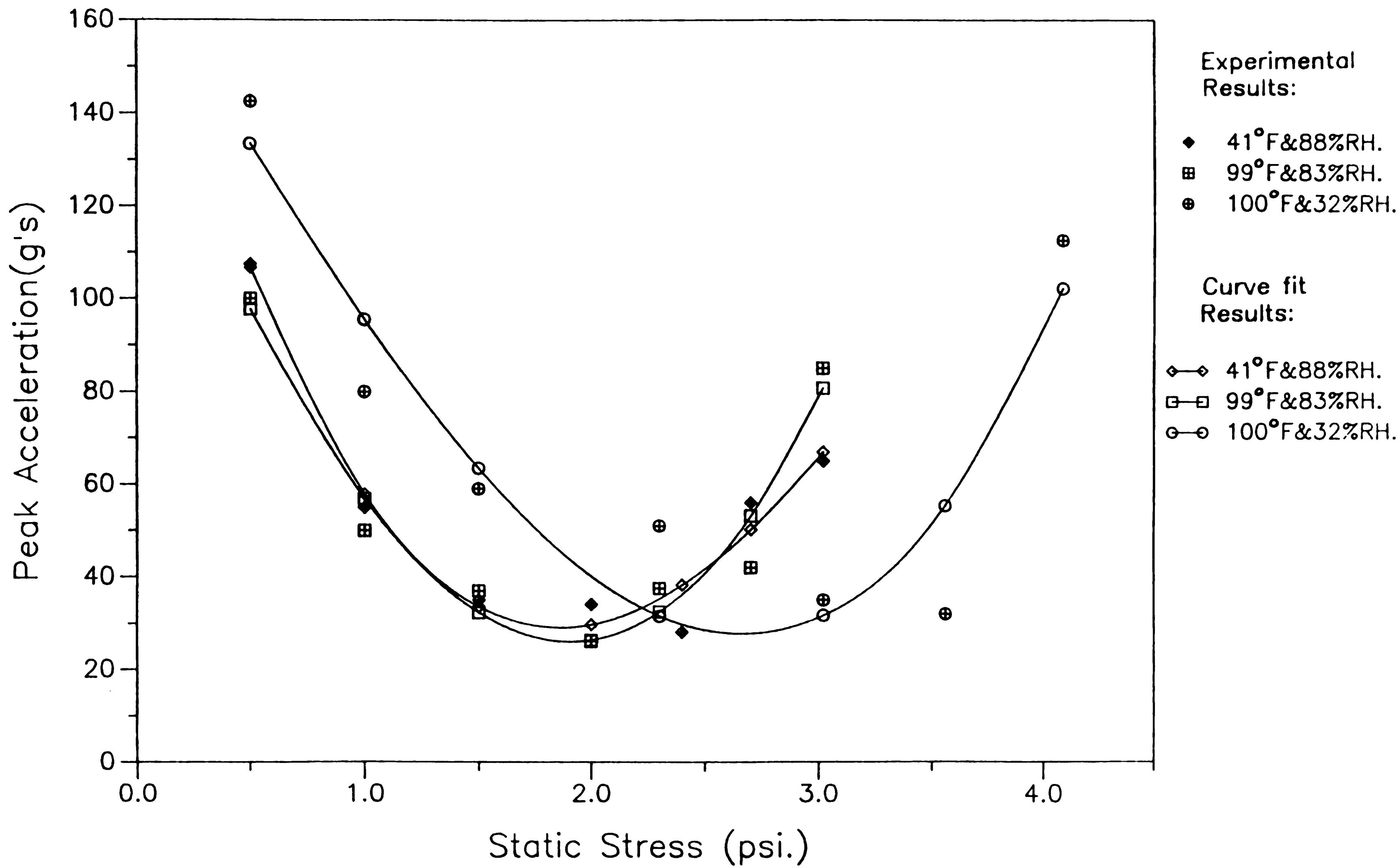


Figure 7 : Comparison between the curve fit and experimental results for the 1/2 inch cell size for a 36 inch drop height at 3 moisture conditions

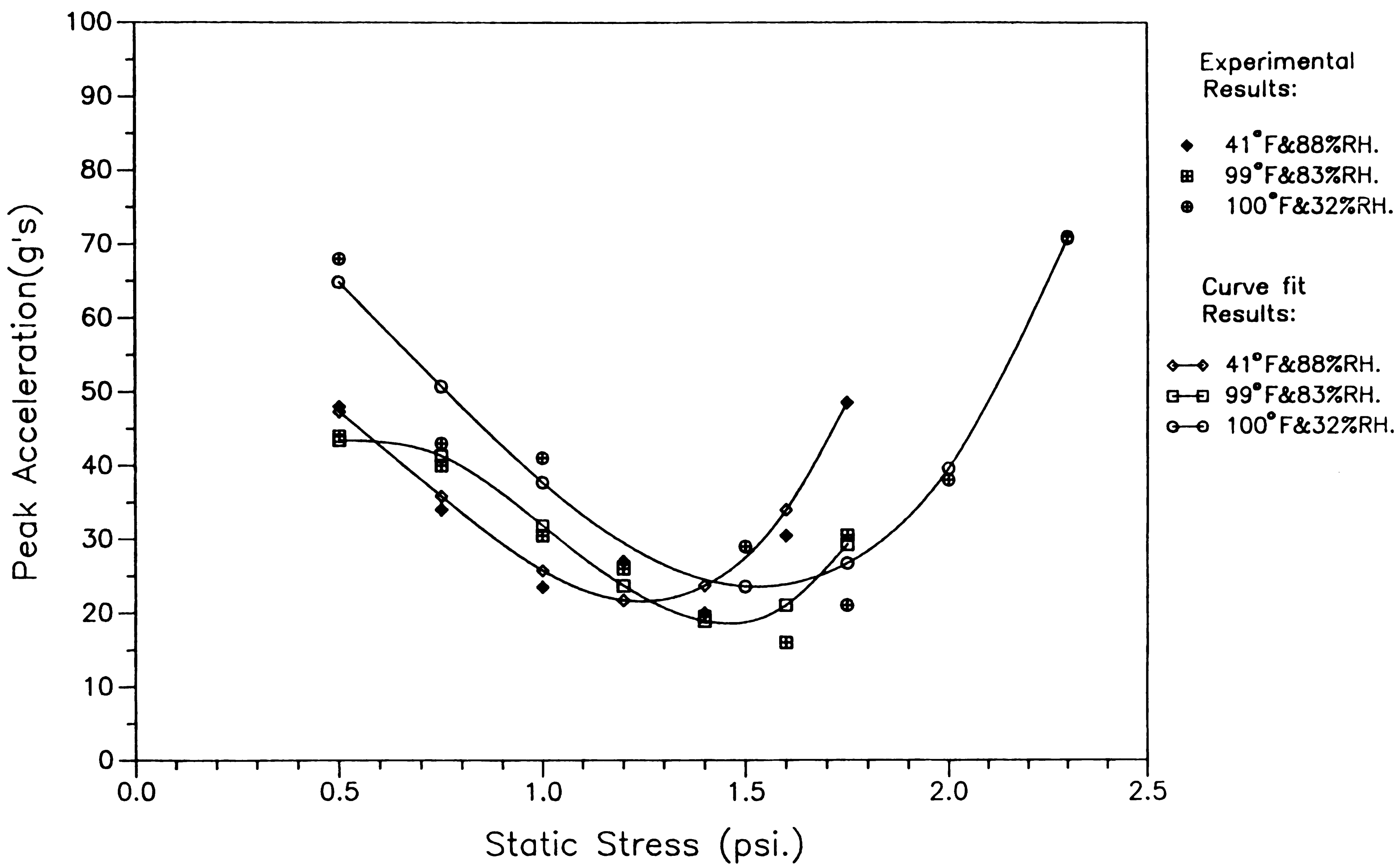


Figure 8 : Comparison between the curve fit and experimental results for the 3/4 inch cell size for a 24 inch drop height at 3 moisture conditions

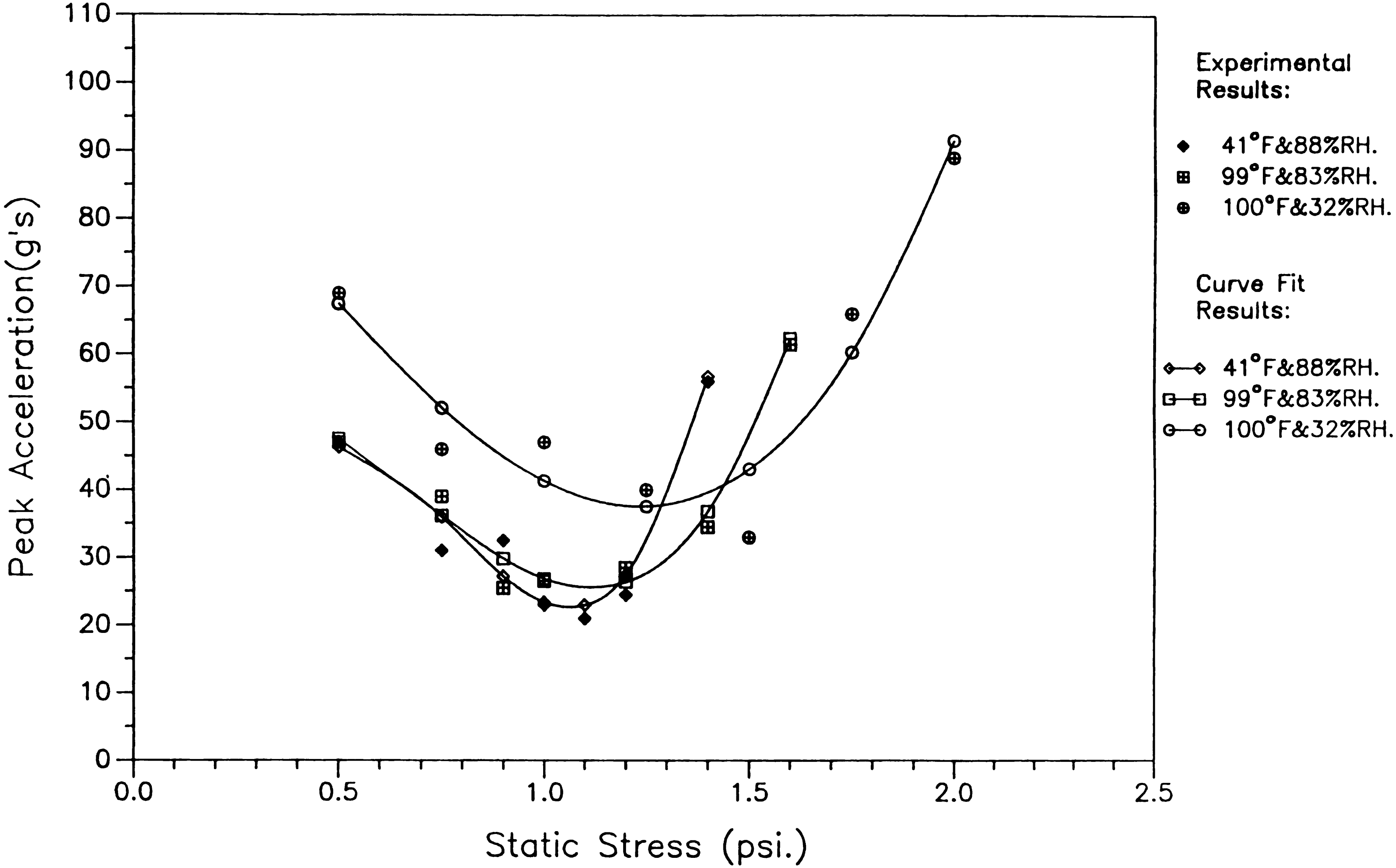


Figure 9 : Comparison between the curve fit and experimental results for the 3/4 inch cell size for a 30 inch drop height at 3 moisture conditions

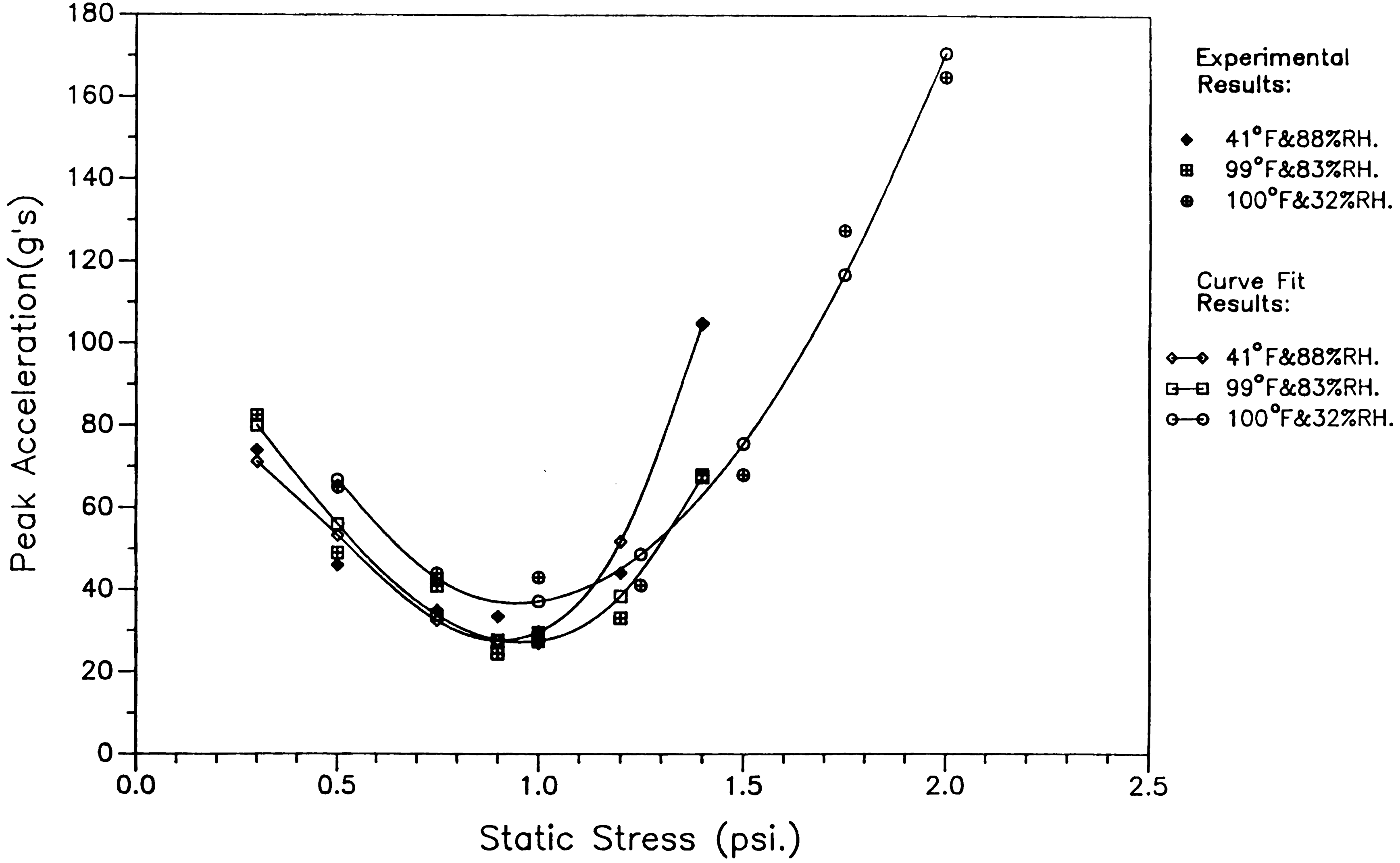


Figure 10 : Comparison between the curve fit and experimental results for the 3/4 inch cell size for a 36 inch drop height at 3 moisture conditions

CHAPTER 5

DISCUSSION AND CONCLUSIONS

Honeycomb cushioning is a unique structure considering the effects of the cell on overall cushion strength. It is because of this structure that certain errors associated with the measurement of shock transmission values are unavoidable. The first of these errors is related to the strength of a normal cell compared to that of a partial cell. If the cells of a specimen are cut during cushion fabrication, the strength of sample will significantly decrease as compared to a foam cushion composed of much smaller cell sizes. The reason for this is the effective bearing area. A partial cell has virtually no strength whatsoever and since the crossectional area of a single cell makes up a significant portion of the actual load bearing area, the overall effect of an edge of severed cells considerably reduces the true bearing area. For example, for an 8"×8" sample with 1/2" cells where all four edges have been cut, the apparent bearing area is 64 $inch^2$ and the true bearing area is 55.2044 ± 16% $inch^2$. For the 3/4" cell size, the true bearing area is 51.1426 ± 25% $inch^2$. These areas were determined by subtracting the area associated with the row of cut cells along the perimeter from the apparent bearing area. The shape of the cell used in this calculation was taken from actual measurements. For the 1/2" cell, an ellipse with diameters 0.5" and 0.6875" was used and for 3/4" cell, an ellipse with diameters 0.75" and 1.0625". Evidently, the smaller the sample size, the more effect the loss of the partial borderline cells has on bearing area.

Another source of error is the compound instrument error associated with the signal sent from the accelerometer to the oscilloscope. From section 2.4 under apparatus used in the Drop Test, the errors associated with the accelerometer, coupler, oscilloscope and the width of the trace are ±2%, ±5%, ±3%, and ±6.25, respectively. The compound signal error is therefore ±16.25. The errors associated with the cushion curves themselves may therefore be split into two parts : the error on G is ±16.25% and the error on static loading is ±16% for the 1/2" cell size and ±25% for the 3/4" cell size.

The effect of moisture is evident on both the crushing strength and on the cushion curves. Since moisture weakens the fibers in paper, both the crushing strength and the shock transmission properties tend to decrease. In general, the effect of moisture content can be assessed by examining the rate of change of G with respect to mc in the fitted curve. For example, for the 1/2" cell size, from equation (28)

$$
\begin{aligned}
\frac{\partial G}{\partial mc} = {} & [\ (-586.6335 + 56.46792mc) + (40.1117 - 3.91194mc)h \\
& \quad + (-0.67702 + 0.066444mc)h^2\ ] \\
& + [\ (1592.872 - 149.6095mc) + (-111.7416 + 10.547mc)h \\
& \quad + (1.887945 - 0.179162mc)h^2\ ]\sigma \\
& + [\ (-1102.514 + 101.59404mc) + (77.60213 - 7.174574mc)h \\
& \quad + (-1.314057 + 0.1220074mc)h^2\ ]\sigma^2 + \ldots
\end{aligned}
$$

$$+ \left[\; (217.7587 - 19.7922mc) + (-15.36812 - 1.399692mc)h + (0.261585 - 0.023885mc)h^2 \; \right] \sigma^3 \qquad (32)$$

Using values for mc in the range studied (5.56% to 18.28%) and drop heights h in the range 24" to 36", the value for $\partial G/\partial mc$ is always negative which shows that the peak acceleration decreases when the moisture content increases in agreement with the experimental results.

The average percent difference between the curve fit and experimental results for the 1/2" cell size is 15.189% and for the 3/4" cell size is 9.253%. The maximum percent difference for the 1/2" cell size is 107.492% and for the 3/4" cell size is 31.306%. Most of the high percent difference points occurred at the low points of the curves where the values of peak acceleration were low. Even though the maximum percent difference for the 1/2" cell size was very high, there were only two results that exceeded 50 percent difference which was most likely the result of an error in collecting the experimental data. All of these percentages were based directly on the experimental results without considering experimental errors which can be as much as ±16.25% for G. By varying each experimental G up to ±16.25% to obtain the best and worst agreement with the fitted curve, the average minimum and maximum percent differences were recalculated. The average minimum difference was 4.523% for the 1/2" cell size and 0.821% for the 3/4" cell size and the average maximum difference was 32.396% for 1/2" cell size and 26.735% for 3/4" cell size. Both are still acceptable.

The curve fitting method is not a mathematical model which means that its validity is limited to the range of experimental data collected. Equations (28) and (29) can be used to predict the peak acceleration within the range of experimental drop heights and moisture contents studied. It is hoped that these equations can also be used to extrapolate the data for moisture contents below 5% and above 20% and for drop heights less than 24" and above 36". Equation (28) was used to predict the shock transmission value for the 1/2" cell size with an 8% moisture content in an 18" drop with a static loading of 2 psi. The predicted result of 50 g's was lower than the experimental result of 62 g's with a percent difference of 24.792% which is within the limits of accuracy for the cushion curve equations.

APPENDICES

APPENDIX A

DATA TABLES

Table 3 Data for the moisture content for the 3/4 inch and 1/2 inch cell sizes at the 4 moisture conditions

Condition	Cell Size (inch)	Sample No.	%mc 7days	%mc 14days
100°F&32%RH.	3/4	1	5.64	5.37
		2	5.396	5.15
	1/2	1	5.80	5.62
		2	5.83	5.49
99°F&83%RH.	3/4	1	14.19	14.41
		2	14.27	14.27
	1/2	1	13.91	14.65
		2	13.77	14.65
41°F&88%RH.	3/4	1	17.94	19.13
		2	17.95	19.32
	1/2	1	18.05	18.29
		2	17.71	18.27
Freezer(5°F)	3/4	1	14.51	15.31
		2	14.87	15.97
	1/2	1	15.66	15.79
		2	15.43	15.93

Table 4.A Data for the initial peak stress and strain for the 3/4 inch cell size at 4 moisture conditions

Condition	Sample No.	Stress(psi.)	strain(%)
100°F&32%RH.	1	24.33	0.050
	2	24.67	0.043
	3	23.61	0.047
	4	24.59	0.043
	5	25.00	0.043

Table 4.A (continued)

99°F&83RH.	1	13.73	0.030
	2	13.91	0.027
	3	14.36	0.030
	4	14.77	0.027
	5	14.86	0.027
41°&88%RH.	1	13.42	0.030
	2	13.92	0.027
	3	12.59	0.033
	4	13.20	0.030
	5	12.86	0.027
FREEZER(5°F)	1	12.81	0.040
	2	14.69	0.030
	3	14.02	0.043
	4	14.08	0.033
	5	14.52	0.050

Table 4.B Data for the initial peak stress and strain for the 1/2 inch cell size at 4 moisture conditions

Condition	Sample No.	Stress(psi.)	strain(%)
100°F&32%RH.	1	52.75	0.057
	2	53.14	0.047
	3	52.38	0.047
	4	51.83	0.043
	5	49.56	0.043
99°F&83%RH.	1	33.75	0.033
	2	33.08	0.040
	3	32.34	0.040
	4	31.47	0.040
	5	30.80	0.037
41°F&88%RH.	1	23.91	0.033
	2	23.81	0.033
	3	25.09	0.033
	4	25.78	0.037
	5	-	-
FREEZER(5°F)	1	28.91	0.047
	2	30.38	0.037
	3	31.17	0.040
	4	27.89	0.037
	5	30.33	0.033

Table 5.A Shock transmission data for the 3/4 inch cell size for a 24 inch drop height for 4 moisture conditions

Condition	Static Stress (psi.)	Sample No.	G
100°F&32%RH.	0.5	1	68
		2	68
	0.75	1	42
		2	44
	1.0	1	44
		2	38
	1.5	1	30
		2	28
	1.75	1	20
		2	22
	2.0	1	36
		2	40
	2.3	1	74
		2	68
99°F&83%RH.	0.5	1	42
		2	46
	0.75	1	40
		2	40
	1.0	1	30
		2	31
	1.2	1	27
		2	25
	1.4	1	20
		2	19
	1.6	1	17
		2	15
	1.75	1	31
		2	30
41°F&88%RH.	0.5	1	50
		2	46
	0.75	1	34
		2	34
	1.0	1	24
		2	23
	1.2	1	28
		2	26
	1.4	1	20
		2	20
	1.6	1	30
		2	31
	1.75	1	47
		2	50

Table 5.A (continued)

FREZZER(5°F)	0.5	1	58
		2	52
	0.75	1	54
		2	54
	1.0	1	30
		2	30
	1.25	1	40
		2	42
	1.5	1	28
		2	28
	1.75	1	30
		2	30
	2.0	1	60
		2	50

Table 5.B Shock transmission data for the 3/4 inch cell size for a 30 inch drop height for 4 moisture conditions

Condition	Static Stress (psi.)	Sample No.	G
100°F&32%RH.	0.5	1	68
		2	70
	0.75	1	48
		2	44
	1.0	1	50
		2	44
	1.25	1	38
		2	42
	1.5	1	30
		2	36
	1.75	1	68
		2	64
	2.0	1	90
		2	88
99°F&83%RH.	0.5	1	46
		2	48
	0.75	1	40
		2	38
	0.9	1	25
		2	26
	1.0	1	28
		2	25
	1.2	1	28
		2	29
	1.4	1	33
		2	36

Table 5.B (continued)

	1.6	1	65
		2	58
41°F&88%RH.	0.5	1	48
		2	46
	0.75	1	32
		2	30
	0.9	1	34
		2	31
	1.0	1	24
		2	22
	1.1	1	20
		2	22
	1.2	1	26
		2	23
	1.4	1	54
		2	58
FREEZER(5°F)	0.3	1	90
		2	92
	0.5	1	56
		2	60
	0.75	1	56
		2	58
	1.0	1	28
		2	26
	1.25	1	42
		2	42
	1.5	1	30
		2	28
	1.75	1	88
		2	82

Table 5.C Shock transmission data for the 3/4 inch cell size for a 36 inch drop height for 4 moisture conditions

Condition	Static Stress (psi.)	Sample No.	G
100°F&32%RH.	0.5	1	64
		2	66
	0.75	1	44
		2	44
	1.0	1	44
		2	42
	1.25	1	40
		2	42
	1.5	1	68
		2	68

Table 5.C (continued)

	1.75	1	130
		2	125
	2.0	1	170
		2	160
99°F&83%RH.	0.3	1	80
		2	85
	0.5	1	50
		2	48
	0.75	1	40
		2	42
	0.9	1	24
		2	25
	1.0	1	27
		2	32
	1.2	1	32
		2	34
	1.4	1	72
		2	64
41°F&88%RH.	0.3	1	72
		2	76
	0.5	1	48
		2	44
	0.75	1	36
		2	34
	0.9	1	35
		2	32
	1.0	1	28
		2	26
	1.2	1	42
		2	46
	1.4	1	100
		2	110
FREEZER(5°F)	0.3	1	88
		2	90
	0.5	1	54
		2	56
	0.75	1	56
		2	54
	1.0	1	26
		2	28
	1.25	1	40
		2	44
	1.5	1	84
		2	80
	1.75	1	160
		2	150

<u>Table 6.A</u> **Shock transmission data for the 1/2 inch cell size for a 24 inch drop height for 4 moisture conditions**

Condition	Static Stress (psi.)	Sample No.	G
100°F&32%RH.	0.5	1	140
		2	145
	1.0	1	78
		2	74
	2.0	1	50
		2	54
	3.02	1	32
		2	30
	4.09	1	30
		2	35
	4.4	1	26
		2	32
	5.0	1	40
		2	40
99°F&83%RH.	0.5	1	98
		2	97
	1.0	1	52
		2	48
	2.0	1	30
		2	24
	2.49	1	20
		2	23
	3.02	1	18
		2	20
	3.56	1	24
		2	22
	4.0	1	42
		2	40
41°F&88%RH.	0.5	1	105
		2	100
	1.0	1	58
		2	58
	2.0	1	32
		2	32
	2.49	1	20
		2	24
	3.02	1	15
		2	18
	3.56	1	24
		2	20
	4.0	1	38
		2	34

Table 6.A (continued)

FREEZER(5°F)	0.5	1	130
		2	125
	1.0	1	80
		2	76
	2.0	1	36
		2	38
	3.02	1	34
		2	32
	4.0	1	20
		2	18
	4.4	1	45
		2	40
	5.0	1	72
		2	75

Table 6.B Shock transmission data for the 1/2 inch cell size for a 30 inch drop height for 4 moisture conditions

Condition	Static Stress (psi.)	Sample No.	G
100°F&32%RH.	0.5	1	150
		2	145
	1.0	1	76
		2	76
	2.0	1	44
		2	50
	3.02	1	38
		2	36
	3.56	1	30
		2	27
	4.09	1	65
		2	62
	4.4	1	84
		2	80
99°F&83%RH.	0.5	1	100
		2	97
	1.0	1	46
		2	48
	1.5	1	32
		2	28
	2.0	1	32
		2	28
	2.49	1	28
		2	25
	3.02	1	31
		2	32

Table 6.B (continued)

	3.56	1	42
		2	38
41°F&88%RH.	0.5	1	105
		2	100
	1.0	1	60
		2	58
	1.5	1	34
		2	36
	2.0	1	35
		2	36
	2.4	1	34
		2	34
	3.02	1	20
		2	17
	3.56	1	88
		2	80
FREEZER(5°F)	0.5	1	138
		2	135
	1.0	1	78
		2	74
	2.0	1	44
		2	44
	2.49	1	30
		2	30
	3.02	1	30
		2	36
	3.56	1	34
		2	32
	4.0	1	74
		2	78

Table 6.C Shock transmission data for the 1/2 inch cell size for a 36 inch drop height for 4 moisture conditions

Condition	Static Stress (psi.)	Sample No.	G
100°F&32%RH.	0.5	1	150
		2	135
	1.0	1	80
		2	80
	1.5	1	60
		2	58
	2.3	1	52
		2	50
	3.02	1	36

Table 6.C (continued)

		2	40
	3.56	1	35
		2	29
	4.09	1	115
		2	110
99°F&83%RH.	0.5	1	100
		2	100
	1.0	1	52
		2	48
	1.5	1	40
		2	34
	2.0	1	26
		2	26
	2.3	1	38
		2	37
	2.703	1	44
		2	40
	3.02	1	82
		2	88
41°F&88%RH.	0.5	1	105
		2	110
	1.0	1	56
		2	54
	1.5	1	34
		2	36
	2.0	1	34
		2	34
	2.4	1	28
		2	28
	2.7	1	58
		2	54
	3.02	1	66
		2	64
FREEZER(5°F)	0.5	1	130
		2	130
	1.0	1	72
		2	76
	1.5	1	42
		2	42
	2.0	1	36
		2	40
	2.49	1	36
		2	34
	3.02	1	40
		2	40
	3.56	1	90
		2	80

APPENDIX B

THE CORRELATION COEFFICIENTS

The correlation coefficients for the 1/2" and 3/4" cell size between the experiment data and calculated data using equations (28) and (29) are determined as shown below

$$\bar{G} = \frac{\sum Gexp}{N} \tag{B-1}$$

$$R = \sqrt{\frac{\sum[\ Gc - \bar{G}\ ]^2}{\sum[\ Gexp - \bar{G}\ ]^2}} \tag{B-2}$$

where R = correlation coefficient
Gexp = experimental peak acceleration (g's)
Gc = calculated peak acceleration (g's)
N = number of total data (63 for each cell size)

Table 7 Comparison between experimental and calculated data and the correlation coefficient for the 3/4 inch cell size

No.	Gexp	Gc	% Difference
1	64.841	68.0	4.646
2	50.713	43.0	17.937
3	37.697	41.0	8.065
4	23.561	29.0	18.755
5	26.721	21.0	27.243
6	39.555	38.0	4.092
7	70.736	71.0	0.372
8	67.443	69.0	2.257
9	52.048	46.0	13.148
10	41.307	47.0	12.113
11	37.553	40.0	6.117
12	43.120	33.0	30.667
13	60.343	66.0	8.571
14	91.556	89.0	2.872
15	66.731	65.0	2.663
16	42.717	44.0	2.916

Table 7 (continued)

17	37.133	43.0	13.644
18	48.565	41.0	18.451
19	75.595	68.0	11.169
20	116.810	127.5	8.384
21	170.794	165.0	3.512
22	43.453	44.0	1.243
23	41.270	40.0	3.175
24	31.810	30.5	4.295
25	23.673	26.0	8.950
26	18.886	19.5	3.149
27	21.009	16.0	31.306
28	29.276	30.5	4.013
29	47.500	47.0	1.064
30	36.200	39.0	7.179
31	29.820	25.5	16.941
32	26.848	26.5	1.313
33	26.386	28.5	7.418
34	36.798	34.5	6.661
35	62.362	61.5	1.402
36	80.059	82.5	2.959
37	55.930	49.0	14.143
38	33.874	41.0	17.380
39	27.691	24.5	13.024
40	27.452	29.5	6.942
41	38.340	33.0	16.182
42	67.412	68.0	0.865
43	47.283	48.0	1.494
44	35.799	34.0	5.291
45	25.737	23.5	9.519
46	21.696	27.0	19.644
47	23.680	20.0	18.400
48	33.963	30.5	11.354
49	48.490	48.5	0.021
50	46.283	47.0	1.526
51	35.952	31.0	15.974
52	27.201	32.5	16.305
53	23.404	23.0	1.757
54	22.973	21.0	9.395
55	27.395	24.5	11.816
56	56.750	56.0	1.339
57	71.163	74.0	3.834
58	53.185	46.0	15.620
59	32.511	35.0	7.111
60	27.582	33.5	17.666
61	29.675	27.0	9.907
62	51.656	44.0	17.400
63	104.606	105.0	0.375

The average percent difference is 9.253%
The maximum percent difference is 31.306%.
The correlation coefficient is - 0.9927

Table 8 Comparison between experimental and calculated data and the correlation coefficient for the 1/2 inch cell size

No.	Gexp	Gc	% Difference
1	134.268	142.5	5.777
2	91.648	76.0	20.589
3	43.200	52.0	16.923
4	29.345	31.0	5.339
5	33.474	32.5	2.997
6	35.279	29.0	21.652
7	36.430	40.0	8.925
8	139.588	147.5	5.364
9	91.708	76.0	20.668
10	37.245	47.0	20.755
11	29.870	37.0	19.270
12	42.111	28.5	47.756
13	63.042	63.5	0.721
14	78.787	82.0	3.918
15	133.420	142.5	6.372
16	95.549	80.0	19.436
17	63.455	59.0	7.551
18	31.445	51.0	38.343
19	31.640	35.0	9.600
20	55.303	32.0	72.822
21	102.101	112.5	9.244
22	93.623	97.5	3.976
23	58.010	50.0	16.020
24	22.336	27.0	17.274
25	18.335	21.5	14.721
26	21.114	19.0	11.126
27	29.168	23.0	26.817
28	37.914	41.0	7.527
29	96.389	98.5	2.143
30	51.977	47.0	10.589
31	30.097	30.0	0.323
32	24.306	30.0	18.980
33	28.028	26.5	5.766
34	35.467	31.5	12.594
35	38.950	40.0	2.625
36	97.738	100.0	2.262
37	56.902	50.0	13.804
38	32.322	37.0	12.643
39	26.255	26.0	0.981
40	32.440	37.5	13.493
41	53.159	42.0	26.569
42	80.705	85.0	5.053
43	99.071	102.5	3.345
44	65.291	58.0	12.571
45	26.891	32.0	15.966

Table 8 (continued)

46	20.018	22.0	9.009
47	19.739	16.5	19.630
48	25.705	22.0	16.841
49	34.224	36.0	4.933
50	97.957	102.5	4.432
51	66.800	59.0	13.220
52	41.536	35.0	18.674
53	25.797	35.5	27.332
54	22.503	34.0	33.815
55	38.386	18.5	107.492
56	77.740	84.0	7.452
57	106.727	107.5	0.719
58	57.870	55.0	5.218
59	33.565	35.0	4.100
60	29.594	34.0	12.959
61	38.222	28.0	36.507
62	50.164	56.0	10.421
63	66.931	65.0	2.971

The average percent difference is 15.189%
The maximum percent difference is 107.492%
The correlation coefficient is = 0.9672

APPENDIX C

THE COMPUTER PROGRAM FOR THE CURVE FIT COEFFICIENTS

```
10  REM " PROGRAM FOR PREDICTING SHOCK TRANSMISSION VALUES FOR HONEYCOMB
          CUSHION "
20  DIM S(10)
30  PRINT " INPUT CELL SIZE OF THE HONEYCOMB IN INCH (0.5 OR 0.75)
40  INPUT Z
50  IF Z = 0.5 OR 0.75 THEN GOTO 60 ELSE PRINT " YOUR SELECTED CELL SIZE
    IS NOT AVAILABLE ,TRY AGAIN !! " ; GOTO 30
60  PRINT " INPUT MOISTURE CONTENT IN PERCENT AND DROP HEIGHT IN INCHES"
70  INPUT MC,H
80  PRINT " HOW MANY STATIC STRESS POINTS DO YOU WANT ? "
90  INPUT N
100 PRINT " INPUT THE STATIC STRESSES "
110  FOR I = TO N
120   INPUT S(I)
130  NEXT I
140 IF Z = 0.5 THEN GOSUB 500
150 IF Z = 0.75 THEN GOSUB 800
160  A = E1 + F1*H + G1*H^2
170  B = E2 + F2*H + G2*H^2
180  C = E3 + F3*H + G3*H^2
190  D = E4 + F4*H + G4*H^2
200 LPRINT
210 LPRINT
220 LPRINT " HONEYCOMB CUSHION CELL SIZE =";Z " INCH"
230 LPRINT " MOISTURE CONTENT =";MC "%  AT DROP HEIGHT =";H  "INCHES"
240 LPRINT
250 LPRINT " STATIC STRESS (psi.)            G (g's)"
260  FOR I = 1 TO N
270    G = A + B*S(I) + C*S(I)^2 + D*S(I)^3
280    LPRINT USING "       ##.##        ";S(I);
290    LPRINT USING "     ####.###";G
300  NEXT I
310 END
500 E1 = 2141.7 - 586.6335*(MC) + 28.23396*(MC^2)
510 F1 = -131.05190 + 40.1117*(MC) - 1.95597*(MC^2)
520 G1 = 2.187297 - 0.67702*(MC) + 0.033222*(MC)
530 E2 = -5921.151 + 1592.872*(MC) - 74.80475*(MC^2)
540 F2 = 403.0712 - 111.7416*(MC) + 5.2735*(MC^2)
550 G2 = -6.738682 + 1.887945*(MC) - 0.089581*(MC^2)
560 E3 = 4278.041 - 1102.514*(MC) + 50.79702*(MC^2)
570 F3 = -296.6764 + 77.60213*(MC) - 3.587287*(MC^2)
580 G3 = 4.973702 - 1.314057*(MC) + 0.0610037*(MC^2)
```

Appendix C (continued)

```
590 E4 = -869.4235 + 217.7587*(MC) - 9.8961*(MC^2)
600 F4 = 60.77629 - 15.36812*(MC) + 0.699846*(MC^2)
610 G4 = -1.02519 + 0.261585*(MC) - 0.0119425*(MC^2)
620 RETURN
800 E1 = 3696.99 - 784.0774*(MC) + 37.36841*(MC^2)
810 F1 = -235.6423 - 49.61091*(MC) - 2.393295*(MC^2)
820 G1 = 3.84767 - 0.77626*(MC) + 0.375613*(MC^2)
830 E2 = -12776.91 + 2769.62*(MC) - 132.8082*(MC^2)
840 F2 = 848.1788 - 179.4374*(MC) + 8.65857*(MC^2)
850 G2 = -13.97149 + 2.85055*(MC) - 0.13741*(MC^2)
860 E3 = 12907.01 - 2889.705*(MC) + 141.7144*(MC^2)
870 F3 = -868.3288 + 189.815*(MC) - 9.344711*(MC^2)
880 G3 = 14.31966 - 3.04068*(MC) + 0.14913*(MC^2)
890 E4 = -4056.462 + 943.0456*(MC) - 47.34888*(MC^2)
900 F4 = 273.6282 - 62.48795*(MC) + 3.14268*(MC^2)
910 G4 = -4.474995 + 1.00335*(MC) - 0.050125*(MC^2)
920 RETURN
```

APPENDIX D

METHODS OF MANUFACTURING HONEYCOMB MATERIALS

There are two main methods that are used to manufacture Honeycomb materials, the expansion process and the corrugation process. The expansion process is the most commonly used. All of the samples used in this research were made by this process. The corrugation process is mainly used for higher density honeycomb materials. Both of these processes are briefly described below in reference to Figure 11.

Expansion Process : Fabrication starts with paper sheeting cut from web stock on which adhesive node lines have already been placed. Layers of these sheets are stacked on top of each other with alternating glue lines and cured to form the block. The block is then cut to the required dimensions and the stack is expanded by pulling it apart. The cell size of the Honeycomb is controlled by the distance between the glue lines and by the amount of expansion.

Corrugation Process : Here the web is first passed through corrugating rolls to form the corrugated sheet and then the corrugated sheets are stacked, glued, and cured. The core thickness, width, and length are then cut directly from the Honeycomb block.

Illustrations for both processes are shown in Figure 11.

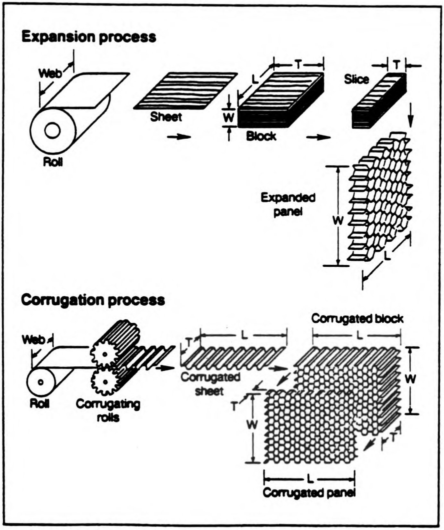


Figure 11 : Methods of manufacturing Honeycomb materials [12]

LIST OF REFERENCES

LIST OF REFERENCES

1. Karnes, C.H., J.W. Turnbow, E.A. Ripperger, and J.N. Thompson, "High- Velocity Impact Cushioning, Part IV, The Effect of Moisture Content and Impact Velocity on Energy-Absorption Characteristics of Paper Honeycomb", Structural Mechanics Research Laboratory, The University of Texas, Austin, May 1, 1959.

2. Karnes, C.H., J.W. Turnbow, E.A. Ripperger, J.N. Thompson, " High Velocity Impact Cushioning, Part V, Energy Absorption Characteristics of Paper Honeycomb", Structural Mechanics Research Laboratory, The University of Texas, Austin, May 1959.

3. Hopf, J.P., "Equilibrium Moisture Content of Paper Honeycomb and Its Effect on Energy Absorbtion", Forest Products Laboratory, Project No. 7-87-03-004B, Report NO.1, December 1955.

4. Ripperger, E.A., "Energy Absorption Characteristics of Paper Honeycomb", Engineering Mechanics Research Laboratory, The University of Texas, Austin, May 18, 1967.

5. Singh, S.P., N. Graham, J. Cornell, "Cushion Testing of Kraft Paper Honeycomb", School of Packaging, Michigan State University, April 1986.

6. Witting, R.H., "Investigation of Paperboard Honeycomb Material for Use as Cushioning in Aerial Delivery of Supplies And Equipment", Quatermaster Food and Container Institute for the Armed Forces, Project No. 7-87-03-002, March 9, 1954.

7. ASTM D 644-55, "Determining Moisture Content of Paper Material by Oven Drying", American Society for Testing and Materials, 1982.

8. ASTM D 1596-78a, "Test Method for Shock Absorbing Characteristics of Package Cushion Materials", American Society for Testing and Materials, 1983.

9. Taw, N.K., "Developing a Mathematical Model For a 45 Degree Edge Drop to Predict the Dynamic Behavior of a Low Density Closed-Cell Foam", Master's Thesis, School of Packaging, Michigan State University, 1988.

10. Spiegel, R.M., "Theory and Problems of Advance Calculus", Schaum Publishing Company, New York, 1963.

11. Freund, E.J., "Modern Elementary Statistics", Sixth Edition, Prentice-Hall, Inc., New Jersey, 1984.

12. English, K.L., "Honeycomb : Million-Year Old Material of the Future", Materials Engineering, January 1985, P.29-33.