Use of LS-DYNA® to Assess the Energy Absorption Performance of a Shell-Based Kevlar™/Epoxy Composite Honeycomb

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Abstract

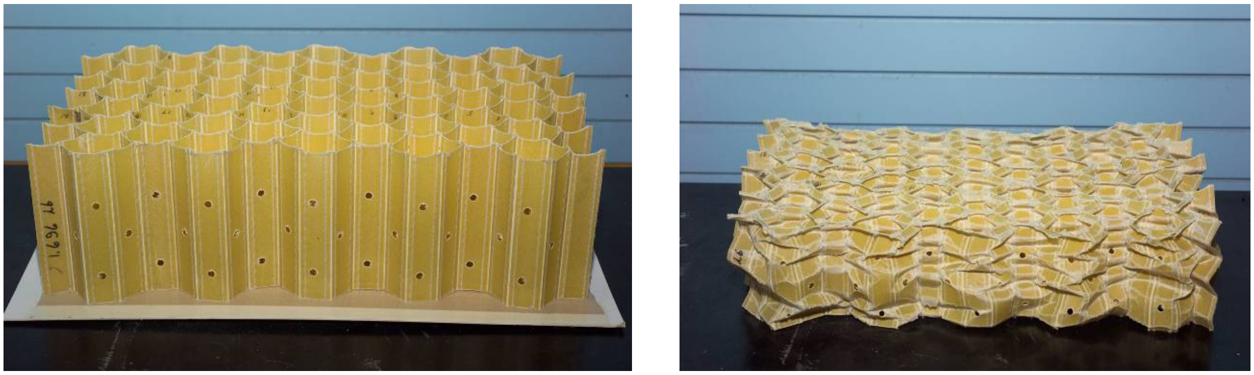
The forward and vertical impact stability of a composite honeycomb Deployable Energy Absorber (DEA) was evaluated during a full-scale crash test of an MD-500 helicopter at NASA Langley's Landing and Impact Research Facility. The lower skin of the helicopter was retrofitted with DEA components to protect the airframe subfloor upon impact and to mitigate loads transmitted to Anthropomorphic Test Device (ATD) occupants. To facilitate the design of the DEA for this test, an analytical study was conducted using LS-DYNA® to evaluate the performance of a shell-based DEA incorporating different angular cell orientations as well as simultaneous vertical and forward impact conditions. By conducting this study, guidance was provided in obtaining an optimum design for the DEA that would dissipate the kinetic energy of the airframe while maintaining forward and vertical impact stability.*

Introduction

The development of an externally Deployable Energy Absorbing (DEA) [1, 2] concept is a major task being addressed by NASA's Subsonic Rotary Wing Crashworthiness program. The DEA is a composite honeycomb cellular structure with flexible hinged walls designed for omnidirectional and linear external deployment to provide energy dissipation. Once expanded, the DEA becomes an efficient cellular structure, possessing high strength and stiffness along the cell axis compared to the transverse direction. The cell walls of the DEA are comprised of 1-inch wide single woven plies of Kevlar™-129 fabric, whose fibers contain a ±45° orientation, and impregnated with RenInfusion™ 8601 epoxy. The DEA is also designed to have a crush strength of about 20 psi. Photos of the DEA are found in Figure 1.

The development of the DEA has included static and dynamic tests conducted to characterize the Kevlar™-129 fabric/epoxy DEA material. Tensile tests of single Kevlar™-129 fabric/epoxy coupons, three-point bend tests of single hexagonal cells, dynamic vertical compression tests of multi-cell DEA components, and multi-terrain impact tests of DEA components retrofitted underneath a composite fuselage section were all conducted and simulated in support of this development. Testing for all these components are described in References 1 and 3.

* *Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.*



(a) Undeformed DEA (b) Deformed DEA

Figure 1. Undeformed and deformed configurations of the DEA

A finite element model (FEM) of each test was created and analyzed using the nonlinear, transient dynamic code LS-DYNA® [4]. In all these cases, the DEA was modeled using shell elements to accurately represent the thin-walled geometry of the cells. Reference 5 describes a comparison of two material models in LS-DYNA® used to replicate the behavior of Kevlar™-129 fabric/epoxy during these tests: *MAT_LAMINATED_COMPOSITE_FABRIC (*MAT_58), and *MAT_PIECEWISE_LINEAR_PLASTICITY (*MAT_24). It was shown that *MAT_24 did a better job at predicting the crushing and folding characteristics of the DEA under pure vertical impact.

Generally, the ability to analytically represent deformation modes in composites subjected to impact loading is challenging, often leading to large model sizes that can take up to several days to run. Existing analytical tools lack the capability to accurately capture failure modes of composites, such as delamination; thus, special modeling techniques are often needed. Beams [6] and cohesion elements [7] that include failure criteria have been implemented in composite laminates to simulate delamination. The inclusion of these element formulations could lead to larger model sizes and longer run times. The use of shell elements is typically preferred due to their decreased run times for large composite structures and to represent thin-walled geometry of composite laminates. Shells have also consistently proven to capture key geometric deformations essential to predicting accurate crush response of honeycomb structures [8, 9].

The development of the DEA has recently been expanded to include its application in a full-scale crash test of an MD-500 helicopter, conducted in December 2009 at NASA Langley's Landing and Impact Research Facility [10]. The test was conducted to evaluate the effectiveness of the DEA in protecting the helicopter structure and its occupants under severe, but potentially survivable, crash conditions. The total weight of the test article and the occupants was approximately 3,000 pounds total, and was dropped with a prescribed horizontal and vertical velocity of 40 feet per second and 26 feet per second, respectively, resulting in an effective flight path angle of 33 degrees. A picture of the test article is shown in Figure 2.

Figure 2. MD-500 Test Article

To prepare for this test, the DEA was first implemented on a reusable and simpler vehicle. An impact test was conducted in July 2009 on an MD-500 mass simulator, which consisted of a 2,500 pound aluminum plate attached to a skid gear via stainless steel brackets and lateral supports. Two DEA components were fabricated for the test, and the planned impact conditions were the same as those for the MD-500 helicopter. For both tests, an optimum shape for the DEA was needed to ensure stability of the vehicle during simultaneous forward and vertical impact while attenuating as much kinetic energy as possible. This paper will discuss the results of a parametric study that was conducted to guide the design of the DEA for these tests and predict the accuracy and energy absorption mechanisms of a shell-based DEA model under various impact conditions and cell angle orientations.

Parametric Study Description

The velocity vector orientations (impact angles) and the cell wall angles were individually varied during the course of the study. A picture of a typical model setup is found in Figure 3. The impact angle, denoted by phi (φ), was varied between 0 and 60 degrees from the vertical in 15-degree increments. The cell wall angle was varied between 0 and 30 degrees in 5-degree increments, and denoted by theta (θ). A total of 35 cases were considered for this study. A block weighing 1,000 pounds was attached to the DEA in all cases using *CONTACT_TIED_SHELL_EDGE_TO_SURFACE, and had dimensions of 27 inches by 26.5 inches by 2 inches. The block was modeled using a rigid material definition in LS-DYNA® and contained 1,512 elements. The height of the DEA was 20 inches, the width was 24 inches, and the depth was 24.2 inches. A 2-inch curvature height was also provided on the bottom of each component. The magnitude of the resultant velocity was prescribed at 20 feet per second, which is about 40% of the impact velocity for the MD-500 helicopter. An impact surface was also modeled using 2,100 shell elements that were assigned a *MAT_RIGID material definition. The thickness of these shells was 1 inch.

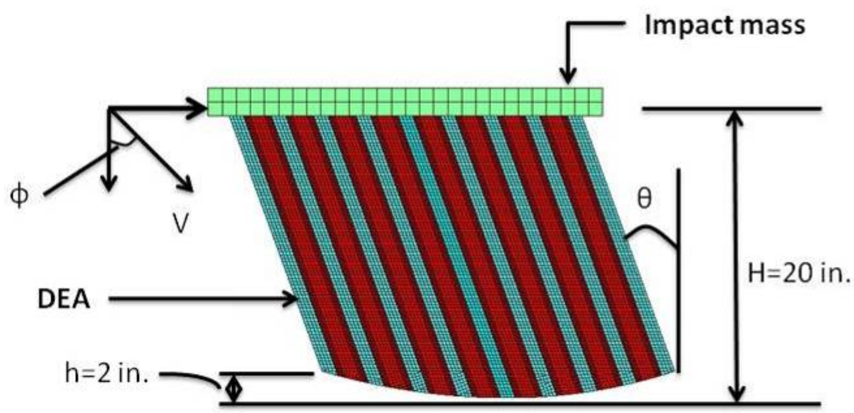


Figure 3. Typical DEA model setup for the Parametric Study

Based on good results obtained from previous impact studies conducted with the shell-based DEA model [5], the cell walls were modeled using *MAT_PIECEWISE_LINEAR_PLASTICITY, or *MAT_24. This material model uses an isotropic configuration that allows for input of elastic properties, and an effective stress-plastic strain curve can be input to define the plastic properties of the material. The tensile response from a single layer coupon of Kevlar™-129 fabric/epoxy at a ±45 degree orientation was input as the plastic response for this material model, where the tensile response was assumed equal to that in compression. The stress-plastic strain curve input for *MAT_24 can be found in Figure 4. In the plastic portion of the curve, the steep rise in stress is attributed to scissoring of the fibers, or a tendency of the fibers to align with the load direction. The input elastic properties can be found in Table 1.

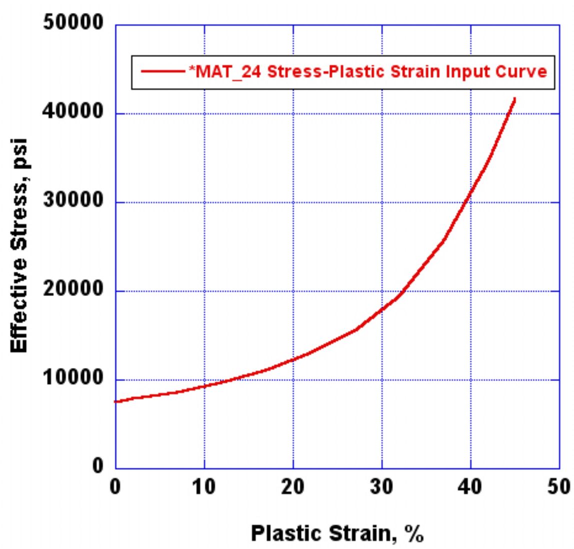


Figure 4. Input stress-plastic strain curve for *MAT_24

Table 1. Input properties for *MAT_24

Property	Parameter values
Young's Modulus (psi), E	**340000**
Poisson's Ratio, PRBA	**0.3**
Yield Stress (psi), SIGY	**7500**

A large number of shell elements was needed in modeling the cell walls to effectively capture the buckling and folding modes of the cells critical to the energy absorption of the DEA. On average, between 215,000 and 250,000 elements were used to model the DEA. A ¼-inch element size was prescribed on all DEA components resulting from mesh convergence studies conducted. Internal contact between the shell elements was needed to capture the proper folding and compaction of the DEA. Thus, the *CONTACT_AUTOMATIC_SINGLE_SURFACE card was used to capture the internal contact, in addition to contact between the DEA and the impact surface. The SOFT=1 option was used to model the contact due to the large difference in moduli between the DEA and the impact surface.

To obtain an appropriate value of friction defining contact between the DEA and concrete, a friction drag test was conducted at the Landing and Impact Research Facility. Three 32-cell DEA components with dimensions of 8.33 inches by 13 inches by 6 inches were attached to a plywood plate with weights added and dragged for 90 feet for a duration of 40 seconds. The total test article weighed approximately 230 pounds. The DEA contact surfaces were covered with Teflon™ Impregnated Glass Fabric face sheets to transmit load to the cells. The average friction load between the DEA and the impact surface was measured to be 139 pounds, and, thus, the coefficient of friction was determined to be 0.5. Pictures and results from the drag test can be found in Figures 5 and 6, respectively.

Figure 5. DEA Friction Drag Test

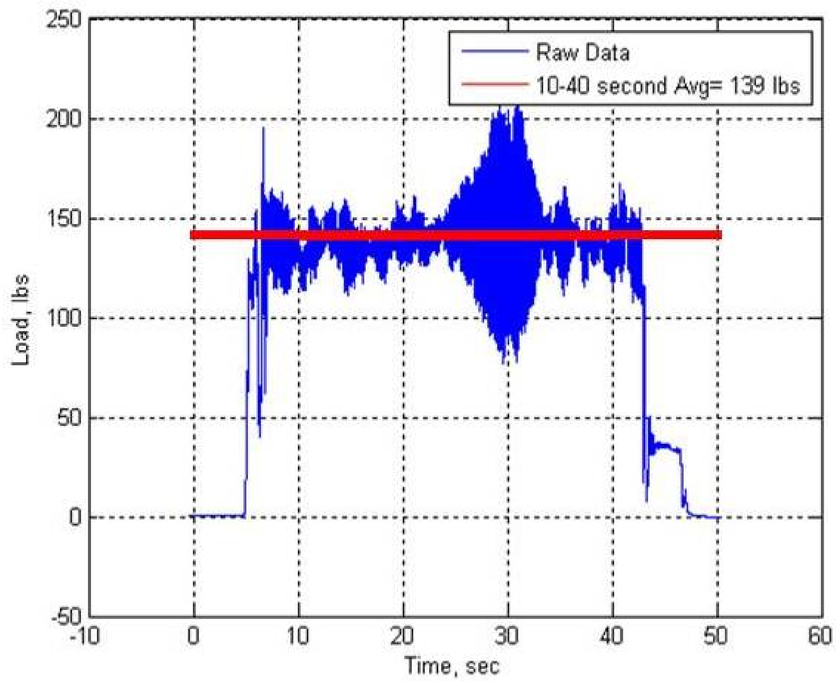


Figure 6. Time History for Friction Load

Parametric Study Results

To determine which cell wall orientation would be selected for the full-scale crash test, results of the study were evaluated by comparing the stability and the maximum internal energy of each simulation. To support the evaluations, three classifications of stability were identified. An impact case was considered stable if there was negligible pitch of the block due to cell wall orientation and friction. A case was considered marginally stable if there was some pitch of the block exhibited in the model, and the rotational velocity peaked before dropping to zero. A case was considered to be unstable if the rotational velocity of the block diverged, and the block either made contact with, or was close to contacting, the impact surface. All models were run using LS-DYNA® v971 R3.1 using double precision and two processors on a Windows 64-bit Workstation. The run times of all models varied between 4 hours and 20 hours for a termination time of 0.1 seconds.

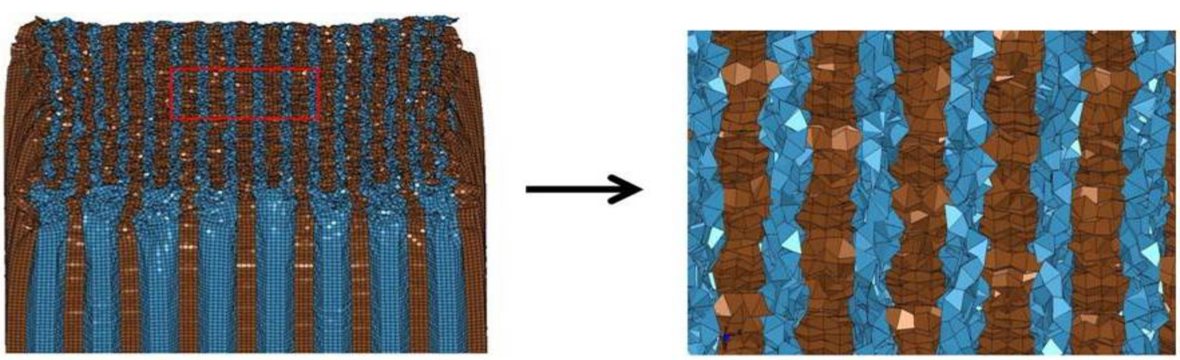
To assess the amount of energy absorbed by the DEA in each simulation, the maximum internal, or strain, energy was used. Table 2 shows stability results and values of maximum strain energy absorbed by the DEA for various cell wall orientations and impact angles. A few key phenomena were captured during this study. A diagonal band of stability is found as both the cell wall and impact angles increase, while the highlighted numbers indicate regions of instability as a result of both the cell wall orientation and impact conditions. Stability can also be seen as the cell wall angle is close or equal to the impact angle. Also, the maximum energy absorbed is seen when the impact and the cell wall orientation are both purely vertical. The folding and crushing mechanisms of the DEA were also captured during the course of the study. A picture of the deformed DEA model can be found in Figure 7.

To check the validity of the values in Table 2, the energy balance of the system was checked as calculated by LS-DYNA, and then compared with the theoretical energy balance. In reality, the energy balance should only account for Potential Energy and Kinetic Energy of the block. While the Kinetic Energy goes to zero from an initial value based on the mass and velocity of the system, in the model, not all of the energy is converted to deformation of the cells. In general, some of the Kinetic Energy is converted to Rigid Wall, Damping, Hourglass, and Sliding (Contact) Energies [11]. Thus, it was crucial that these energies remain low relative to the internal energy of the DEA in order to move forward with the parametric study. In the baseline case where both the impact velocity and cell orientation are purely vertical, the difference between the internal energy calculated in LS-DYNA® and the theoretical deformation energy of the DEA, derived from the energy conservation principle, was 6.5%. A second check was performed where the crush stress of the DEA model was calculated for the baseline case. Taking from the acceleration time history for the baseline case for vertical cell orientation and vertical impact, the crush stress was calculated to be 21 psi, which was close to the 20 psi crush design for the DEA. From these two calculation checks, it was concluded that the amount of energy absorbed in the DEA model for each case could be used as a guide for its design.

ϕ \ θ →	0°	5°	10°	15°	20°	25°	30°
0°	76000	76000	75450	72600	68700	63200	49800
15°	69500	73700	75750	75200	73700	67550	50400
30°	55300	63100	66250	66700	66450	59000	39400
45°	37900	45200	47000	49650	50000	41000	25700
60°	21800	26500	28000	30300	29900	23600	13700

Test Attitude= 33°

Table 2. Internal energy values (in pound-inch) and stability for all 35 impact cases



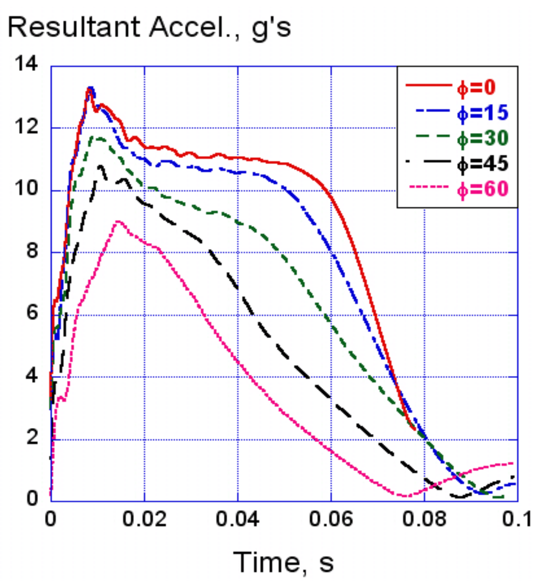
(a) Crushed DEA (b) Close-up of crushed DEA

Figure 7. Deformed DEA pattern

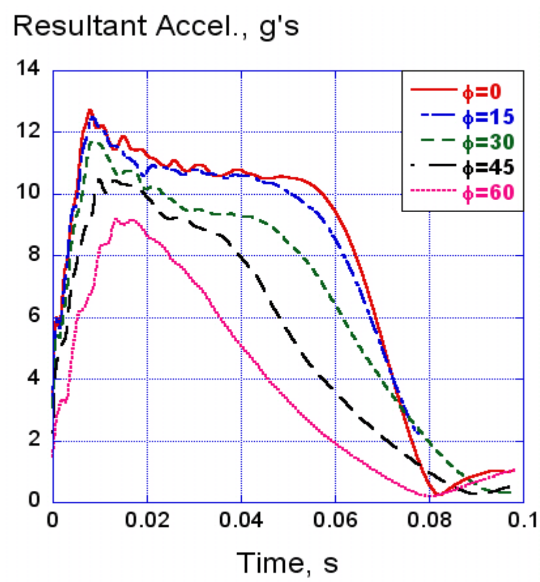
The acceleration traces for all 35 cases analyzed are shown in Figure 8. All acceleration time histories were taken from a node centered on the block and filtered using an SAE J211 CFC 180 [12] configuration. The trend follows that as the cell wall angles, or θ values, increase, the average acceleration levels decrease and get narrower. The pulse duration decreases as the impact angle, or φ value, increases for each orientation angle. Also, the peak acceleration level occurs when both the impact condition and the DEA orientation are purely vertical. Afterwards, a decrease in crush load can be seen as the cell orientation and the impact angles increase. As this happens, friction between the impact surface and the DEA becomes more important in dissipating Kinetic Energy of the block as the horizontal impact velocity component increases. However, it does not contribute much to the deformation patterns of the DEA, since the direction of applied dynamic loading to the DEA cells also varies with the φ value. When the cell orientation angles are not in line with the impact angles, the dynamic forces acting upon the DEA impose a crushing deformation on the cells, as opposed to localized folding and buckling deformations along the cell wall axis that lead to increased energy absorption.

Instability of the block with the DEA becomes more apparent as the cell angle orientation increases. In fact, in the case where θ equals 30 degrees and the φ angle equals zero, there is a spike in the acceleration that occurs towards the end of the simulation, as shown in Figure 8(g). This spike is attributed to the rigid block hitting the impact surface as a result of the instability from the steep cell wall orientation. Generally, while higher φ angles result in reduced acceleration levels, the impact directions allowed for greater instability of the block as a result of increased in-plane shearing of the cells relative to the cell wall axis. Thus, a configuration for the DEA was desired which greatly reduced the energy transferred to the structure and simultaneously provided structural stability of the DEA upon horizontal impact.

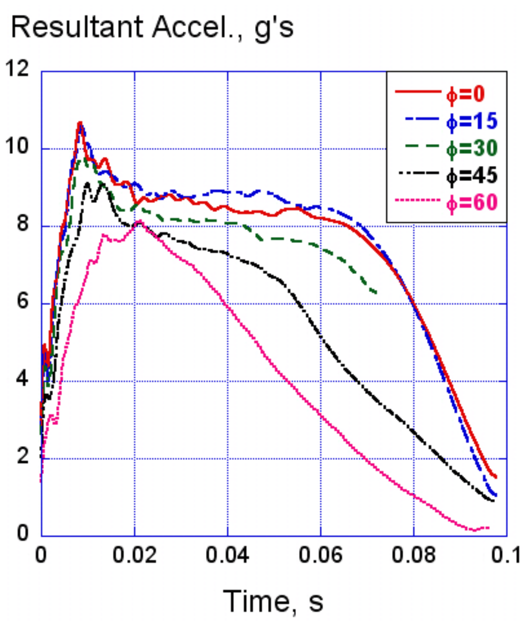
Given that the flight path angle for the full-scale crash test is 33 degrees, the cell wall angle that exhibited the most stability was 20 degrees. Ultimately, this orientation was selected for the DEA for both the MD-500 mass simulator and helicopter tests. The orientation of 20 degrees was selected on the condition that the DEA would be attached to a level surface. However, the helicopter subfloor under which the DEA components attach slopes upward in the aft direction of the helicopter. As a result, the configuration for the aft DEA component needed to be modified to adjust for the change in floor curvature. A picture of the subfloor from the MD-500 FEM is shown in Figure 9. The second DEA component was fabricated which contained purely vertical cell walls because the relative angle between the subfloor and the cell axis was such that impact stability could be provided at this orientation. DEA component models containing a 20 degree cant angle were incorporated into a FEM of the MD-500 mass simulator. In addition, DEA models for both configurations were later incorporated into a system integrated model of the MD-500 helicopter. Test/analysis correlation for both models is documented in [13].



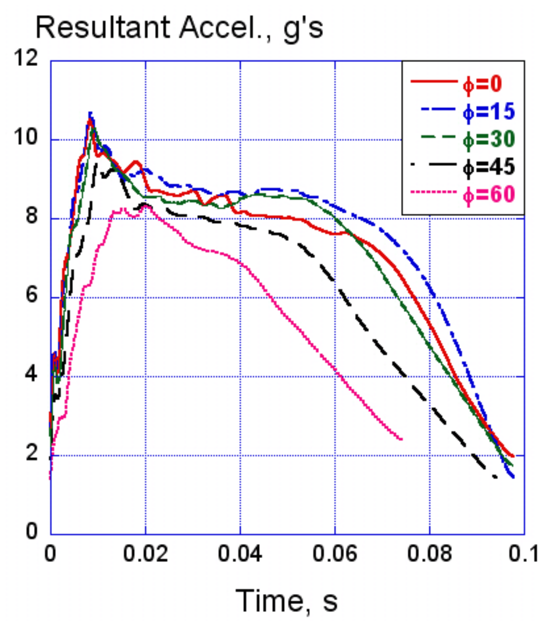
(a) θ=0°



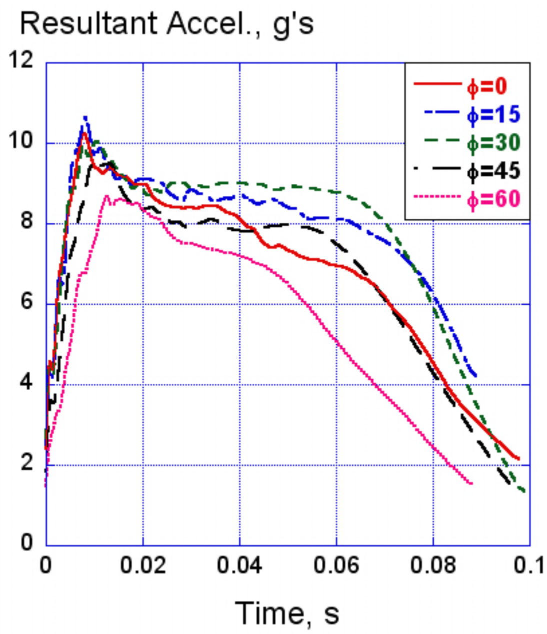
(b) θ=5°



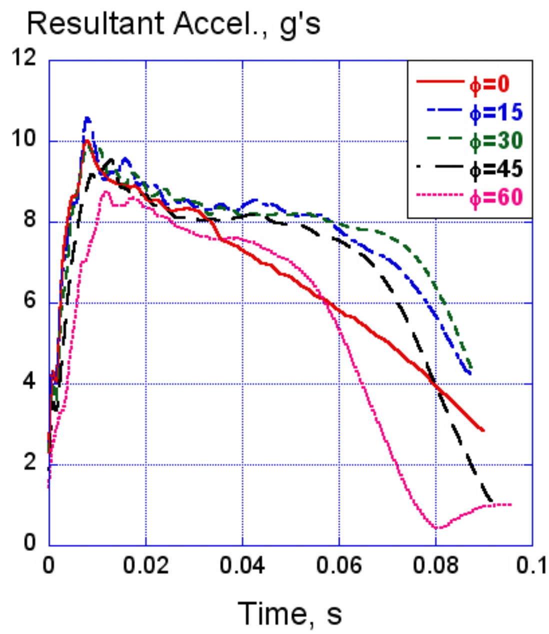
(c) θ=10°



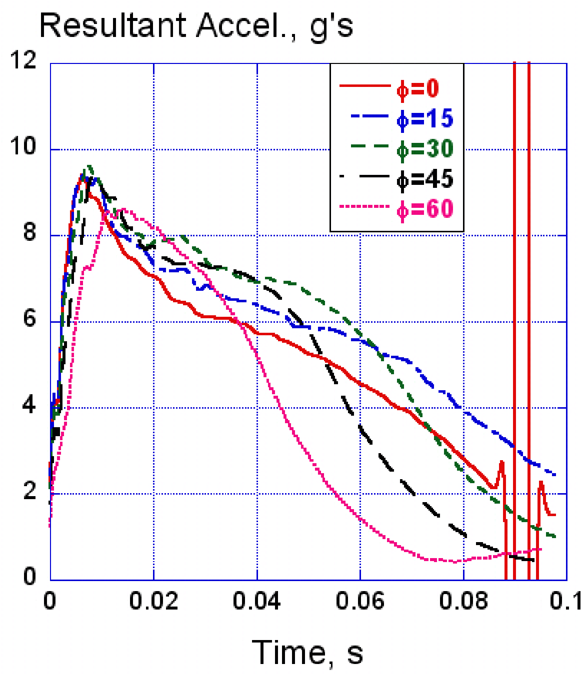
(d) θ=15°



(e) θ=20°



(f) θ=25°



(g) θ=30°

Figure 8. Acceleration Time Histories of DEA Impact Response

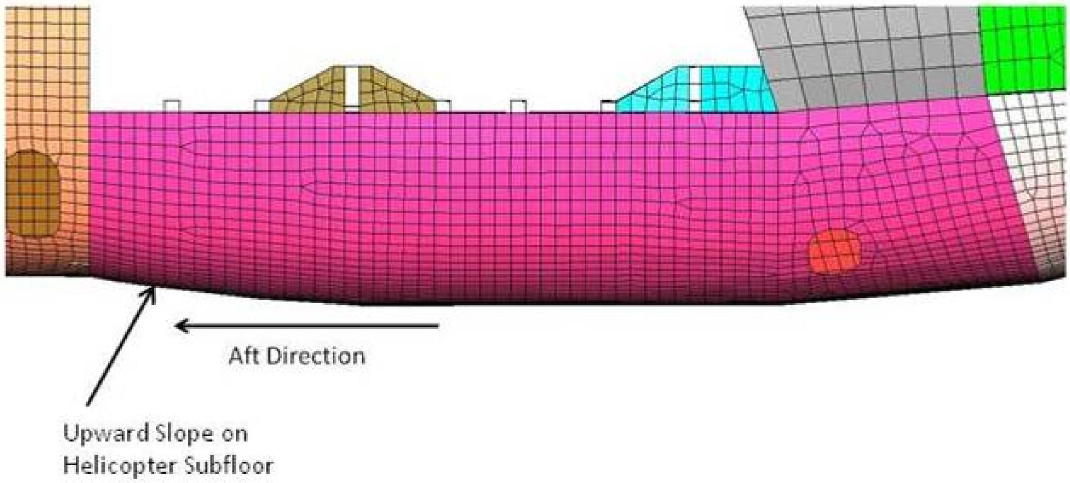


Figure 9. MD-500 Subfloor FEM

Additional Parametric Studies

Separation of Friction Coefficients

Side studies were conducted to investigate the influence of certain model parameters on the crush response of the DEA. Since a coefficient of friction (μ) of 0.5 has been assumed for internal contact within the DEA as well as contact between the DEA and the impact surface, a case was executed where the contacts were separated. A different coefficient of friction was desired for internal contact within the DEA. Thus, two new contacts were defined. The contact between the DEA and the impact surface was now defined using *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE, while the *CONTACT_AUTOMATIC_SINGLE_SURFACE algorithm was still needed to define internal contact within the DEA. To determine the appropriate coefficient of friction needed to define internal contact between the DEA plies, a series of static friction tests were conducted on the DEA plies. The test setup consisted of three flat strips of Kevlar™-129 fabric/epoxy on a servo-hydraulic axial static load machine being loaded in compression. The outer two strips were attached onto platens, while the middle strip was free and attached to an external load indicator. A compressive load of approximately 70 pounds was prescribed normal to the flat strips, while the middle strip was pulled out from between the end strips. The peak pulling load was recorded and divided by the compressive load placed on the outer strips. This result was determined to be the μ value between the DEA plies. The μ value was approximately 0.35, and was put into the *CONTACT_AUTOMATIC_SINGLE SURFACE algorithm for this run. This approach was used for the case where θ equals 20 degrees and the φ angle equals 30 degrees. As indicated in Figure 10, the change in friction coefficients between the DEA plies did not affect the energy absorption response of the DEA.

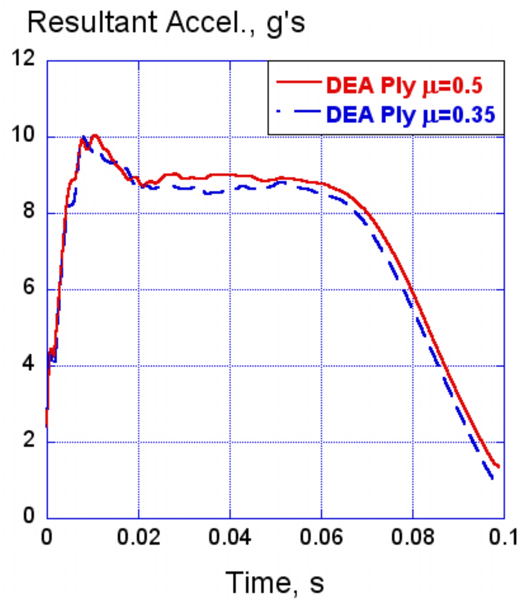
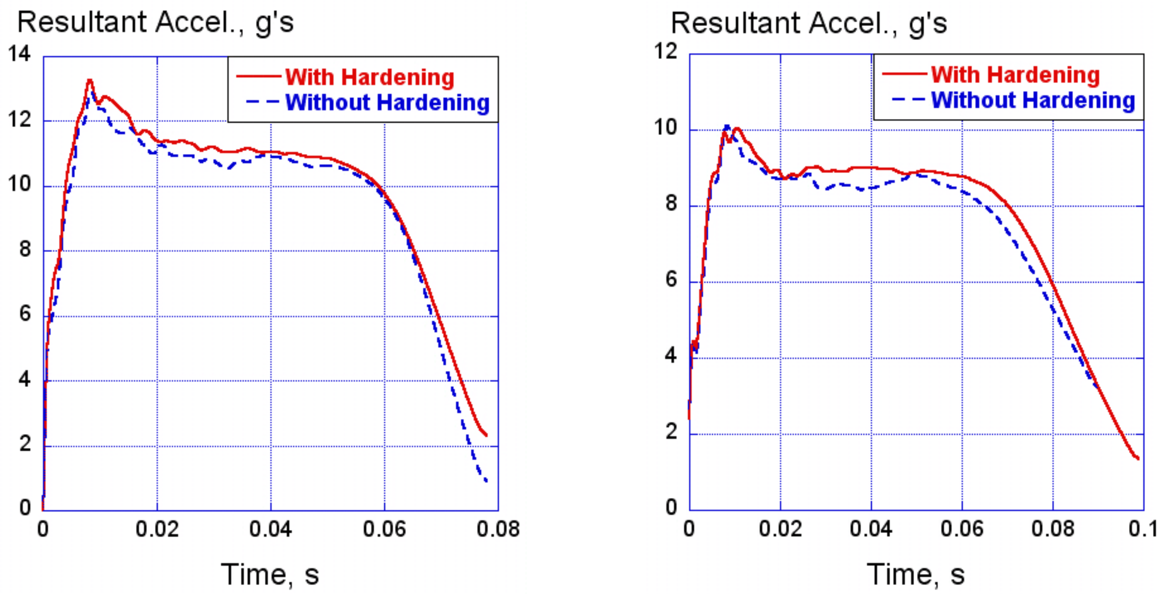


Figure 10. Acceleration time history for DEA contact differentiation

Effects of Plastic Hardening on Energy Absorption of DEA

Plastic hardening within the DEA material was also investigated in this study. A simulation was executed to determine how much of an effect plasticity had on the amount of energy absorbed by the DEA. One case was tried where strain hardening was removed from the stress-strain input curve in the *MAT_24 material model. The stress-strain response of the material would thus be assumed to act elastic-perfectly plastic. This new material response was implemented for the baseline impact case in the study as well as the impact case where θ equals 20 degrees and φ equals 30 degrees. It was found that the removal of strain hardening did not have an effect on the energy absorption of the DEA, since elements in the crush front did not go far into the plastic regime of the stress-strain input curve. It could then be concluded that the nonlinear geometric deformations of the cell walls played a substantial role in determining the energy absorption of the DEA. Analytical comparisons are found in Figure 11.



(a) θ=0°, Φ=0° (b) θ=20°, Φ=30°

Figure 11. Comparisons between Inclusion and Exclusion of hardening in Stress-Strain curves

Conclusions

A parametric study was conducted on a Deployable Energy Absorber to guide its design for impact tests of an MD-500 mass simulator and the MD-500 helicopter. A total of 35 cases was analyzed where both the impact angle and the cell wall angle were varied. Energy absorption trends as a function of cell and impact orientation and deformation characteristics were captured through the use of shell elements. Despite the relatively large model sizes, each run took less than a day to complete. Following the study, a cell orientation angle of 20 degrees was found to exhibit the most stability for the flight path angle of 33 degrees being prescribed for a full-scale crash test of an MD-500 helicopter. Other factors were of interest in the study to assess their sensitivity to the energy absorption of the DEA, such as friction differentiation and removal of hardening from the stress-strain curve inputs. Neither action proved to play a significant role in affecting the amount of energy absorbed by the DEA. These results demonstrated that accurately modeling the cell wall geometry using shell elements was very crucial in capturing energy absorption of the DEA, and the analysis could be used as a reliable guide to predict an optimum shape for the DEA that ensured stability of the vehicle during impact.

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