COVER SHEET

Paper Number: **1556**

Title: **Impact Testing and Simulation of a Sinusoid Foam Sandwich Energy Absorber**

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ABSTRACT

A sinusoidal-shaped foam sandwich energy absorber was developed and evaluated at NASA Langley Research Center through multi-level testing and simulation performed under the Transport Rotorcraft Airframe Crash Testbed (TRACT) research project. The energy absorber, designated the "sinusoid," consisted of hybrid carbon-Kevlar® plain weave fabric face sheets, two layers for each face sheet oriented at ±45° with respect to the vertical or crush direction, and a closed-cell ELFOAM® P200 polyisocyanurate (2.0-lb/ft^3) foam core. The design goal for the energy absorber was to achieve an average floor-level acceleration of between 25- and 40-g during the full-scale crash test of a retrofitted CH-46E helicopter airframe, designated TRACT 2. Variations in the design were assessed through quasi-static and dynamic crush testing of component specimens. Once the design was finalized, a 5-ft-long subfloor beam was fabricated and retrofitted into a barrel section of a CH-46E helicopter. A vertical drop test of the barrel section was conducted onto concrete to evaluate the performance of the energy absorber prior to retrofit into TRACT 2. Finite element models were developed of all test articles and simulations were performed using LS-DYNA®, a commercial nonlinear explicit transient dynamic finite element code. Test-analysis results are presented for the sinusoid foam sandwich energy absorber as comparisons of load-displacement and acceleration-time-history responses, as well as predicted and experimental structural deformations and progressive damage for each evaluation level (component testing through barrel section drop testing).

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INTRODUCTION

In 2012, the NASA Rotary Wing (RW) Crashworthiness Program [1] initiated the Transport Rotorcraft Airframe Crash Testbed (TRACT) research project by obtaining two CH-46E helicopter airframes from the Navy CH-46E Program Office (PMA-226) at the Navy Flight Readiness Center in Cherry Point, North Carolina. Full-scale crash tests were planned to assess dynamic responses of transport-category rotorcraft under combined forward and vertical impact loading. The first crash test, TRACT 1 [2], was performed at NASA Langley Research Center's Landing and Impact Research (LandIR) Facility. Impact tests conducted at LandIR provide data that enable the study of critical interactions between the airframe, seat, and occupant during a controlled crash environment. The CH-46E airframe is categorized as a medium-lift rotorcraft with length and width of 45- and 7-ft, respectively, and a capacity for 5 crew and 25 troops. TRACT 1 was conducted in August 2013 under combined conditions of 300-in/s (25-ft/s) vertical and 396-in/s (33-ft/s) forward velocity onto soil, which is characterized as a sand/clay mixture. The primary objectives for TRACT 1 were to assess improvements in occupant loads and flail envelope with the use of crashworthy features such as pre-tensioning active restraints and energy absorbing seats and to develop novel techniques for photogrammetric data acquisition to measure occupant and airframe kinematics. Pre- and post-test photographs of the TRACT 1 crash test are shown in Figure 1.

(a) Pre-test photograph. (b) Post-test photograph.

Figure 1. Pre- and post-test photographs of the TRACT 1 full-scale crash test.

The TRACT 1 airframe was tested in a baseline configuration with no changes to the structural design, including the discrete aluminum shear panels in the subfloor. It is important to note that the CH-46E does not contain a center keel beam; hence the airframe relies on the aluminum shear panels, the cargo rails in the floor, and the airframe structure to provide longitudinal and torsional stiffness. A final objective of TRACT 1 was to generate crash test data in a baseline configuration for comparison with data obtained from a similar TRACT 2 crash test. The crash test of the second CH-46E airframe (TRACT 2) was conducted on October 1, 2014 and was performed for the same nominal impact velocity conditions and onto the same sand/clay surface [3]. The difference between the two tests is that the TRACT 2 airframe was retrofitted with three different composite energy absorbing subfloor concepts located in the mid-cabin region: a corrugated web design [4, 5] fabricated of graphite fabric; a conical-shaped design, designated the "conusoid," fabricated of four layers of hybrid carbon-Kevlar® fabric [6-8]; and, a sinusoidal-shaped foam sandwich design, designated the "sinusoid," fabricated of the same hybrid fabric face sheets with a foam core [7, 8].

While the TRACT 2 airframe contained similar seat, occupant, and restraint experiments, one of the major goals of the test was to evaluate the performance of novel composite energy absorbing subfloor designs for improved crashworthiness.

This paper will focus specifically on the development of the sinusoid foam sandwich energy absorber, whereas details regarding the conusoid energy absorber may be found in References [6-8]. Farley [9, 10], Bannerman [11], Kindervater [12], and Hanagud [13] have investigated the crushing response of composite structural elements and sine wave beams. Sine wave energy absorbers have been studied extensively because they offer desirable features under compressive loading [14-17]. Energy absorption values from sine wave concepts can be similar to values obtained from crush tubes. In addition, sine wave concepts tend to deform in a stable manner through plastic hinge formation and crushing, rather than global buckling. Often, the actual shape of the energy absorber is not truly a sine wave, but a series of alternating half circles. In fact, the sinusoid concept described in this paper is actually a series of half circles with a diameter of 1.75-in.; however, the designation of "sinusoid" will continue to be used.

Farley [9] has shown that high values of energy absorption are obtained when using hybrid graphite-Kevlar® composites in which the graphite fibers are oriented in the same direction as the loading axis and the Kevlar® fibers are oriented at 45° to the loading axis. As stated in Reference 9, "the Kevlar® fibers are positioned in the laminate to provide containment and support for the graphite fibers, which absorb energy through a combination of crushing and fracturing modes." As described in Reference [6], this same behavior was noted during quasi-static crush testing of conusoid and sinusoid energy absorbers fabricated of hybrid graphite-Kevlar® composite fabrics.

In this paper, multi-level evaluations of the sinusoid energy absorber are discussed including quasi-static and dynamic crush testing and simulation of component specimens, and vertical drop testing and simulation of a retrofitted barrel section. Results of full-scale crash testing and simulation of the TRACT 2 retrofitted helicopter are not presented, but are described in References [3] and [8]. Finite element models were developed of all test articles and simulations were performed using LS-DYNA® [18, 19], a commercial explicit nonlinear, transient dynamic finite element code. Thus, a final objective of this research program is to assess finite element simulations, developed using LS-DYNA®, in predicting the dynamic response and progressive failure behavior of composite energy absorbing airframe structures.

DESIGN GOALS FOR THE ENERGY ABSORBER

Following the TRACT 1 crash test, a research effort was initiated to develop composite energy absorbers for retrofit into the TRACT 2 test article. The design goals were to limit the average vertical accelerations to 25- to 40-g on the floor, to minimize peak crush loads, and to generate relatively long crush stroke limits under dynamic loading conditions, typical of those experienced during the TRACT 1 full-scale crash test [2]. To further clarify the design goals, it is important to note that the individual frames of the TRACT 1 full-scale test article experienced dynamic crush loads of approximately 2,500- to 4,000-lb. per linear foot, as measured from one side of the floor to the other, a distance of approximately 60-in. or 5-ft. These values are determined by multiplying the design acceleration levels (25- to 40-g) by the floor mass loading of 100-lb per linear foot. Note that the weight times the g-factor equals the force. The loading condition was a conservative assumption based on expected seat and occupant loads that were introduced in the TRACT 2 crash test. An idealized schematic of the floor and subfloor located at an individual fuselage frame is shown in Figure 2. The floor, which is approximately 5-ft wide, is divided into 5 segments of 1-ft. length, each having an associated floor loading of 100-lb. The energy absorbers, depicted as individual springs, are designed to limit average floor-level accelerations to 25- to 40-g.

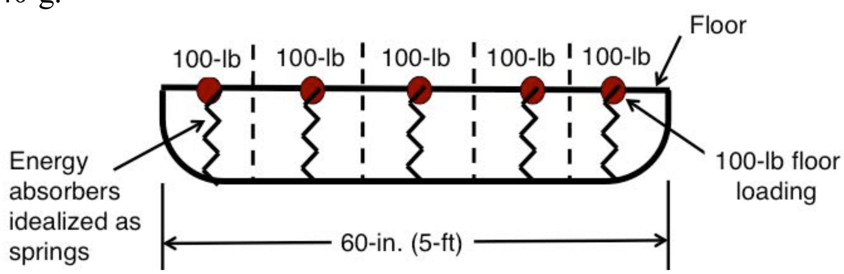
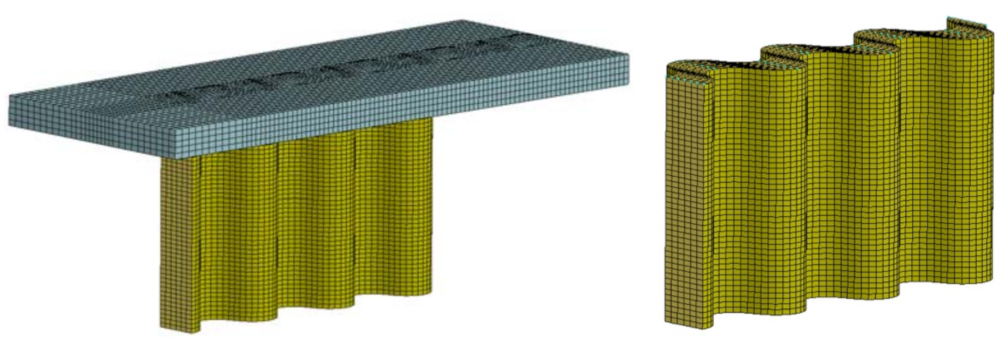


Figure 2. Floor loading condition schematic.

SINUSOID COMPONENT TESTING AND SIMULATION

The sinusoid foam sandwich energy absorber was initially evaluated through quasi-static and dynamic crush testing of components. Design parameters were assessed through component testing including different materials for the face sheets and different laminate stacking sequences. Variations in sinusoid geometry were not evaluated since an existing mold was used in construction. The final design configuration consisted of hybrid carbon-Kevlar® plain weave fabric face sheets, two layers for each face sheet oriented at ±45° with respect to the vertical or crush direction, and a 1.5-in.-thick closed-cell ELFOAM® P200 polyisocyanurate (2.0-lb/ft^3) foam core. The total nominal thickness of a sinusoid component was 1.5-in. with a length of 12-in. and a height of 7.5-in.

The LS-DYNA® finite element model representing the sinusoid component is shown in Figure 3. The model contained: 53,540 nodes; 7,380 Belytschko-Tsay shell elements; 37,515 solid elements; 1 rigid loading mass; Single Point Constraints (SPCs) to fully constrain the bottom nodes of the sinusoid; 1 automatic single surface contact; and 3 material definitions. The nominal element edge length was 0.2-inches.



(a) Sinusoid component model. (b) Model without drop mass.

Figure 3. Depictions of the finite element model of the sinusoid component.

The shell elements, used to represent the composite face sheets, were assigned Mat 58, a material model in LS-DYNA® for simulating composite laminates and fabrics that is based on continuum damage mechanics [19, 20]. Properties for Mat 58, listed in Table I, were obtained through detailed test-analysis comparisons with experimental data obtained from standard material characterization tests, such as tensile testing of fabric coupons oriented at 0°, 90°, and ±45° to obtain longitudinal stiffness and strength, transverse stiffness and strength, and shear stiffness and strength, respectively. Note that Mat 58 includes certain parameters, such as the SLIM parameters and ERODS (element erosion parameter), which cannot be determined entirely based on experimental data. For these parameters, estimates were input based on past experience of the analysts.

TABLE I. MAT 58 MATERIAL PROPERTIES FOR HYBRID CARBON-KEVLAR® FABRIC

Material Property Description	Symbol	Values
Density, lb-s^2/in^4	RO	0.903E-4
Young's modulus longitudinal direction, psi	EA	6.3E+6
Young's modulus transverse direction, psi	EB	2.76E+6
Poisson's ratio, ν_{21}	PRBA	0.03
Stress limit of nonlinear portion of shear curve, psi	TAU1	4,500.
Strain limit of nonlinear portion of shear curve, in/in	GAMMA1	0.06
Shear modulus AB, BC, and CA, psi	GAB	3.0E+5
Min stress factor for limit after max stress (fiber tension)	SLIMT1	0.8
Min stress factor for limit after max stress (fiber comp)	SLIMC1	1.0
Min stress factor for limit after max stress (matrix tension)	SLIMT2	0.8
Min stress factor for limit after max stress (matrix comp)	SLIMC2	1.0
Min stress factor for limit after max stress (shear)	SLIMS	1.0
Material axes option (model dependent)	AOPT	0.0
Maximum effective strain for element layer failure	ERODS	0.5
Failure surface type	FS	-1.0
Strain at longitudinal compressive strength, in/in	E11C	0.007
Strain at longitudinal tensile strength, in/in	E11T	0.0143
Strain at transverse compressive strength, in/in	E22C	0.012
Strain at transverse tensile strength, in/in	E22T	0.025
Strain at shear strength, in/in	GMS	0.45
Longitudinal compressive strength, psi	XC	40,000.
Longitudinal tensile strength, psi	XT	89,000.
Transverse compressive strength, psi	YC	25,000.
Transverse tensile strength, psi	YT	54,000.
Shear strength, psi	SC	7,100.

The solid elements representing the foam core in the sinusoid model were assigned Mat 63, which is a crushable foam material model in LS-DYNA® that allows user input of the stress-strain response of the material in tabular format. The stress-strain response of the P200 foam was determined through quasi-static testing of 4-in. x 4-in. x 3-in. rectangular blocks. The experimental curves obtained at crush rates of 0.1- and 1.0-in/minute are plotted in Figure 4, along with the corresponding stress-strain responses used as input to Mat 63. Note that the input curves match the test data to a strain of 0.67-in/in. At this point, the test data ends, yet the Mat 63 input responses continue and increase dramatically up to 10,000-psi at a strain of 1-in/in (note that these data points are not shown in the plot). The large "tail" added to the end of the stress-strain response represents compaction of the foam and is needed to stabilize the response of the solid elements for high values of volumetric strain.

During the development of the sinusoid energy absorber, a quasi-static crush test was performed. The component was placed in a servo-hydraulic test machine and the specimen was statically crushed at a rate of 0.1-in/minute until a total crush displacement of 2-in. was achieved. The model, shown in Figure 3, was executed to replicate quasi-static loading. The foam core was assigned Mat 63 properties with input stress-strain data matching the 0.1-in/minute response, shown in Figure 4. The rigid loading mass was assigned a prescribed vertical displacement to achieve a maximum of 2.6-in. by the termination time. SPC nodal forces were summed and plotted versus displacement of the loading mass. The simulation was executed using LS-DYNA® SMP version 971 on a Linux-based workstation with 8 processors and required 17 hours of clock time to execute the simulation for 0.3-seconds.

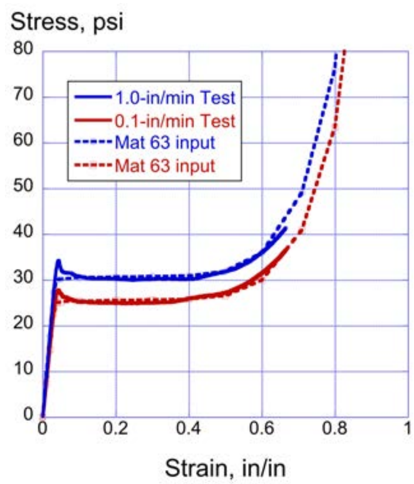


Figure 4. Plots of P200 foam stress-strain responses at two strain rates.

The experimental and analytical load-displacement curves are plotted in Figure 5. For the test, a peak load of 4,610-lb was recorded and a sustained crush load of 1,778-lb was determined over a displacement range of 0.3- to 2.0-in. The initial simulation over predicted the peak load (6,267-lb compared with 4,610-lb for the test) and over predicted the sustained crush load (2,417-lb compared with 1,778-lb for the test). Based on these results, modifications were made to the model. A slight 2° tilt angle was added to the loading mass as a means of incorporating eccentricity into the model. This change lowered the peak load of the simulation to 4,559-lb, which closely matches the test. In addition, a sensitivity study was conducted by varying the ERODS parameter. A value of 0.2 provided simulation results that closely matched the sustained crush load of the test (1,832-lb for the model compared with 1,778-lb for the test). Consequently, the modified model results shown in Figure 5 were generated from a simulation that contained two changes from the original model: a 2° tilt of the loading mass and an ERODS value of 0.2.

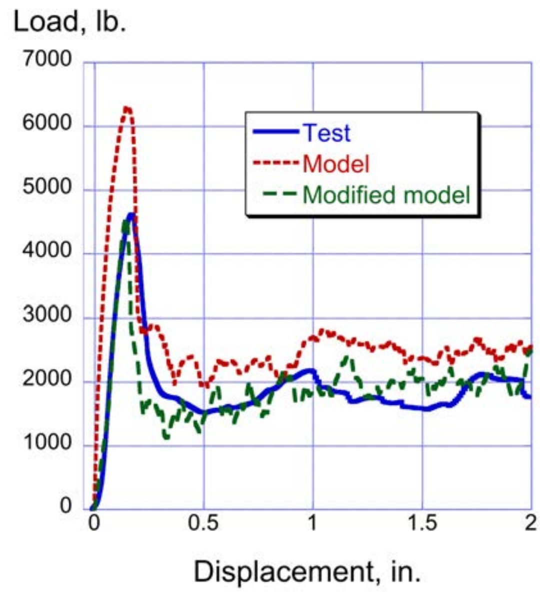
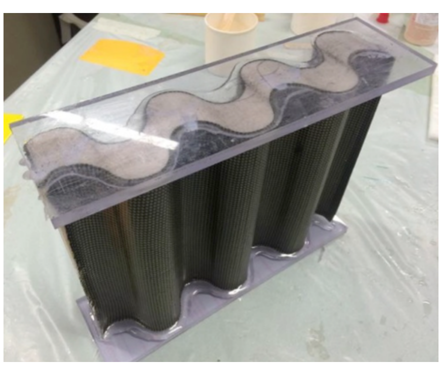
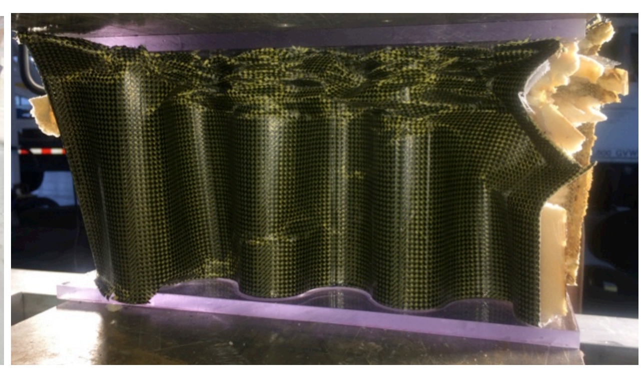


Figure 5. Test-analysis load-displacement responses for the quasi-static crush test.

A dynamic impact test of the sinusoid component was performed using a 14-ft. vertical drop tower. Pre- and post-test photographs of the sinusoid component are shown in Figures 6(a) and (b), respectively, for a dynamic crush test in which a 113.5-lb mass impacted the sinusoid at 265-in/s (22.08-ft/s). Prior to the drop test, 0.5-in.-thick polycarbonate mounting plates were attached to both the top and bottom surfaces of the specimen. The specimen exhibits stable, plastic-like deformation with uniform folding of the face sheets and crushing of the foam core. Crushing of the component initiates along the top edge of the specimen. Note that the sides of the specimen were not covered with face sheets, which allowed splaying of the foam core.



(a) Pre-test photograph.

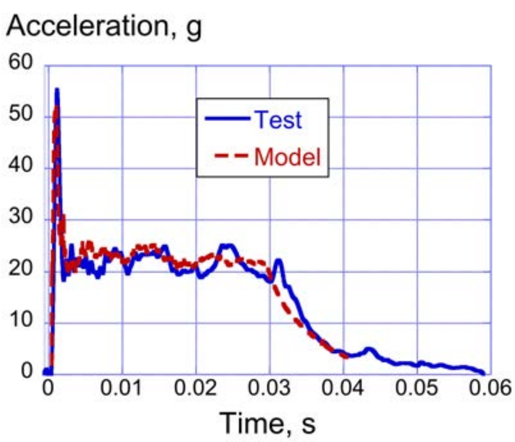


(b) Post-test photograph.

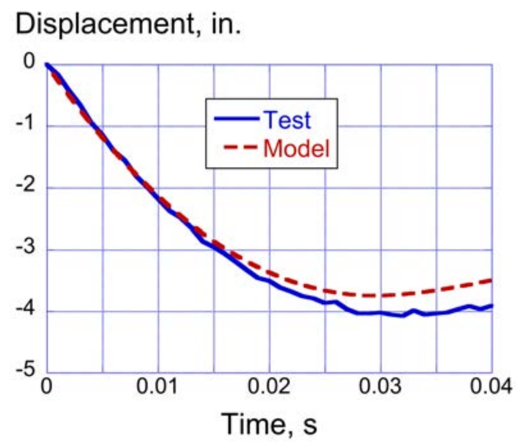
Figure 6. Pre-test photograph of a sinusoid foam sandwich component.

The sinusoid model, shown in Figure 3, was executed to generate analytical predictions of the dynamic crushing response of the sinusoid component. For the dynamic model, the foam core was assigned Mat 63 properties with input stress-strain data matching the 1.0-in/min test response. Also, the baseline value of ERODS (0.5) was used. All nodes forming the rigid loading mass were assigned an initial velocity matching the measured velocity of the test (265-in/s). The simulation was executed using LS-DYNA® SMP version 971 on a Linux-based workstation with 8 processors and required 10 hours and 34 minutes of clock time to execute the simulation for 0.04-seconds. Model output included time-history responses of the drop mass, and image sequences of structural deformation.

Test-analysis comparisons of time-history responses are plotted in Figure 7 for the sinusoid component impact test. These results demonstrate excellent test-analysis agreement. As can be seen in Figure 7(a), the acceleration response of the drop mass achieves an initial peak of 55-g, then drops to approximately 22-g, where it remains constant until the end of the pulse. The model mimics this response, even predicting the unloading response near the end of the pulse. The average acceleration calculated for the test is 21.8-g for pulse duration of 0.0- to 0.03-s, whereas the average acceleration of the predicted response is 22.9-g for the same duration. The experimental and analytical displacement responses, shown in Figure 7(b), exhibit maximum values of 4- and 3.8-in., respectively, which represents approximately 50% stroke. The average acceleration results for the sinusoid fall slightly below the required design goal of 25- to 40-g. The lower average crush acceleration for the sinusoid simply translates into a larger crush stroke.



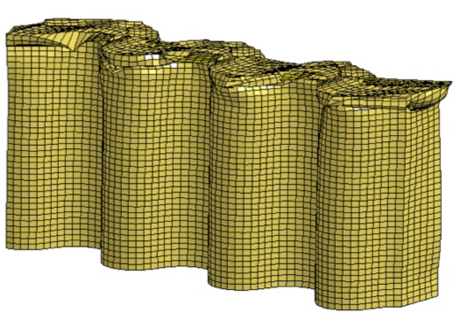
(a) Acceleration responses.



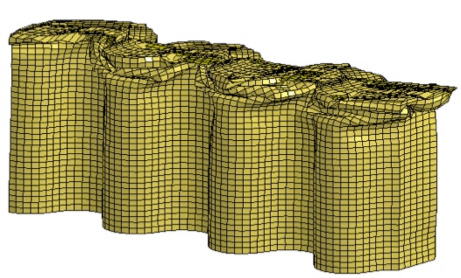
(b) Displacement responses.

Figure 7. Test-analysis time history comparisons for the sinusoid component.

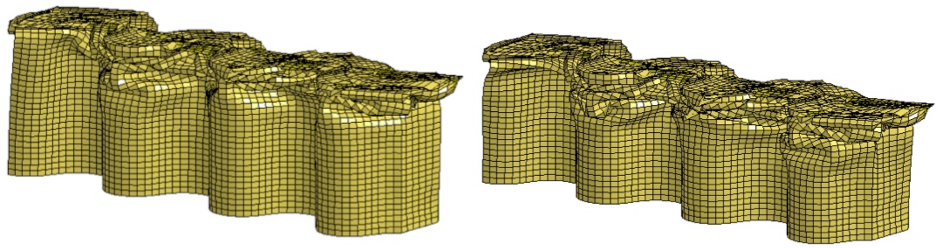
The predicted sinusoid model deformation is shown in Figure 8 for six discrete time steps. The model exhibits stable folding and plastic-like deformation of the face sheets and crushing of the foam core. The deformation pattern matches the post-test response, shown in Figure 6(b).



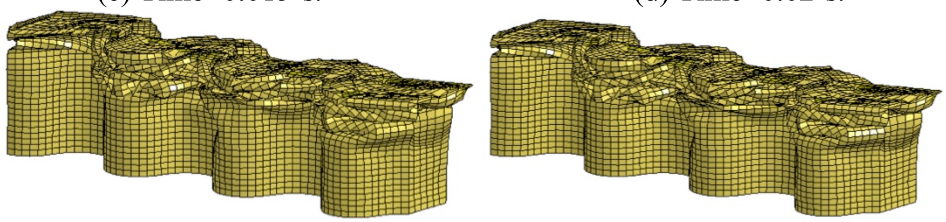
(a) Time=0.005-s.



(b) Time=0.01-s.



(c) Time=0.015-s. (d) Time=0.02-s.



(e) Time=0.025-s. (f) Time=0.03-s.

Figure 8. Predicted sinusoid model deformation.

RETROFITTED BARREL SECTION DROP TESTING AND SIMULATION

Following the TRACT 1 crash test, a portion of the forward cabin, Fuselage Station (FS) 164 through FS250, was separated from the remainder of the post-test specimen. The resulting 7.2-ft-long barrel section was essentially undamaged during the TRACT 1 test and was retrofitted with two of the energy absorbing concepts planned for TRACT 2, including the conusoid and the sinusoid foam sandwich designs. The original floor in the barrel section was removed and was replaced with a sheet of 0.5-in.-thick polycarbonate. The reason for this change was to enable viewing of the crushing response of the energy absorbers using high-speed cameras. The total weight of the fully loaded barrel section was 1,810-lb. It was impacted onto concrete at 297.6-in/s (24.8-ft/s). The objectives of the barrel section test were to evaluate: (1) the performance of two energy absorbers during a full-scale drop test prior to the TRACT 2 test, (2) the fabrication methods for the energy absorbers, (3) the structural integrity of the retrofit, (4) the strength of the polycarbonate floor, and (5) imaging techniques used during the test.

Pre-test photographs of the barrel section test article are shown in Figures 9(a) and (b), highlighting front and rear views, respectively. A close-up photograph showing the sinusoid foam sandwich energy absorber that was retrofitted into the barrel section is shown in Figure 10. The sinusoid energy absorber was located at FS190, in front of the conusoid. Both energy absorbers were painted white and vertical tick marks were added to aid in deformation tracking. The floor of the fuselage section was loaded with a 320-lb concentrated mass on the right-hand side and a double seat with two 50th percentile male Anthropomorphic Test Devices (ATDs) on the left-hand side, both centered about FS190 and located just above the sinusoid energy absorber. The seat was attached to the floor using standard seat tracks and the seated dummies were restrained using lap belts only. The combined weight of the seat and dummies was 405-lb. Thus, the total floor loading above the sinusoid energy absorber was 725-lb. This loading condition was intended to replicate the anticipated TRACT 2 configuration. Note that the conusoid was loaded by a 681-lb concentrated mass centered about FS220, as shown in Figure 9(b).

(a) Front view.

(b) Rear view.

Figure 9. Front and rear view photographs of the CH-46E barrel section.

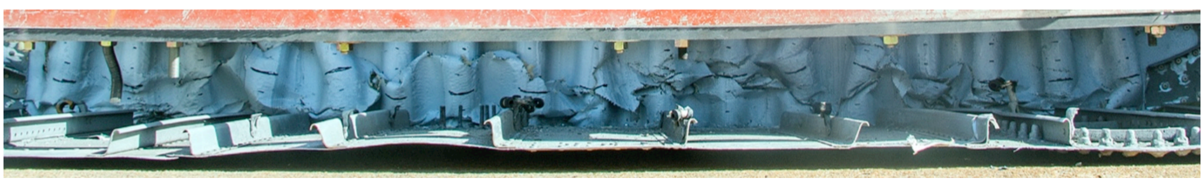
Figure 10. Pre-test photograph of the sinusoid energy absorber, as retrofitted into the barrel section.

The barrel section test was conducted by raising the test article to a height of 115.2-in. (9.6-ft) and releasing it to impact a concrete surface at 297.6-in/s (24.8-ft/s). Data were collected at 25-kHz primarily from accelerometers located throughout the cabin and on the 320- and 681-lb masses.

Post-test photographs of the barrel section and the sinusoid energy absorber are highlighted in Figure 11. The original height of the sinusoid energy absorber was 8.75-in. and the measured post-test height was 4.44-in., providing a crush stroke of 49.3%. As seen in Figure 11(b), the sinusoid foam sandwich energy absorber displayed crushing of the foam core, and fracturing of the face sheets starting from the bottom, curved edge. The sinusoid energy absorber in the barrel section did not exhibit the uniform folding pattern seen in the face sheets of the component specimen.

One issue with the barrel section drop test was noted following the impact event. Two 0.5-in.-diameter steel bolts were used to attach the 320-lb mass to the polycarbonate floor of the section. These bolts were approximately 12-in. in length, and one bolt was located 12-in. in front of the other. After drilling through the lead mass and floor, the bolts extended approximately 3.5- to 4-in. into the subfloor crush zone. The extra bolt lengths were not trimmed prior to the test and the bolts impacted the bottom skin of the fuselage section during the test. The forward bolt can be seen on the left side of Figures 10 and 11(b). Following the test, the bolts were removed and they are depicted in the photograph of Figure 12. The forward bolt impacted the bottom fuselage skin and deformed plastically. Much less permanent deformation is seen in the second bolt. The presence of these bolts affected the acceleration response of the 320-lb mass during the latter portion of the time history response, which will be discussed later in the paper.

(a) Post-test photograph of the barrel section.



(b) Post-test photograph highlighting the post-test crush response of the sinusoid.

Figure 11. Post-test photographs of the barrel section drop test.

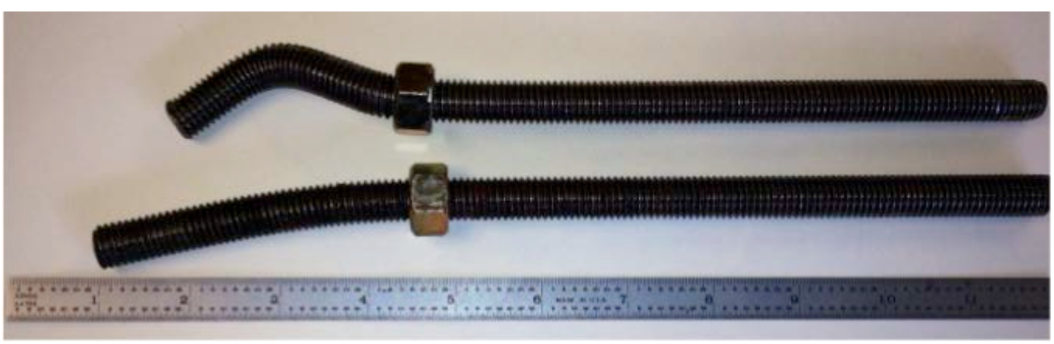


Figure 12. Post-test photograph of exposed steel bolts.

The finite element model of the barrel section is shown in Figure 13. This model contains: 105,986 nodes; 22 parts; 10 material definitions; 57,041 Belytschko-Tsay shell elements; 63,591 solid elements; 1,677 beam elements; 1 initial velocity; 1 contact definition; 20 discrete masses; 2 lumped masses representing the 320- and 681-lb blocks used in the test article; and 1 planar rigid wall representing the impact surface, which is not shown in Figure 13. The seat and occupants were represented using 20 discrete masses assigned to nodes at the approximate seat track attachment locations. All nodes in the barrel section model were assigned an initial velocity of 297.6-in/s (24.8-ft/s), matching the measured test velocity.

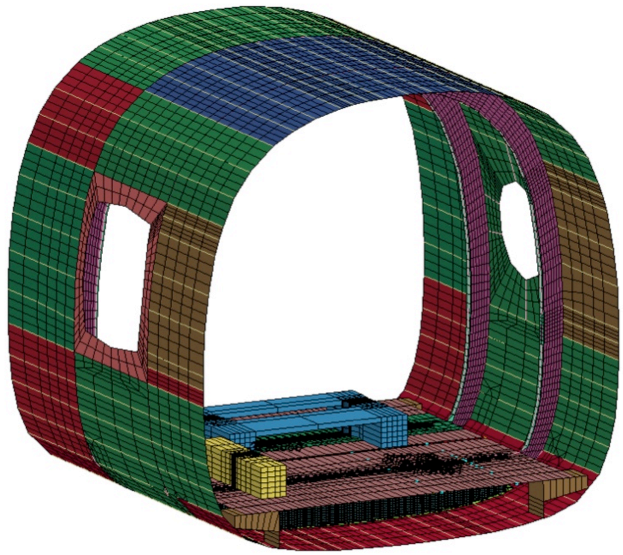


Figure 13. Finite element model of the CH-46E barrel section.

The finite element model of the sinusoid subfloor is shown in Figure 14. As before, the face sheets were represented as two layers of hybrid carbon-Kevlar® plain weave fabric with a stacking sequence of ±45° that were assigned Mat 58 material properties (see Table I). The solid elements representing the foam core were assigned Mat 63 with input stress-strain data matching the 1.0-in/min response, shown in Figure 4. A nominal element edge length of 0.25-in. was used in the sinusoid mesh. Note that in the test article, the energy absorbers were attached to the outer skin and floor using rivets. In the model, the rivets were not physically modeled; however, coincident nodes were used to tie the parts together. The aluminum outer skin and frames were assigned properties of Mat 24, an elastic-plastic material model. The steel bolts were simulated using beam elements that were assigned material properties of steel.

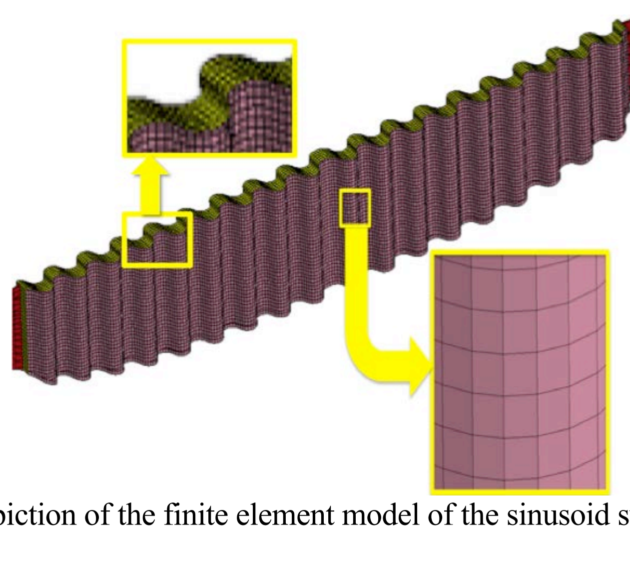
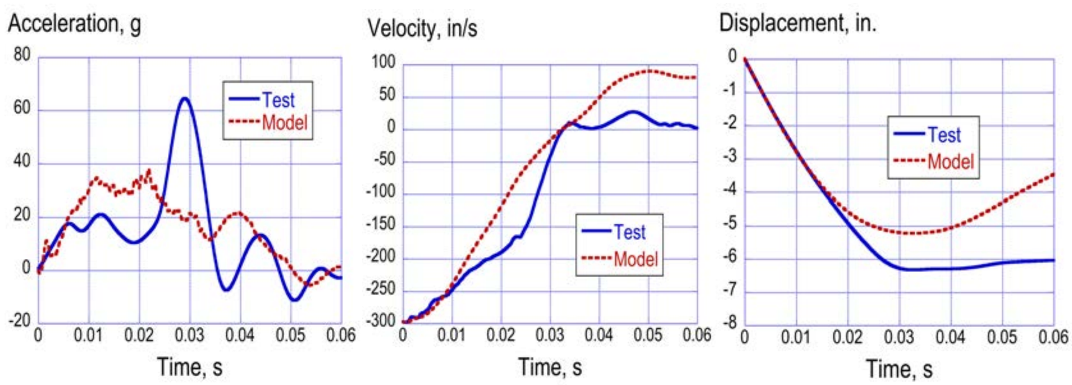


Figure 14. Depiction of the finite element model of the sinusoid subfloor.

An automatic single surface contact was assigned to the model with static and dynamic coefficients of friction of 0.3. This general contact definition is used to prevent any node from penetrating any element within the model. The model was executed using LS-DYNA® SMP version 971 on a Linux-based workstation with 8 processors and required 31.75 hours of clock time to execute the simulation for 0.065-seconds. Model output included time-history responses of the 320- and 681-lb lumped masses, and image sequences of structural deformation.

Test-analysis time-history responses of the 320-lb mass, located above the sinusoid energy absorber, are plotted in Figure 15. While the predicted responses demonstrate reasonable comparison with test, the model fails to predict the large increase in acceleration that occurs just prior to 0.03-s. This 64-g peak is attributed to impact of the steel bolts with the outer skin. Even though the model includes the bolts, the predicted acceleration response does not match the test. Average accelerations of 14.2- and 17.0-g were calculated for the test and predicted responses, respectively, for a pulse duration of 0.0- to 0.06-s. It should be noted that average test and predicted accelerations are well below the design goal of 25- to 40-g. The test-analysis velocity responses are shown in Figure 15(b), both of which cross zero at the same time (0.033-s), even though the test and predicted curves deviate shortly after 0.01-s. The model predicts a much higher rebound velocity than the test, which indicates that the model returns too much elastic energy and that the unloading response is not adequately represented. The experimental and predicted maximum crush displacements are 6.3- and 5.24-inches, respectively, a difference of 1-in.



(a) Acceleration. (b) Velocity. (c) Displacement.

Figure 15. Comparisons of experimental and predicted responses of the 320-lb mass.

Three images from the high-speed video are compared with predicted model deformation in Figure 16 at times of 0.01-, 0.03-, and 0.043-s. By 0.043-s, fairly severe deformations are evident in the upper portion of the fuselage section. This deformation is asymmetric, and is not captured by the model. While the model exhibits some oscillatory motion in the outer skin, it does not show the large deformation evident in the test. It should be noted that the deformation in the test article is elastic, since the upper fuselage section returns to its normal shape by the end of the simulation, as indicated in the post-test photograph shown in Figure 11(a).

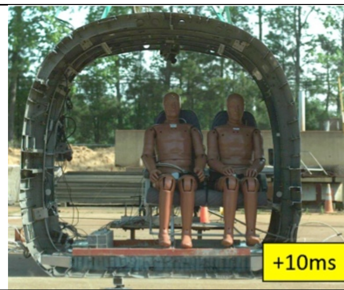
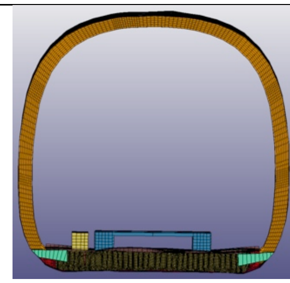
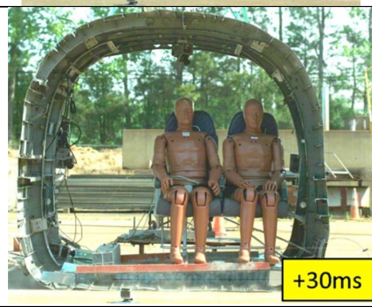
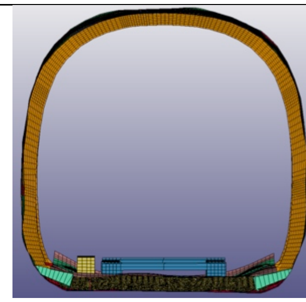
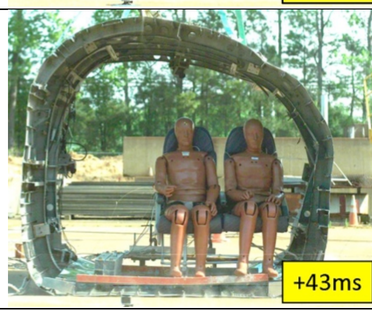
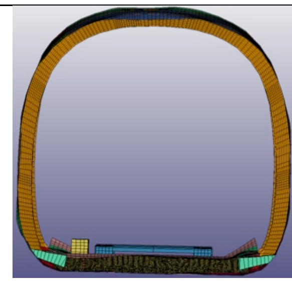
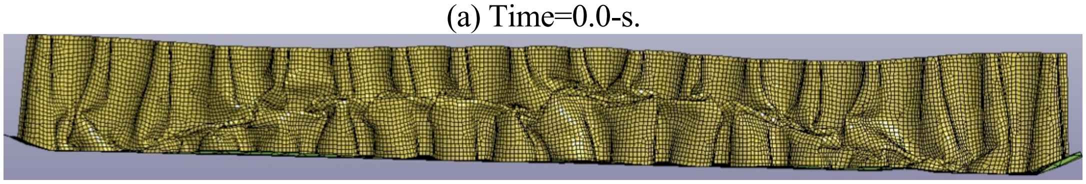
Time, s	Test	Model
0.01-s		
0.03-s		
0.043-s		

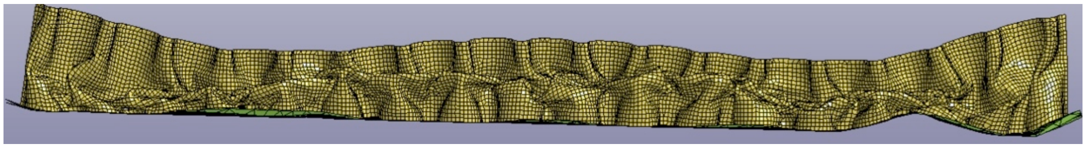
Figure 16. Comparison of experimental and predicted deformation patterns.

A time sequence of predicted sinusoid foam sandwich deformations is shown in Figure 17. Initially, the crush pattern is non-uniform due to the fact that the subfloor is loaded by two discrete masses, the 320-lb mass on one side and the seat and occupants on the other. Note that the sides of the sinusoid subfloor that attach to the fuselage frames are relatively undamaged. Finally, a post-test photograph of the sinusoid subfloor, which was removed from the test article, is shown in Figure 18. The deformation and failure pattern of the sinusoid is more uniform than the predicted response; however, the locations and types of damage are similar.

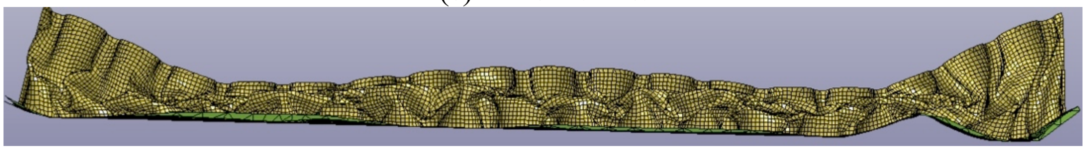
(a) Time=0.0-s.



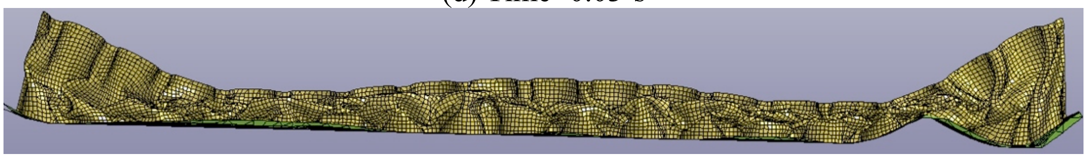
(b) Time=0.01-s



(c) Time=0.02-s.



(d) Time=0.03-s



(e) Time=0.04-s

Figure 17. Predicted deformation pattern of the sinusoid foam sandwich subfloor.

Figure 18. Photograph of the sinusoid foam sandwich energy absorber, removed from the test article. Note that the subfloor section is lying on its side with a portion of the polycarbonate floor still attached.

DISCUSSION OF RESULTS

Two objectives of the TRACT 2 project were to develop composite energy absorbers for retrofit into the second CH-46E airframe prior to crash testing, and to assess the capability of finite element simulations, developed using LS-DYNA®, to predict their dynamic crushing behavior. The design goals for the energy absorbers were to achieve between 25- to 40-g average crush accelerations, to minimize peak crush loads, and to generate relatively long crush stroke limits under dynamic loading conditions, typical of those experienced during the TRACT 1 [2] full-scale crash test. Results of component impact testing proved that the sinusoid energy absorber met the goal with an average crush acceleration of 21.8-g. Note that the lower average crush acceleration exhibited by the sinusoid simply translates into a larger crush stroke.

Test-analysis comparisons are listed in Table II for each level of evaluation, component through barrel-section testing. Results are presented as percentage differences of peak load, sustained crush load, average crush acceleration, and maximum crush displacements, as appropriate. Note that component test-analysis comparisons agree within 5%. As shown in Table II, barrel section comparisons are not as good as for the component tests, mainly due to the fact that some anomalies occurred during the drop test. Two steel bolts interfered with crushing of the sinusoid. However, despite this anomaly, test-analysis comparisons were within 20%.

TABLE II. TEST-ANALYSIS COMPARISONS

Test Article Description	Metric	Test	Model	% Difference
Sinusoid Component (Quasi-Static Test)	Peak load, lb.	4,610	4,559	1.1
Sinusoid Component (Quasi-Static Test)	Sustained Crush Load, lb.	1,778	1,832	-3.0
Sinusoid Component (Impact Test)	Avg. Acceleration, g (0.03-s pulse duration)	21.8	22.9	-5.0
Sinusoid Component (Impact Test)	Max crush displacement, in.	4.0	3.8	5.0
Barrel section, 320-lb mass, above the sinusoid	Avg. Acceleration, g (0.0575-s pulse)	14.2	17.0	-19.7
Barrel section, 320-lb mass, above the sinusoid	Max crush displacement, in.	6.3	5.2	16.8

CONCLUSIONS

This paper has described the development and multi-level evaluation of a sinusoidal-shaped foam sandwich energy absorber, which was designed to achieve between 25- to 40-g sustained average crush accelerations, to minimize peak crush loads, and to generate relatively long crush stroke limits during retrofit onto the second Transport Rotorcraft Airframe Crash Testbed (TRACT 2) full-scale crash test. The energy absorber, designated the "sinusoid," consists of two face sheets, oriented at ±45° with respect to the vertical or crush direction and fabricated of hybrid graphite-Kevlar® fabric material, and a 1.5-in. closed-cell polyisocyanurate foam core separating the face sheets.

The sinusoid was evaluated using a multi-level, building-block approach, including both testing and LS-DYNA® simulation. Initially, component specimens were subjected to both quasi-static crushing and vertical impact loading. The components had nominal dimensions of 12-in. in length, 7.5-in. in height and an overall width of 1.5-in. The component tests were used to assess the energy absorption capabilities of the design. The impact condition for all of the dynamically crushed specimens was approximately 264-in/s (22-ft/s).

Next, a 5-ft-long subfloor beam of the sinusoid foam sandwich configuration was manufactured and retrofitted into a barrel section of a CH-46E helicopter airframe. A vertical drop test of the barrel section was conducted at 297.6-in/s (24.8-ft/s) onto concrete. The sinusoid energy absorber, located at FS190, was loaded by a 320-lb concentrated mass on the right side, as well as a double seat with two Anthropomorphic Test Devices on the left side. The objectives of the test were to evaluate: (1) the performance of the two energy absorbers during a full-scale drop test prior to the TRACT 2 test, (2) the fabrication methods for the energy absorbers, (3) the structural integrity of the retrofit, (4) the strength of the polycarbonate floor, and (5) imaging techniques used during the test.

For each multi-level evaluation of the subfloor concepts, test data were used to validate simulations performed using the commercial nonlinear explicit, transient dynamic finite element code, LS-DYNA®. Finite element models were developed to represent quasi-static and dynamic crushing of the component specimens, as well as the vertical impact of the retrofitted barrel section onto concrete.

Major findings of this research effort are listed, as follows:

- The sinusoid foam sandwich concept proved to be an excellent energy absorber, as demonstrated through component testing. During quasi-static testing, the energy absorber demonstrated an average sustained crush load of 1,778-lb. During impact testing, the sinusoid component absorbed energy through localized uniform folding of the face sheets and foam crushing. An average acceleration of 21.8-g was recorded for the sinusoid over 50% crush stroke.
- For the sinusoid component, LS-DYNA® predictions showed excellent comparison with test data, within ±5%. The model predicted an average acceleration of 22.9-g. In addition, the model was able the capture the predominant failure modes exhibited by the test specimen.
- The barrel section drop test results were complicated by the fact that two long bolts, used to attach the concentrated mass to the floor over the sinusoid, were untrimmed prior to the drop test, allowing the bolts to invade the subfloor crush zone. The bolts impacted the outer skin of the fuselage section and deformed plastically. This event resulted in a large increase in the acceleration response near the end of the pulse, as measured on the 320-lb. concentrated mass located over the sinusoid energy absorber. Despite this complication, average accelerations of 14.2-g were recorded on the 320-lb concentrated mass.
- During the barrel section impact, the sinusoid foam sandwich energy absorber exhibited 49.3% crush stroke and displayed crushing of the foam core, and fracturing of the face sheets starting from the bottom, curved edge. The sinusoid energy absorber in the barrel section did not exhibit the uniform folding pattern seen in the face sheets of the component specimen.
- LS-DYNA® model predictions for the barrel section drop test were reasonable, within 20%; however, results indicated that the model was generally too stiff. For example, the predicted maximum crush displacement of the sinusoid was 5.2-in. and the experimental maximum crush displacement was 6.3-in., a difference of approximately 1-in.

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