Energy Absorbing Sandwich Structures Under Blast Loading

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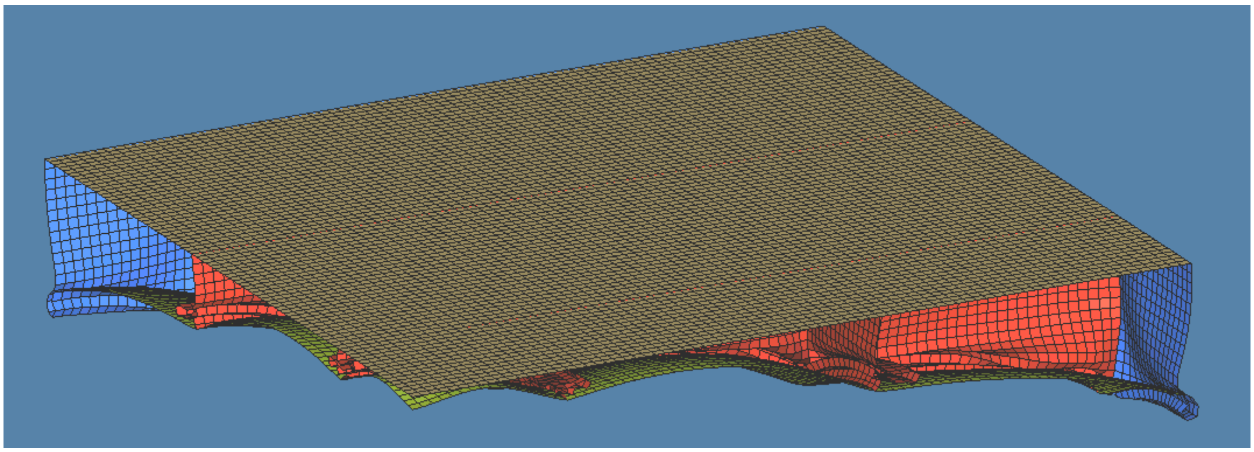


Abstract

A recent experimental study at the Army Research Laboratories shows that flat panels with various foam or honeycomb faceplates transferred more energy to a structure under blast loading relative to a structure without an energy absorbing faceplate. Ideally, the foam or honeycomb material should transfer less energy to the structure since it absorbs energy while it deforms plastically. Non-uniform deformation of the energy absorbing material may lead to increased pressure on the panel, causing kinetic energy transfer to the plate. One objective of this work is to simulate the non-uniform response of the honeycomb panel subject to blast loading. Most of the work involves an investigation into the optimum design of the honeycomb structure for energy absorption during blast loading. In this paper, only a square-celled honeycomb structure is studied. Variables under investigation for this paper are the core and face sheet thicknesses of the honeycomb sandwich structure. Results of a DOE study are attained, which evaluate the relative contribution of panel variables to energy absorption. Also, the results of a preliminary optimization study are discussed along with some of problems faced during this study.

Introduction

Honeycomb sandwich structures with buckling (crushing) cores are broadly employed as the main load bearing members of structures since they have a high-strength-to-weight-ratio and excellent energy absorption capabilities under dynamic loading conditions. The core of the sandwich structure can sustain large deformations (strains) under a constant load enabling it to absorb energy. Additional energy is also absorbed by the face sheets if significant bending or stretching occurs in the structure. The use of sandwich panels might be an effective method to mitigate or reduce the damaging effects of blast loading on vehicle or building structures. Several research studies have investigated this phenomenon.

Many commercially available honeycomb and foam materials can be used for energy absorbing structures. The U.S. Army Research Laboratories (ARL) and others have experimentally investigated the effects of panel geometry and core material properties on the dynamic response of ballistic pendulums to blast loads. Unpredictably, the flat foam and honeycomb-faced panels transmitted more energy to the pendulum than a flat rigid panel without energy absorbing material on the blast face. This phenomenon may be due to the non-uniform deformation (dishing) of the front face, which may increase the overall pressure loading on the panel from the blast. There were some variations in panel response depending on the type of foam/honeycomb used and it is not clear what the optimum material properties should be.

Customized sandwich panels can also be designed with truss-like rods, vertical walls, or angled walls as the core structure. Can the core be tailored to minimize the energy transferred from a blast load to the main structure? The main objective involves an investigation into the optimum design of a square-cell shaped honeycomb subject to blast loading. The variables under investigation include the core and face-sheet thicknesses, number of cells, core height, and additional horizontal layer(s) in the core. However, this paper only presents the effects of core and face-sheet thickness variations. Another objective is to determine if the dishing effect observed in experiments can be simulated computationally. The paper includes a model description, Design of Experiments (DOE) study, and an optimization study to maximize energy absorption under blast load.

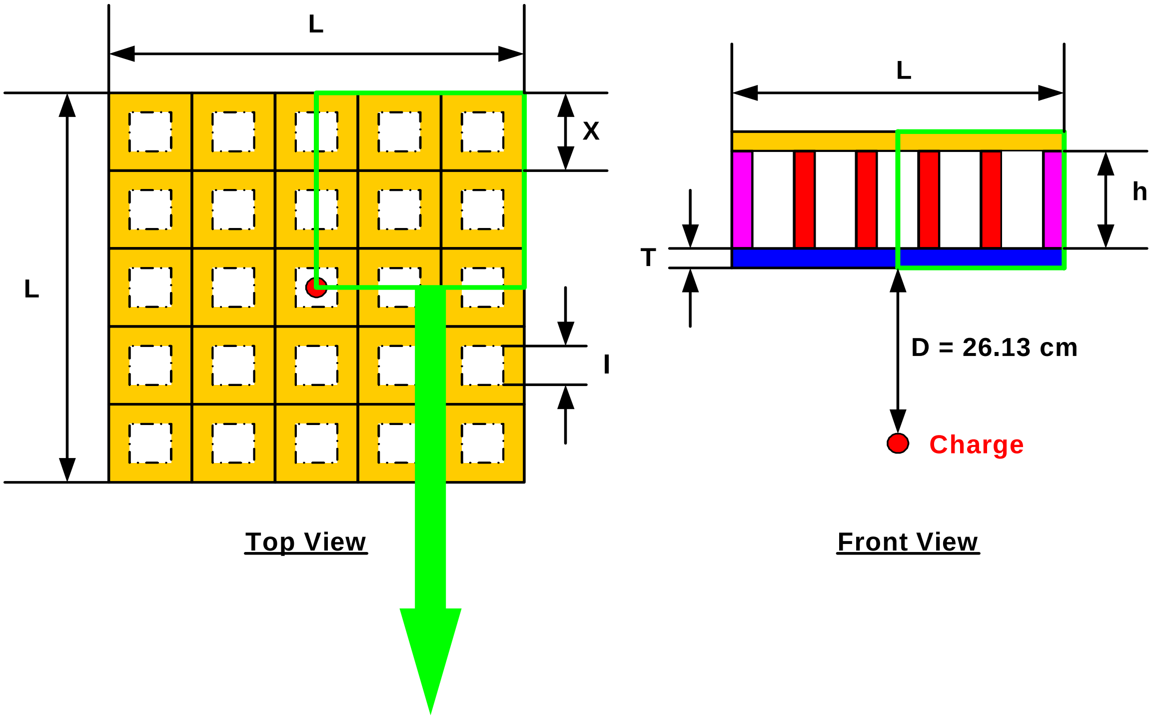
LS-DYNA is used to simulate the non-uniform dynamic response of the honeycomb sandwich structure to blast loading. Altair HyperStudy 6.0 is used for DOE study to evaluate the factors that contribute the values of responses and is also used to investigate into the optimum design for energy absorption subject to blast loading.

Model Description

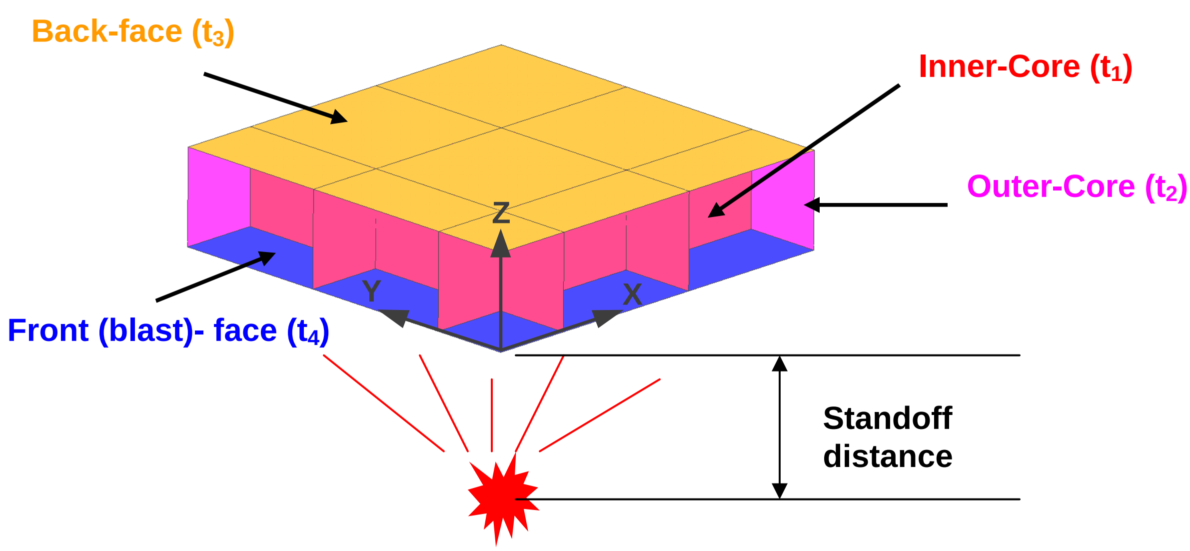
A simple structural configuration is used for comparing the response of different honeycomb geometries. The flat square panel is subject to an explosive blast that is located a fixed standoff distance from the center of the panel. The panel is free-floating in space and is symmetric about its' center so a quarter-symmetry model can be used for simulation as shown in Figure 1. For the results presented in this paper, the overall dimensions of the panel are fixed and the number of core cells are fixed (25 cells in the entire panel). The height of the core is also fixed.

The consistently used units for modeling are grams (g) for mass, centimeters (cm) for length, microsecond (μs) for time, and mega-bar (Mbar) for pressure. These units are preferred to go with the units on *LOAD_BLAST card, where "IUNIT" is set to 4. A 518-g mass of TNT is used for the explosive, which is equivalent to a 1.0-pound C-4 charge assuming a 1.14 TNT/C-4 energy release ratio. A standoff distance of 26.13-cm is used as shown in Figure 1.

We ultimately want to determine the energy transmitted to the panel by determining its steady state velocity or kinetic energy. We are also interested in determining the peak acceleration of the panel. The total mass of the structure is constrained at 4000-g so that all panels have the same mass. An equation is generated that relates the thickness of the back face to all other dimensions in the model so that the mass is the same for all panels.



(a)



(b)

Figure 1. (a) Configuration of Square-cell Honeycomb Sandwich. (b) ¼ Section Model.

The total mass of the structure can be expressed as:

$$M_t = \rho_{mat} \cdot V_t = \rho_{mat}\left(4A_c \cdot t_1 + 2A_c \cdot t_2 + A_f \cdot t_3 + A_f \cdot t_4\right) \quad \text{(Eq. 1)}$$

where M_t = total mass

ρ_{mat} = material density

V_t = total volume

A_c = area of core

A_f = area of face

t_i = thickness of components (i = 1..4)

Rearranging equation Eq. 1 for t_3 yields

$$t_3 = \frac{\left[\frac{M_t}{\rho_{mat}} - A_c\left(4t_1 + 2t_2\right)\right]}{A_f} - t_4 \qquad \text{(Eq. 2)}$$

The thickness variable, t_2, is always a half of t_1 because of the symmetry conditions applied to the panel. The thickness variables t_2 and t_3 are defined as equations in the template file used for the Design of Experiments and Optimization studies.

Finite Element Model

The square-cell shape honeycomb sandwich structure is modeled using Pro/Engineer Wildfire with dimensions of 22.86-cm for the length and width of the panel and 5.76-cm in height as shown on ¼ section model in Figure 2. Altair HyperMesh 6.0 is used to create a shell element model.

The number of shell elements along a honeycomb cell edge is varied from 6 to 60 elements to determine the effect of mesh size on the accuracy of resultant output. A 1:1 length-to-width aspect ratio for the elements is maintained as closely as possible. The results using 36 elements per cell-edge is approximately the same (< 1% error) as the results using 60 elements per cell-edge. Therefore, 36 elements per cell-edge are used for most of the analyses reported in this paper. The total number of elements and nodes in this model is 28620 and 28367, respectively. Four components are created as the inner-core, outer-core, and back and front-face sheets. The front-face sheet is referred to as the 'blast-face' since the blast pressure directly strikes into this face. Appropriate boundary conditions are applied along the symmetry planes in this model. The back face is not constrained in any direction so that structure can act as a pendulum.

This model is constructed from Belytschko-Tsay (ELFORM=2) shell elements with 5 integration points. The material model 3 (*MAT_PLASTIC_KINEMATIC) was used with the properties of Aluminum 5456-H116 for all components. The material properties used for the models are summarized in Table 1a and the corresponding section of the LS-DYNA input file is shown in Table 1b.

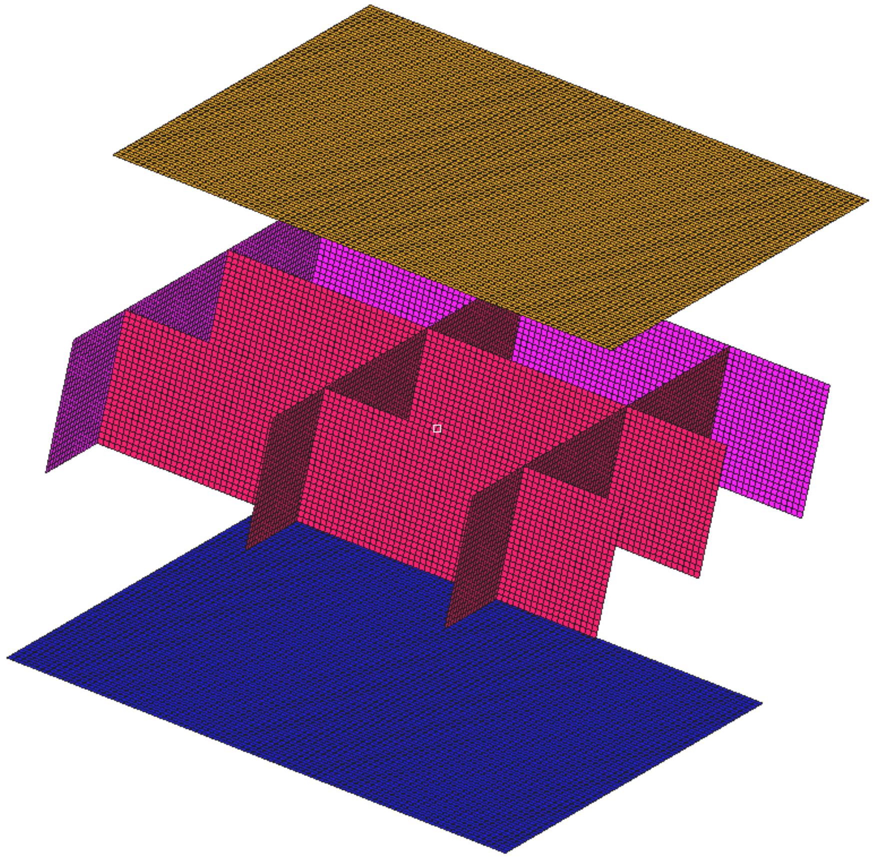


Figure 2. Finite Element Model of ¼ Section Honeycomb Sandwich Model

Table 1a. Material Properties.

Property	Aluminum 5456-H116
Material Model	3
Density (kg/m^3)	2630
Elastic Modulus (MPa)	72000
Yield Strength (MPa)	230
Poisson's Ratio	0.33

Table 1b. Material Property Section in LS-DYNA File.

```
*MAT_PLASTIC_KINEMATIC
$HMNAME MATS        1Aluminum-5456
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7
$       MID        RO         E        PR      SIGY      ETAN      BETA
          1      2.63      0.72       0.3    0.0023
$       SRC       SRP        FS        VP
```

A contact type of *CONTACT_AUTOMATIC_SINGLE_SURFACE is used with default parameters to make sure the contacts between various components. *CONTACT _BULK _ VISCOSITY card is used to treat shock waves based on recommendations found in similar studies.

CONWEP Blast Load Function

The CONWEP blast function is used to apply simple blast loading rather than to explicitly simulate the shock wave from the high explosive, which is adequate for a case that investigates vehicle responses due to the blast from land mines. Table 2 shows the input data required for the CONWEP model in LSDYNA.

Table 2. Load Blast and Blast Surface Section in LSDYNA file for Shell Model.

```
*LOAD_BLAST
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7
$      WGT       XBO       YBO       ZBO       TBO     IUNIT     ISURF
     517.9         0         0    -26.13         0         4         2
$      CFM       CFL       CFT       CFP

$
*SET_SHELL_LIST_GENERATE
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7
$      SID       DA1       DA2       DA3       DA4
       777
$    B1BEG     B1END     B2BEG     B2END
     20521     28620
$
*LOAD_SHELL_SET
$
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7
$      SID      LCID        SF        AT
       777        -2         1         0
```

A TNT equivalent mass of 518-grams is positioned at 26.1-cm in negative Z-direction from the origin, located at the center of the panel as shown on Figure 1b. A value of “2” is selected in ISURF so that the blast load is detonated away from the structure rather than on the surface of the structure. All the shell elements on the blast surface are listed as targets for the blast pressure loading. The Load Curve ID (LCID) is set to “2” for CONWEP function to determine pressure for the segments and load curve scale factor (SF) can be used to increase or decrease the pressure.

Design of Experiment (DOE)

A DOE study is performed using Altair HyperStudy to evaluate the factors that significantly contribute to the response values. Responses of the study are specified as kinetic energy (KE), internal energy (IE), total energy (TE), and rigid body velocity (velocity). Fractional factorial of DOE type and controlled design variables are used to evaluate the factors that contribute the response.

Optimization Study

Altair HyperStudy is also used for an optimization study in conjunction with the LSDYNA solver. Design variables include thicknesses of all four-components: inner-core (t_1), outer-core (t_2), back-face (t_3), and front-face (t_4). Only t_1 and t_4 are independent design variables in HyperStudy since t_2 and t_3 are functions of t_1. Table 3 shows the initial, lower, and upper values for all four of the design variables defined.

Table3. Design Variables with Initial Value and Bounds (unit: centimeters)

Design Variable	Initial Value	Lower Value	Upper Value
Inner-core, (t_1)	0.1	0.04	0.4
Outer-core, (t_2)	0.05	0.02	0.2
Back-face, (t_3)	2.4843	2.4843	2.4843
Front-face, (t_4)	0.3	0.2	0.8

The design problem can be stated mathematically in the form of an optimization problem as

Objective function: $\psi_0(IE) \Rightarrow \max$ (Eq. 3)

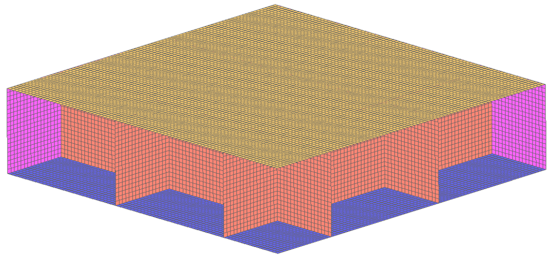
Side constraints: $t_i^l \le t_i \le t_i^u$ (Eq. 4)

The objective of the optimization problem is to maximize the internal energy absorbed by the structure. Equation (2) keeps mass constant by increasing or decreasing the back-face thickness. The side constraint is defined to limit the component thicknesses at lower to upper bounds region.

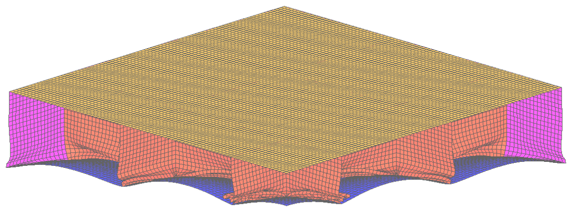
Results and Discussion

A typical series of deformation for a honeycomb sandwich structure is shown in Figure 3. The core is completely crushed without rebound at 700-microseconds, at which point the kinetic and internal energies become steady state with time.

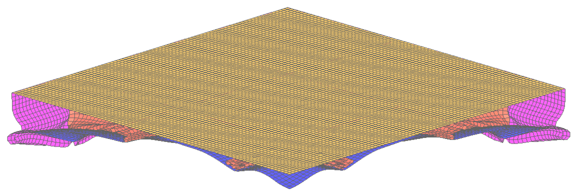
The DOE study went through nine-iterations of varying the two thickness values and measuring changes in the internal energy. As the internal energy of the panel increases due to more structural/material deformation, we expected to see a corresponding decrease in the kinetic energy and final rigid body velocity. The responses of interest that were used for the DOE study are therefore internal energy and rigid body velocity. It is desired to identify which design variable contributes significantly to the internal energy and rigid body velocity. Figures 4a and 4b show the graph of percent contribution by each design variables for internal energy and rigid body velocity, respectively. For the internal energy graph, it is indicating that varying inner-core thickness influences about 7% of internal energy absorption to the structure and varying front-face thickness influences about 93%. This graph is not an indication of percentage that each component has absorbed the internal energy. It is, however, used to indicate the sensitivity of the internal energy absorption to changes in each design variable.



(a) 0 micro-sec

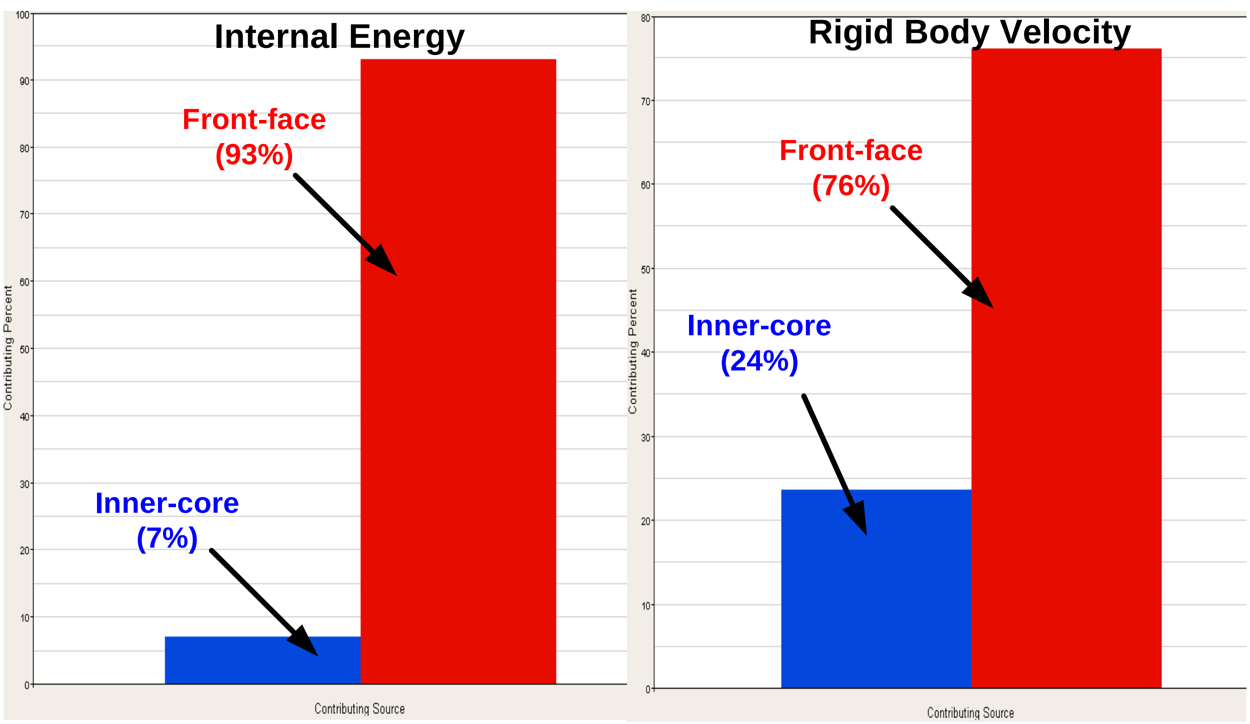


(b) 250 micro-sec



(c) 700 micro-sec

Figure 3. Predicted Deformation History for Honeycomb Sandwich Under Blast Load.



(a) **(b)**

Figure 4. DOE Result of (a) Internal Energy and (b) Rigid Body Velocity

The results of DOE can be verified from the optimization result shown in Table 4. For iterations 1 and 3, when thick1 stays constant and thick4 has varied 22%, internal energy has changed about 21%, which indicates that internal energy changes by almost the same percentage amount as the changes in thick4. Equally, for iteration 7 to 9, when thick4 stays constant and thick1 has varied 31%, internal energy has changed only about 4%, which indicates that internal energy changes fairly small amount to the changes in thick1. Therefore, the DOE results are verified from the result of optimization study. The rigid body velocity graph from the DOE study can be interpreted in the same manner as internal energy.

The HyperStudy optimization results for maximum internal energy were also attained after nine iterations. Table 4 shows the design variables and model responses for each iteration. Table 5 shows the optimum values of variables (over the range prescribed) that maximize internal energy of the structure.

Table 4. History of Optimization Iteration

Iteration	Objective_1	thick1	thick4	MASS	KE	IE	TE	Velocity
1	0.0422274	0.1000000	0.3000000	3999.6600	0.0059163	0.0422274	0.0481076	0.0016852
2	0.0397610	0.1220000	0.3000000	4000.6900	0.0057795	0.0397610	0.0455843	0.0016772
3	0.0332014	0.1000000	0.3660000	3999.6600	0.0057983	0.0332014	0.0389959	0.0016722
4	0.0572231	0.0800000	0.2430000	3999.3400	0.0060300	0.0572231	0.0634022	0.0017085
5	0.0723142	0.0648000	0.2000000	4000.4800	0.0062698	0.0723142	0.0815323	0.0017337
6	0.0612276	0.0518400	0.2380000	4000.0000	0.0062340	0.0612276	0.0702117	0.0017236
7	0.0745510	0.0524880	0.2000000	3999.7500	0.0063379	0.0745510	0.0846609	0.0017425
8	0.0761175	0.0419904	0.2000000	3999.4200	0.0064220	0.0761175	0.0874756	0.0017495
9	0.0778678	0.0400000	0.2000000	4000.0900	0.0064396	0.0778678	0.0880312	0.0017503

Table 5. Optimized Design Variable Values (unit: centimeters)

Design Variable	Optimum Value
Inner-core, (t_1)	0.04
Outer-core, (t_2)	0.02
Back-face, (t_3)	2.66
Front-face, (t_4)	0.2

All of the response values were taken at the termination time (at 2000-microsecond) where energies and velocity had reached a steady state. Table 4 clearly indicated that internal energy increased from 0.042 to 0.078, about 86% from iteration 1 to 9. The inner-core (thick1) decreased 60% and the blast-face (thick4) decreased 33% from iteration 1 to 9, which are at lower bound values. The optimized values indicate that the internal energy increases as the wall thickness decreases for the core and the blast face.

Other energy values were also checked for consistency. LSDYNA calculates total energy in GLSTAT by adding six different energies: internal, kinetic, contact (sliding), hourglass, system damping, and rigidwall. Figure 5 shows all the energies encountered from the model. Adding energies from A to E gives a value of F at any given time.

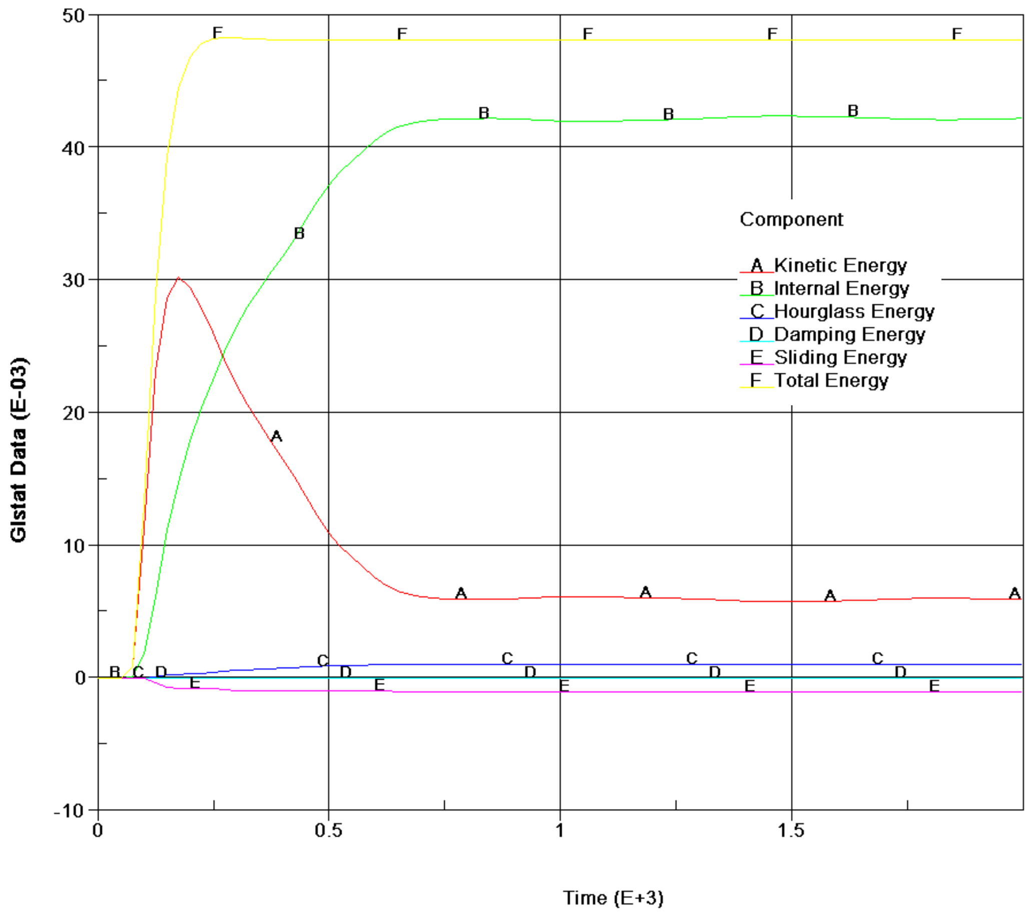


Figure 5. Total Energy Distribution For Iteration 1 of the Optimization Study

One problem observed in the optimization results is that the total energy changes significantly throughout the iterations even though the blast load applied to the structure remains the same for all iterations. Ideally, we expected the total energy to be constant since the applied load is the same. So, even though the internal energy increased by 86% from iteration 1 to 9, the kinetic energy also increased by 8.5%. This is not a desirable result but it also corresponds to some experimental data found from ballistic pendulum experiments.

One possible explanation for the increase in total energy from iteration 1 to 9 is related to the deformation pattern of the blast face. The core of the panel crushes more in the center than at the edges, forming a bowl or dish shape, since the pressure from the blast is higher in the center. As the panel deforms in this manner, the normal direction of each element on the blast face is more closely oriented towards the blast center. The pressure from the blast on each element increases as the elements become more perpendicular to the radially expanding blast wave. The increased pressure on the blast face would account for the increase in total energy to the panel.

A uniform pressure pulse was applied to each element on the blast face to investigate this phenomenon further. Under this pressure loading, the panel crushed uniformly for all iterations of different cell wall and face sheet thicknesses. The applied load in this case was identical at each iteration and the kinetic energy decreased as the internal energy increased.

The results discussed above imply that a honeycomb structure used for blast mitigation can be tailored to maximize energy absorption, but this may also result in an increase in kinetic energy (or final velocity) applied to the structure in back of the panel. In general, this is not desirable but one other result to consider is how fast the back plate is accelerated to its final velocity. Figure 6 shows the peak acceleration of each component at all nine iterations along with the peak acceleration for a plain rigid body plate model with the same total mass of 4.0-kg. The front face and core walls accelerate very fast as the core crushes. But in all iterations, the back face accelerates slower than the rigid plate. The lowest peak acceleration, 6.02E-06 cm/μsec^2, occurs during iteration 4. This is about a 73% reduction in peak acceleration compared to the rigid body plate, which had a value of 2.25E-05 cm/μsec^2. The biggest reduction in peak acceleration did not correspond to the panel with the highest energy absorption.

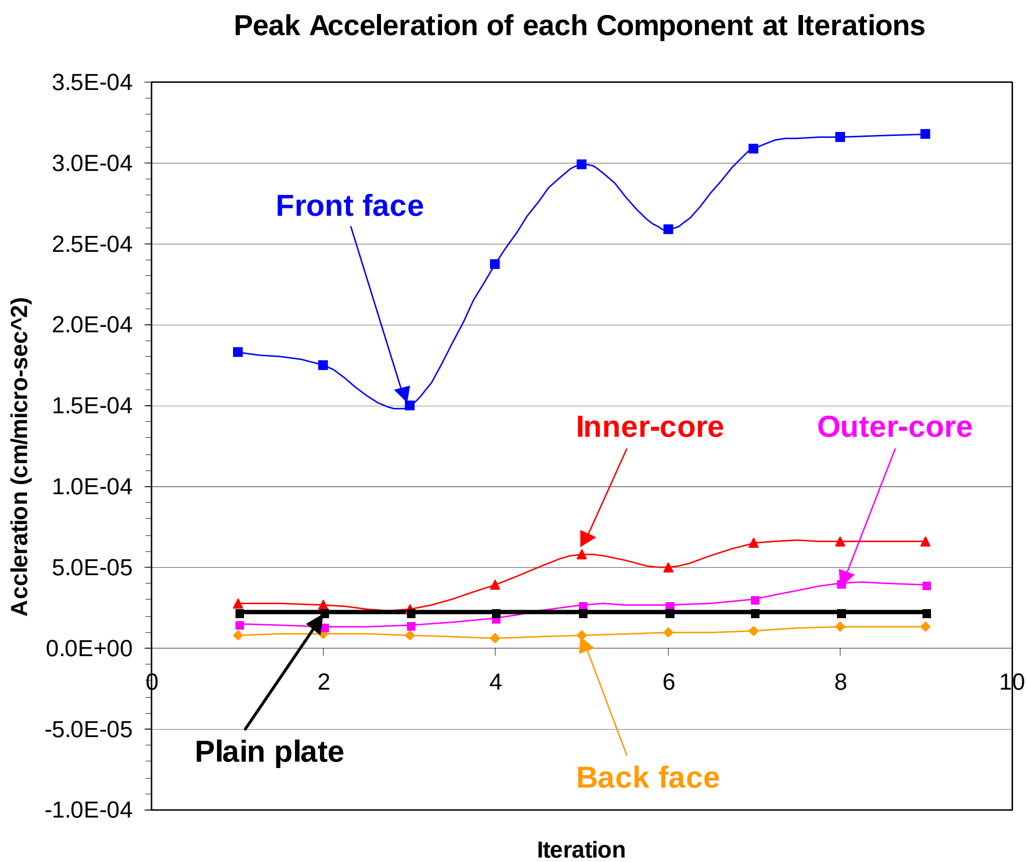


Figure 6. Comparison of Peak Acceleration of Honeycomb vs. Plain-Plate

Conclusions/Discussion

Honeycomb sandwich structures can be used for energy absorption of blast loads for structural applications. The non-uniform deformation pattern (dishing) will tend to increase the total energy applied to the structure, which increases its final velocity. These computational results are in agreement with experimental data found in the literature for ballistic pendulum experiments. However, a significant reduction in peak acceleration of the structure can be attained. The benefits of reduced peak acceleration may outweigh the drawbacks of increased kinetic energy depending on the particular structural application.

Acknowledgements

This material is based upon work supported in part by the U. S. Army Research Laboratory and the U. S. Army Research Office under contract/grant number DAAD19-02-1-0105.

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