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IMPACT TESTING OF FOAM-FILLED
PAPER HONEYCOMB WITH ENERGY-
ABSORPTION CHARACTERISTICS
COMPARED TO BALSA AND REDWOOD

PDO 6989147, Final Report

Project Team:
L. F. Thorne
R. D. Jump

Published May 1974

Prepared for the
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**Kansas City
Division**

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IMPACT TESTING OF FOAM-FILLED PAPER HONEYCOMB WITH ENERGY-ABSORPTION CHARACTERISTICS COMPARED TO Balsa AND REDWOOD

BDX-613-946 (Rev.), UNCLASSIFIED Final Report, Published May 1974

Prepared by L. F. Thorne and R. D. Jump, D/144, under PDO 6989147

Twelve foam-impregnated paper honeycomb structures were impact tested at velocities between 150 and 318 fps (45.7 and 96.9 m/s). The effect of velocity upon crush strength and the energy absorbed per pound of sample material were studied. The efficiency of epoxy-foam-impregnated paper honeycomb as an energy-absorber was compared to balsa and redwood. Test data suggest that epoxy-foam-filled paper honeycomb can be made equivalent to wood for use as an energy-absorber at the velocities studied if its density can be lowered from 24.2 lb/ft³ (387.7 kg/m³) to the approximate density of redwood (17.4 lb/ft³ or 278.4 kg/m³) by changing its composition.

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THE BENDIX CORPORATION

KANSAS CITY DIVISION

KANSAS CITY, MISSOURI

A prime contractor for the
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SUMMARY

Energy-absorption products fabricated from Bendix foam-impregnated paper honeycomb may provide advantages ordinarily not available to the designer of structures to be used in high-energy applications. Foam-filled paper honeycomb will have a distinct advantage over materials (such as wood) having fixed properties if its energy-absorption characteristics can be maximized for each application by changing its composition.

This project evaluates the dynamic properties of foam-impregnated paper honeycomb and its suitability as an energy absorber at the velocity and boundary conditions studied in the evaluation of other candidate materials for protective materials. Seven epoxy-foam-filled samples and five urethane-foam-filled samples, each 6.5 inches (16.51 cm) in diameter, were tested at impact velocities between 150 and 318 fps (45.7 and 96.9 m/s). Crushing force was applied to the samples upon impact by a 30-pound (13.6 kg) test weight. The output from accelerometers mounted on the test weight was recorded and later reduced by computer techniques to velocity-, deflection-, dynamic force-, and strain-versus-time, along with values for impact energy and percent rebound (postcrush recovery) of the material.

To evaluate the efficiency of foam-impregnated paper honeycomb as an energy absorber, graphs were constructed to show the energy absorbed per pound of material versus the percent compression. Similar graphs were constructed for balsa and redwood from data previously collected at the same boundary conditions and at two of the same velocity levels that were being studied.

At the lower velocity level of 207 fps (63.1 m/s), the epoxy-foam-filled sample absorbed the energy in less crush-distance than did the balsa sample. Force-displacement curves show that the epoxy is stronger and crushes more efficiently than balsa, since they more closely resemble a square wave in shape; however, this advantage is offset by the greater crush-distance of balsa. This is evidenced by a peak faired deceleration which is 20 percent lower for balsa than for epoxy. The amount of energy absorbed by the balsa per pound of sample material is enhanced by its low density (14.9 lb/ft³ or 238.7 kg/m³). At maximum crush, it exceeded the energy per pound of material absorbed by the epoxy-foam-filled sample.

At the higher velocity-level, the energy absorbed per pound of sample material was compared for epoxy-foam-filled honeycomb, balsa, and redwood. Impact velocities were 269, 266, and 270 fps (82.0, 81.1, and 82.3 m/s), respectively. The epoxy absorbed the energy in less crush-distance than did either the balsa or redwood. The three force-displacement curves

indicate that the efficiency of redwood and epoxy are similar; balsa has a high terminal peak force which indicates that it is too weak a structure to efficiently absorb the energy. As a result, the peak faired deceleration for balsa was 38 percent higher than that for the epoxy sample.

The peak deceleration for the epoxy sample was 46 percent higher than the deceleration for the redwood. The higher amplitude of the epoxy, however, was due primarily to its higher crush-strength. The material density, a property closely related to crush-strength, was 24.2 lb/ft^3 (387.7 kg/m^3) for the epoxy-foam-filled sample as compared to 17.4 lb/ft^3 (278.4 kg/m^3) for the redwood.

Test data suggests that epoxy-foam-filled paper honeycomb can be made equivalent to wood as an energy-absorber at the test-levels studied provided that its density can be lowered by changing its composition.

DISCUSSION

SCOPE AND PURPOSE

Detailed data concerning the changes in material properties during the action of a dynamic load are quite scarce. Generally, an increase in the rate of deformation of a material will raise its dynamic strength characteristics well beyond the corresponding static values. However, no simple generalization is appropriate to describe all possible changes in material behavior which might occur over wide ranges of impact velocity and boundary conditions. For maximum usefulness, data describing the dynamic behavior of a material should be collected at the velocity and boundary conditions of interest.

A pneumatic shock actuator, modified to fire 8-inch (20.32 cm) diameter projectiles, was used in the Product Test Laboratory to study the dynamic behavior of materials that were being considered for use in protective packaging. Under contract to Sandia Albuquerque, impact test techniques were developed by Bendix and 29 candidate materials, 5.5 and 6.5 inches (13.97 and 16.51 cm) in diameter, were crushed in a series of tests on 54 samples at velocities as high as 300 fps (91.4 m/s).

The need for specific data concerning the dynamic behavior of materials produced at the Bendix Kansas City Division has been recognized. Plastic Structures Engineering (Department 834) and Materials Engineering (Department 814) have requested dynamic testing on samples of plastic foam and paper-honeycomb structures at impact velocities up to 300 fps (91.4 m/s). Dynamic data that is being collected on these and other similar Bendix materials will be a valuable design tool and will enhance the candidacy of Bendix materials for use in future programs.

ACTIVITY

Dynamic Test Requirement

For purposes of simulation, each of the candidate materials evaluated for use in protective packaging was contained in a cylindrical projectile along with a test weight, as shown in Figure 1. Since the data collected on filled paper honeycomb was to be compared to the energy-absorption characteristics of redwood and balsa, the same test method with identical boundary conditions was used for testing all of the honeycomb samples.

Figure 1. Air Gun Test Projectile

The objective was to accelerate the 50-pound (22.7 kg) projectile up to the desired impact velocity by use of the 8-inch (20.32 cm) air gun and allow it to impact a steel reaction-block weighing approximately 5000 pounds (2265 kg). Upon impact, the sample material was crushed by the inertial force of the test weight. The signal from accelerometers mounted on the test weight were recorded for each shot and later were reduced by computer techniques to velocity-, deflection-, dynamic force-, and strain-versus-time, along with values for impact energy and percent rebound (postcrush recovery) of the material.

Preparation of Test Projectile

To insure the collection of data during acceleration of the projectile in the barrel of the air gun and during the flight of the projectile to impact at a distance exceeding ten feet from the end of the barrel, a dual-instrumentation system was used. The cables from both accelerometers were sheathed in rubber tubing and coiled around foam padding in the rear of the projectile to protect the cables and to allow the weight to move several inches when the sample was crushed. The cable protection within the projectile is shown in Figure 2.

Because 7-inch-diameter (17.78 cm) projectiles were to be tested, front and rear guides were fabricated from urethane foam to adapt the projectiles for firing from the 8-inch-diameter (20.32 cm) air gun barrel. After the accelerometer cables were coiled inside the rear of the projectile, the guides were secured in place with epoxy, as shown in Figure 3.

Further protection of the accelerometer cables was provided by threading each cable through the center of hollow, maypole-braided nylon cord. Slack was allowed in the cables at the projectile and at the signal-conditioning equipment 20 feet (6.1 m) away to remove tension from the cable during the tests.

Preparation of Test Area

The 5000-pound (2265 kg) impact block was fabricated from mild steel in two 6-foot (1.83 m) sections which bolt together between the rails of the horizontal track system of the actuator. The impact surface of the block consists of a 4-inch-thick (10.2 cm) hardened steel plate which is bolted in place. The impact block is shown in Figure 4.

A steel box 10 feet long and 4 feet deep (3.05 m by 1.22 m) was fabricated from 3/8-inch-thick (9.53 mm) material to protect the surrounding area from postimpact damage which might be caused by the rebounding projectile. A view of the test area is shown in Figure 5.

Text continued on page 22.

Figure 2. Accelerometer Cable Protection Inside Projectile

Figure 3. Foam Guides Bonded to 6-Inch (15.24 cm) Projectile

Figure 4. Five-Thousand-Pound (2265 kg) Impact Block

Figure 5. Test Area

Impact Velocity Measurement

Magnetic sensors, spaced 1 inch (2.54 cm) apart, were installed near the exit-end of the air gun barrel, as shown in Figure 6. An 8-inch-diameter (20.32 cm) steel ring, 1/16 inch (1.59 mm) thick, was secured with epoxy to the rear guide of each projectile to produce a voltage output from the sensors as the projectile left the barrel. The pulses were recorded on magnetic tape at a tape-speed of 120 ips (3.05 m/s), along with the shock-pulse signal and one-millisecond time marks. The distance from the last magnetic sensor to the face of the impact block, less the length of the projectile, was noted for each shot.

The recorded signals were played back from the tape at a speed of 1-7/8 ips (4.76 cm/s) onto an oscillographic record. Velocity was then calculated by reading the time between the last sensor signal and impact.

Figure 7 is a typical view of a projectile in the rebound box after having been fired. The movement of the impact block is from 5 to 7 cm upon impact of the 50-pound (22.7 kg) projectile at a velocity of 300 fps (91.4 m/s). A graph showing the relationship between the projectile velocity and the firing pressure of the 8-inch (20.32 cm) air gun is presented in Figure 8.

Acceleration Measurement and Calibration

Kistler Model 805A accelerometers, which have a 100,000-g shock capability and a resonant frequency above 60 kHz, were used to capture the shock pulse. Upon impact, the test weight inside the projectile begins crushing the sample material. A block diagram of the instrumentation system employed to measure the deceleration force on the test weight is shown in Figure 9.

Calibration of the instrumentation system is performed by feeding a 1000-Hz sine wave from a Ballentine calibrator to the charge amplifier. The sine wave has a peak-to-peak charge level equivalent to the maximum deceleration level expected during the test. The input level of the tape recorder is set at 20-percent deviation and the calibration signal is recorded on magnetic tape. The signal is then played back onto the oscillographic recorder and the output level of the tape recorder is adjusted to give a 4-inch (10.2 cm) peak-to-peak displacement.

Signal Recording and Playback

Endevco Model 2718 charge amplifiers combined with Burr-Brown 17.5 kHz (-3 db at 10 kHz) 6-pole Bessel filters were used for signal-conditioning. The filters effectively eliminated noise above 10 kHz without introducing undesirable distortion from nonlinear phase shift above the cutoff frequency.

Figure 6. Magnetic Sensors Installed in Air Gun Barrel

Figure 7. Projectile After Impact in Rebound Box

Figure 8. Air Gun Performance Using 40-Inch (101.6 cm) Barrel

The acceleration traces, along with the magnetic-pickup outputs and 1-millisecond time marks, were recorded on magnetic tape at a speed to 120 ips (3.05 m/s) in double-density mode, giving a frequency response to 40 kHz (down 5 percent at 40 kHz). Data records were obtained by playing the data back at a speed reduction of 64:1 (1-7/8 ips or 4.76 cm/s) into a Honeywell oscillograph equipped with M-1000 and M-1650 galvanometers.

Typical recorded data from an impact test is shown in Figure 10. After the data is reviewed, the acceleration traces are scaled for playback into a Biomation Model 810 transient recorder and digitized at a speed of 120 ips. The transient recorder converts the data into digital form and stores it in an internal memory system. The digital data is then punched out on paper tape in a form compatible with CDC 6600 intercom terminals. The instrumentation system used is shown in Figure 11.

Text continued on page 29.

Figure 9. Block Diagram of Instrumentation System

Figure 10. Recorded Impact Test Shot

Figure 11. Recording Equipment

Data Reduction

After the raw data, along with the calibration data and other test parameters, has been entered into the computer terminal, it is converted from binary to decimal form and is printed out. The limits of integration and a base-line value are chosen and entered back into the program. The result obtained is a determination of the velocity-, displacement-, dynamic force-, and strain-versus-time, along with values for impact energy and percent rebound. A second program was written to determine the energy absorbed per pound of sample material versus the percent compression of the material. All of the variables can be displayed in either tabular or graphical format using the CDC 6600 CALCOMP plotter.

Data Accuracy

A study was made to evaluate the effect of input-parameter errors upon the accuracy of the output data compiled for a typical test. An error in pulse amplitude is due to instrumentation uncertainties and to the choice of the base line of the shock pulse for the purpose of integration. The accelerometer calibration is within ± 6 percent, and the calibrator with the charge capacitor is within ± 1 percent. The digital recorder has an amplitude resolution of 0.4 percent (one data point out of 256), but since both the calibration signal and the acceleration pulse cannot always be recorded full-scale, the uncertainty is somewhat greater; generally, it is limited to less than ± 0.7 percent.

The Biomation recorder is a unipolar device. Its input must be biased to assure that any negative portion of the input is not clipped. For this reason, zero-acceleration is an arbitrary digital number. The choice of the correct base line can be made within two data points out of 200, or ± 1 percent. The overall range of amplitude uncertainty is then ± 8.7 percent.

Both the time-mark generator, used with the tape recorder, and the digital recorder are crystal-controlled and are accurate to within ± 0.03 percent. The time-resolution of the digital recorder is 1 segment out of 1000, full scale. A convenient sweep speed for most tests has been 5 microseconds per segment. For an average pulse width of 2.5 microseconds, the resolution is then ± 0.20 percent.

The distance the projectile travels before impact is measured within $\pm 1/8$ inch in 10 feet (3.18 mm in 3.05 m) or ± 0.10 percent. The travel time can be interpreted from the oscillograph record of the time marks within ± 0.1 millisecond, or ± 0.33 percent, for an impact velocity of 300 feet per second (91.4 m/s). The total range of uncertainty in a calculated value for impact velocity, including ± 0.03 percent for the time-mark generator, is therefore ± 0.43 percent.

The accuracy of the value printed out for displacement (crush of the sample) is affected by the selection of the limits of integration. The leading edge of the pulse is generally well defined, and the error for the start of integration usually will be limited to one time segment in 500. The effect upon maximum displacement therefore would be ± 0.4 percent. The end of a shock pulse is not as well defined, and the point selected for stopping integration may be as much as two time segments off. This error changes only the value for the final displacement, and its effect is minimized because of the low final velocity (rebound).

A square-wave pulse best represents the acceleration time-trace obtained during the crush of the sample. To evaluate the effect of input-parameter errors upon the accuracy of the output data, the following equations were developed from the motion-time equations for a square-wave pulse.

$$V_i = \frac{AT(1 \pm V_e)}{(1+RB)}, \quad (1)$$

where

V_i = impact velocity,

A = acceleration,

T = pulse duration at the base line,

V_e = velocity-measurement error,

RB = rebound of material ($V_r / |V_i|$), and

V_r = rebound velocity.

$$S_m = \frac{AT^2(1 \pm V_e)^2}{2(1+RB)^2}, \quad (2)$$

where

S_m = maximum displacement.

The substitution of input-parameter errors into Equations 1 and 2 indicates the total range of uncertainty for a typical impact test. This information is shown in Table 1.

Table 1. Effect of Input Parameter Errors Upon Accuracy of Output Data

Input Data Uncertainty (Percent)	Output Data Uncertainty (Percent)				
	Dynamic Force	Rebound	Maximum Displacement		
			0 Rebound	0.1 Rebound	0.3 Rebound
Pulse Amplitude	±8.7	±8.7	± 8.7	±7.2	±5.2
Accelerometer ±6.0					
Calibrator ±1.0					
Digital Recorder ±0.7					
Choice of Baseline ±1.0					
Pulse Time	0	±0.23	± 0.46	±0.38	±0.27
Digital Recorder ±0.03					
Resolution ±0.20					
Impact Velocity	0	±0.43	± 0.86	±0.71	±0.51
Travel Distance ±0.10					
Travel Time ±0.30					
Tape Recorder ±0.03					
Displacement	0	0	± 0.4	±0.4	±0.4
Integration Start ±0.4					
Total Output Data Uncertainty	±8.7	±9.4	±10.4	±8.4	±6.4

Test Results

Seven epoxy-foam-filled samples and five urethane-foam-filled samples, each 6.5 inches (16.51 cm) in diameter, were tested. The density, length, and the velocity at which the samples were tested are shown in Tables 2 and 3. Samples greater than 2 inches in thickness were obtained by stacking either 2- or 2-1/4-inch-thick samples; in these cases, the density shown in the tables is the average of the two densities. The direction of impact was parallel to the cells of the honeycomb.

Table 2. Sample Description and Test Velocities for Epoxy-Foam-Filled Paper Honeycomb

Sample	Test	Density (lb/ft ³) (kg/m ³)		Thickness (Inches) (cm)		Velocity (fps) (m/s)	
J9 + 11	56	24.0	(384.5)	4.0	(10.2)	207	(63.1)
J10	55	23.5	(376.5)	2.0	(5.1)	159	(48.5)
J13 + 16	61	21.4	(342.8)	4.5	(11.4)	270	(82.3)
J20 + 23	64	21.2	(339.6)	4.5	(11.4)	270	(82.3)
J25 + 27	67	24.8	(397.3)	4.5	(11.4)	318	(96.9)
J26 + 28	66	24.6	(394.1)	4.5	(11.4)	150	(45.7)
J29 + 30	65	24.2	(387.7)	4.5	(11.4)	269	(82.0)

Table 3. Sample Description and Test Velocities for Urethane-Foam-Filled Paper Honeycomb

Sample	Test	Density (lb/ft ³) (kg/m ³)		Thickness (Inches) (cm)		Velocity (fps) (m/s)	
J7 + 8	57	24.0	(384.5)	4.0	(10.2)	205	(62.5)
J12	59	15.0	(240.3)	2.0	(5.1)	165	(50.3)
J14 + 17	60	24.7	(395.7)	4.5	(11.4)	268	(81.7)
J15 + 22	62	22.9	(366.9)	4.5	(11.4)	266	(81.1)
J21 + 24	63	22.8	(365.3)	4.5	(11.4)	265	(80.8)

Because of the severity of the test, valid data was not collected on all test shots. The accelerometer signals were intermittent on shots 62 and 64 and went beyond the calibrated range on shots 59 and 60. A calibration error was evident on shot 61. Sufficient data was collected, however, to meet the test objectives.

Effect of Velocity Upon Energy-Absorption

The effect of velocity upon energy-absorption was studied for epoxy-foam-filled paper honeycomb. Graphs of acceleration-, velocity-, and displacement-versus-time, force-versus-displacement, and the energy absorbed per pound of sample material versus the percent compression for the tests conducted are shown in Appendix A.

Curves showing the energy absorbed at velocities of 150, 207, 269, and 318 fps (45.7, 63.1, 82.0, and 96.9 m/s) are presented together with a static (1 inch/minute or 2.54 cm/minute) curve in Figure E-1. The static curve was calculated from compression data on a 6.5-inch-diameter, 1.5-inch-thick (16.51 by 3.81 cm) sample having a density of 24.43 lb/ft³ (391.4 kg/m³).

Additional testing at the velocities represented will be necessary before firm conclusions can be drawn; however, an increase in the impact velocity appears to lower the rate at which energy is initially absorbed. Beyond 40-percent compression, all dynamic curves show greater energy absorption than does the static curve. The tail on the end of each dynamic curve indicates the energy returned by the postcrush recovery (rebound) of the material.

Epoxy-Filled Compared to Urethane-Filled Paper Honeycomb

Graphs showing acceleration-, velocity-, and displacement-versus-time, force-versus-displacement, and the energy absorbed per pound of material versus the percent compression are shown in Appendix B for the tests on urethane-foam-filled paper honeycomb. Curves showing energy absorbed by the urethane-filled samples compared to the energy absorbed by the epoxy-filled samples are shown for two velocity-levels in Figure E-2.

The data from the urethane-filled samples substantiates the earlier conclusion that an increase in impact velocity lowers the rate at which energy is initially absorbed. Approximately the same total energy was absorbed by both materials at each of the two velocity-levels. The energy was absorbed in less crush-distance by the epoxy-filled samples than by the urethane-filled samples. This could indicate that the epoxy-filled samples had an

overall higher crush-strength; however, the force-displacement curves must be studied to see the efficiency with which each material absorbed the energy.

For the lower test velocity, Figure A-9 indicates that the force-displacement curve for epoxy more closely resembles a square wave (indicating greater efficiency) than does the force-displacement curve for urethane, shown in Figure B-4. As a result, a lower peak faired deceleration was measured on the epoxy samples than on the urethane samples (6700 g in Figure B-1 for urethane, as compared to 4950 g in Figure A-6 for epoxy). Both materials had a density of 24.0 lb/ft³ (384.5 kg/m³).

A study of the curves for the two materials at the higher velocity level indicates comparable results. The force-displacement curve shown in Figure A-14 indicates greater efficiency than the curve in Figure B-9. The peak faired deceleration was 10,400 g for the epoxy and 13,400 g for the urethane. The density was 24.2 lb/ft³ (387.7 kg/m³) for the epoxy-foam-filled sample and 22.0 lb/ft³ (352.4 kg/m³) for the urethane-foam-filled sample.

Epoxy-Filled Paper Honeycomb Compared to Balsa and Redwood

Because the epoxy-foam-filled samples had better energy-absorption characteristics than did the urethane-filled samples, the data from the epoxy samples was chosen for comparison with the energy-absorption characteristics of balsa and redwood. The curves for balsa and redwood were generated from data collected during earlier tests performed at the same velocity and boundary conditions that were being studied.

The curves for balsa and redwood show an absence of superimposed high-frequency oscillations since they originate from faired values for acceleration interpreted from oscillograph records of the shock-pulse traces. The differences in the density of balsa, redwood, and epoxy-foam-filled paper honeycomb are taken into consideration by calculating the energy absorbed per pound of sample material versus the percent compression.

An examination of Figure E-3 indicates that the epoxy-foam-filled sample absorbed the energy in less crush-distance than did the balsa sample at the same impact velocity of 207 fps (63.1 m/s). The force-displacement curves shown in Figures A-9 and C-4 indicate that epoxy is stronger than balsa and crushes more efficiently at the test velocity. This advantage is offset in this instance, however, by the greater crush-distance of balsa, as evidenced by its lower peak faired deceleration (balsa, 4500 g, Figure C-1; epoxy, 4950 g, Figure A-6). The amount of energy absorbed by the balsa per pound of sample material is enhanced by its low density of 14.9 lb/ft³ (238.7 kg/m³);

at maximum crush, it exceeds the energy per pound of material absorbed by epoxy-foam-filled paper honeycomb.

Figure E-4 shows the energy absorbed per pound of material by epoxy-foam-filled honeycomb, balsa, and redwood samples at very nearly the same impact velocity. The epoxy absorbed the energy in less crush-distance. A comparison of the three force-displacement curves (Figures A-14, C-9, and D-4) indicates a similarity between redwood and epoxy, while balsa has a high terminal peak force which indicates too weak a structure to efficiently absorb the test energy. The result, shown in Figures C-6, A-11, and D-1, was a high peak deceleration of 14,400 g for balsa, as compared to 10,400 g for epoxy and 7100 g for redwood. The higher peak acceleration of the epoxy-foam-filled paper honeycomb sample over the redwood is due primarily to its higher crush-strength.

ACCOMPLISHMENTS

Balsa, though providing a large crush-distance, proved to be too weak a structure for efficient energy-absorption at the two velocity-levels studied.

At the higher level, redwood absorbed the impact energy over a greater crush-distance with a subsequent lower peak deceleration than did the epoxy-foam-filled paper honeycomb; however, the force-displacement curve for the epoxy sample showed a higher efficiency. The crush-strength of the two materials, a property closely related to density, was higher for the epoxy-honeycomb structure.

FUTURE WORK

Test data suggests that epoxy-foam-filled paper honeycomb can be made equivalent to wood as an energy-absorber at the velocity-levels studied provided that its density can be lowered by a change in composition.

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Appendix A

ENERGY-ABSORPTION GRAPHS FOR
EPOXY-FOAM-FILLED PAPER HONEYCOMB

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Figure A-1. Test 66, Acceleration Versus Time, 150 fps (45.7 m/s)
Impact

Figure A-2. Test 66, Velocity Versus Time, 150 fps (45.7 m/s)
Impact

Figure A-3. Test 66, Displacement Versus Time, 150 fps (45.7 m/s)
Impact

Figure A-4. Test 66, Force Versus Displacement, 150 fps (45.7 m/s) Impact

Figure A-5. Test 66, Energy Per Sample Pound Versus Percent Compression, 150 fps (45.7 m/s) Impact

Figure A-6. Test 56, Acceleration Versus Time, 207 fps (63.1 m/s)
Impact

Figure A-7. Test 56, Velocity Versus Time, 207 fps (63.1 m/s)
Impact

Figure A-8. Test 56, Displacement Versus Time, 207 fps (63.1 m/s)
Impact

Figure A-9. Test 56, Force Versus Displacement, 207 fps (63.1 m/s)
Impact

SPECIFIC ENERGY VS COMPRESSION

TEST NUMBER 56 EPOXY FILLED HONEYCOMB 207.0 FPS

Figure A-10. Test 56, Energy Per Sample Pound Versus Percent Compression, 207 fps (63.1 m/s) Impact

Figure A-11. Test 65, Acceleration Versus Time, 269 fps (82.0 m/s)
Impact

Figure A-12. Test 65, Velocity Versus Time, 269 fps (82.0 m/s)
Impact

Figure A-13. Test 65, Displacement Versus Time, 269 fps (82.0 m/s)
Impact

Figure A-14. Test 65, Force Versus Displacement, 269 fps (82.0 m/s)
Impact

Figure A-15. Test 65, Energy Per Sample Pound Versus Percent Compression, 269 fps (82.0 m/s) Impact

Figure A-16. Test 67, Acceleration Versus Time, 318 fps (96.9 m/s)
Impact

Figure A-17. Test 67, Velocity Versus Time, 318 fps (96.9 m/s)
Impact

Figure A-18. Test 67, Displacement Versus Time, 318 fps (96.9 m/s)
Impact

Figure A-19. Test 67, Force Versus Displacement, 318 fps (96.9 m/s)
Impact

SPECIFIC ENERGY VS COMPRESSION

TEST NUMBER 67 EPOXY FILLED HONEYCOMB 318.0 FPS

Figure A-20. Test 67, Energy Per Sample Pound Versus Percent Compression, 318 fps (96.9 m/s) Impact

Appendix B

ENERGY-ABSORPTION GRAPHS FOR
URETHANE-FOAM-FILLED PAPER HONEYCOMB

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Figure B-1. Test 57, Acceleration Versus Time, 205 fps (62.5 m/s)
Impact

Figure B-2. Test 57, Velocity Versus Time, 205 fps (62.5 m/s)
Impact

Figure B-3. Test 57, Displacement Versus Time, 205 fps (62.5 m/s)
Impact

Figure B-4. Test 57, Force Versus Displacement, 205 fps (62.5 m/s) Impact

SPECIFIC ENERGY VS COMPRESSION

TEST NUMBER 57 URETHANE FILLED HONEYCOMB 205.0 FPS

Figure B-5. Test 57, Energy Per Sample Pound Versus Percent Compression, 205 fps (62.5 m/s) Impact

Figure B-6. Test 63, Acceleration Versus Time, 265 fps (80.8 m/s)
Impact

Figure B-7. Test 63, Velocity Versus Time, 265 fps (80.8 m/s) Impact

Figure B-8. Test 63, Displacement Versus Time, 265 fps (80.8 m/s)
Impact

Figure B-9. Test 63, Force Versus Displacement, 265 fps (80.8 m/s) Impact

SPECIFIC ENERGY VS COMPRESSION

TEST NUMBER 63 URETHANE FILLED HONEYCOMB 265.0 FPS

Figure B-10. Test 63, Energy Per Sample Pound Versus Percent Compression, 265 fps (80.8 m/s) Impact

Appendix C

ENERGY-ABSORPTION GRAPHS FOR Balsa

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Figure C-1. Test 52, Acceleration Versus Time, 207 fps (63.1 m/s)
Impact

Figure C-2. Test 52, Velocity Versus Time, 207 fps (63.1 m/s) Impact

Figure C-3. Test 52, Displacement Versus Time, 207 fps (63.1 m/s)
Impact

Figure C-4. Test 52, Force Versus Displacement, 207 fps (63.1 m/s)
Impact

Figure C-5. Test 52, Energy Per Sample Pound Versus Percent Compression, 207 fps (63.1 m/s) Impact

Figure C-6. Test 50, Acceleration Versus Time, 266 fps (81.1 m/s)
Impact

Figure C-7. Test 50, Velocity Versus Time, 266 fps (81.1 m/s) Impact

Figure C-8. Test 50, Displacement Versus Time, 266 fps (81.1 m/s)
Impact

Figure C-9. Test 50, Force Versus Displacement, 266 fps (81.1 m/s)
Impact

SPECIFIC ENERGY VS COMPRESSION

TEST NUMBER 50

Figure C-10. Test 50, Energy Per Sample Pound Versus Percent Compression, 266 fps (81.1 m/s) Impact

Appendix D

ENERGY-ABSORPTION GRAPHS FOR REDWOOD

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Figure D-1. Test 46, Acceleration Versus Time, 270 fps (82.3 m/s) .
Impact

Figure D-2. Test 46, Velocity Versus Time, 270 fps (82.3 m/s) Impact

Figure D-3. Test 46, Displacement Versus Time, 270 fps (82.3 m/s)
Impact

Figure D-4. Test 46, Force Versus Displacement, 270 fps (82.3 m/s) Impact

Figure D-5. Test 46, Energy Per Sample Pound Versus Percent Compression, 270 fps (82.3 m/s) Impact

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Appendix E

COMPARATIVE ENERGY-ABSORPTION
GRAPHS FOR EPOXY- AND URETHANE-
FOAM-FILLED PAPER HONEYCOMB,
BALSA, AND REDWOOD

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Figure E-1. Energy Absorption of Epoxy-Foam-Filled Paper Honeycomb

Figure E-2. Energy Absorption of Epoxy- and Urethane- Foam- Filled Paper Honeycomb

Figure E-3. Energy Absorption of Epoxy-Foam-Filled Paper Honeycomb and Balsa

Figure E-4. Energy Absorption of Epoxy-Foam-Filled Paper Honeycomb, Balsa, and Redwood