Simulating the Response of a Composite Honeycomb Energy Absorber: Part 2. Full-Scale Impact Testing

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ABSTRACT

NASA has sponsored research to evaluate an externally deployable composite honeycomb designed to attenuate loads in the event of a helicopter crash. The concept, designated the Deployable Energy Absorber (DEA), is an expandable Kevlar® honeycomb. The DEA has a flexible hinge that allows the honeycomb to be stowed collapsed until needed during an emergency. Evaluation of the DEA began with material characterization of the Kevlar®-129 fabric/epoxy, and ended with a full-scale crash test of a retrofitted MD-500 helicopter. During each evaluation phase, finite element models of the test articles were developed and simulations were performed using the dynamic finite element code, LS-DYNA®. The paper will focus on simulations of two full-scale impact tests involving the DEA, a mass-simulator and a full-scale crash of an instrumented MD-500 helicopter. Isotropic (MAT24) and composite (MAT58) material models, which were assigned to DEA shell elements, were compared. Based on simulations results, the MAT58 model showed better agreement with test.

INTRODUCTION

Since 2006, the NASA Subsonic Rotary Wing Aeronautics Program has sponsored research to evaluate and demonstrate an externally deployable composite honeycomb structure that is designed to attenuate impact energy during helicopter crashes (Jackson, 2009). The concept, which is designated the Deployable Energy Absorber (DEA), utilizes an expandable Kevlar® honeycomb structure to dissipate kinetic energy through crushing (Kellas, 2004, 2010). The DEA incorporates a unique flexible hinge design that allows the honeycomb to be packaged and stowed collapsed until needed for deployment. Experimental evaluation of the DEA utilized a building block approach that included material characterization testing of its constituent, Kevlar®-129 fabric/epoxy; flexural testing of single hexagonal cells; dynamic crush tests of multi-cell honeycomb components; and vertical drop tests of a composite fuselage section retrofitted with external DEA blocks. As a final demonstration, a full-scale crash test of an MD-500 helicopter, retrofitted with DEA blocks, was conducted in December 2009 at NASA Langley Research Center (Kellas, 2010 and Littell 2010, 2011). During each stage of the DEA evaluation process, finite element models of the test articles were developed and simulations were performed using the explicit, nonlinear transient dynamic finite element code, LS-DYNA® (Hallquist, 2006). As part of the simulation effort, both solid- and shell-element models of the DEA were considered, and several different material models available in LS-DYNA® were evaluated (Fasanella, 2008; Jackson, 2010, 2010; Polanco, 2009; and Annett, 2010, 2010).

This paper presents results of simulations of two full-scale impact tests involving the DEA, a mass-simulator of a MD-500 helicopter and a full-scale crash of an instrumented MD-500 helicopter. Isotropic (MAT24) and composite (MAT58) material models, which were assigned to shell elements used to represent the DEA, are compared in this paper.

MATERIAL MODELS

In the finite element models, the Kevlar cell walls are assigned two different material models: MAT24 (MAT_PIECEWISE_LINEAR_PLASTICITY) and MAT58 (MAT_LIMINATED_COMPOSITE_FABRIC). The MAT58 material model takes into account nonlinear material properties in the fiber longitudinal (parallel) and transverse directions for tension, compression, and shear. The MAT58 model allows a constant stress to be specified after the maximum strength is reached in tension, compression, and shear by using a multiplier (SLIM) from 0 to 1 times the maximum strength. For the simulations presented herein, the multiplier was set to 1 for compression and shear, and to 0.8 for tension. Since the honeycomb absorbs energy by folding, the material model for compression is perfectly plastic after maximum strength is reached. Also, the model allows for element failure and deletion. The theoretical development of MAT58 is described in Matzenmiller (1995), while its implementation in the LS-DYNA code is described in Schweizerhof (1998). As described in Polanco (2009, 2010), MAT58 accurately predicted 3-point bending response and failure of a single hexagonal cell of Kevlar DEA honeycomb, where tensile strength is important. However, the MAT24 predicted failure load for the 3-point bend test was only 25% of that measured. The MAT58 DEA model used by Polanco (2009, 2010) over predicted the crushing strength of the DEA as its compressive strength was excessively high at 60,000-psi along the fiber direction. Subsequently, the compressive strength along the fiber direction was re-examined and lowered to 10,000-psi in the current model. Thus, the current MAT58 model, with corrected compression strength, accurately predicts both 3-point bending and crushing of Kevlar structures.

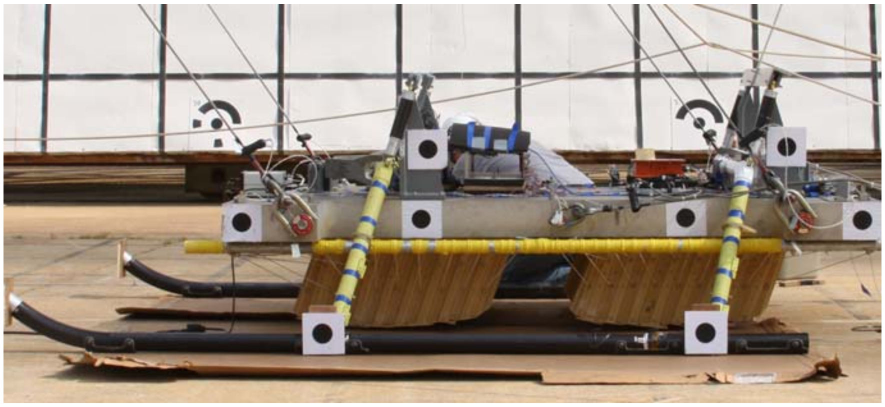
The compression response of the Kevlar is the most important parameter for accurately predicting the crushing response of the DEA. Since direct compression data is difficult to obtain for very thin material, multiple coupons of the Kevlar fabric used in the construction of the DEA were tested in tension at 0°/90° and at ±45° orientations (Kellas, October 2010). In the isotropic piecewise-linear-plasticity material model (MAT24), the 0°/90° tensile test data was ignored. The ±45° tensile coupon data was input and mirrored for compression. The yield for the MAT24 model was input as 7500-psi. After yield, material strengthening was input from test data using a *DEFINE_CURVE in LS-DYNA.

In contrast, the orthotropic composite MAT58 model requires input for each layer, including ply thickness, and orientation angle. Since the Kevlar was a cloth, the inplane material properties were assumed to be the same for the longitudinal (fiber) and transverse directions. Moduli and strengths for the fiber and transverse directions in tension and shear were calculated from the material tests conducted by Kellas (2010). The orientation of the fabric in the cell walls was specified as ±45° to the direction of crush. Direct compression data was not obtained due to difficulties in performing crush testing of thin specimens. The input compression strength for the MAT58 model was estimated to be 10,000-psi in the fiber direction based on the ±45° tensile test with associated scissoring observed due to matrix failure. After the maximum strength was reached in tension or compression, the strength was held constant by setting the SLIM factor to 1 for compression and shear and to 0.8 for tension. In tension, the strength along the fiber direction was input as 80,000 psi. Strain at the maximum compression strength is 2%, while strain at maximum tensile strength is 5%. Additional information regarding material model development can be found in Jackson (2012).

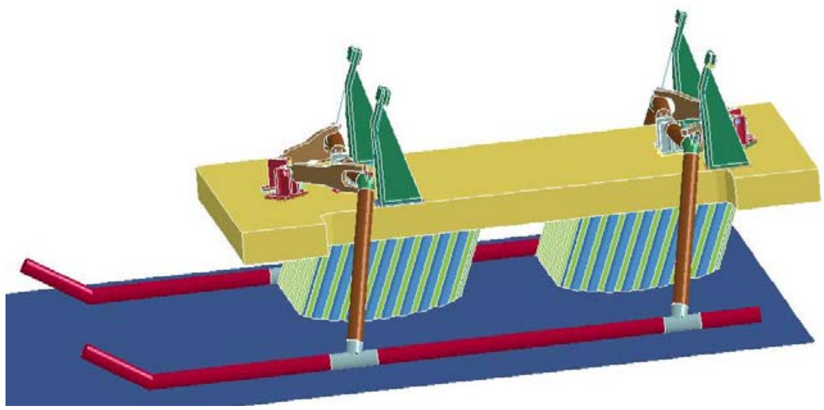
MASS SIMULATOR SWING TEST AND SIMULATION

The MD-500 mass simulator consisted of a 2,500-lb aluminum plate onto which two DEA blocks and modified MD-500 skid gear were attached, as shown in Figure 1(a). The targets on the test article that can be observed in Figure 1(a) were tracked using large-field 3D photogrammetry software to accurately determine the velocities and attitudes of the test article at impact. The impact condition (combined velocities of 26-ft/s vertical and 40-ft/s horizontal) is considered to be severe, but survivable. The design goal was to obtain an average acceleration of 20-g vertical as measured at the center of the top of the plate. The height of the DEA is approximately 14 inches, with the bottom surface of the DEA positioned just above the skid gear at a 20° angle from vertical. The LS-DYNA model is illustrated in Figure 1(b). The impact surface was modeled using the RIGIDWALL_PLANAR option in LS-DYNA. Contact between the shell elements forming the DEA was defined using the CONTACT_AUTOMATIC_SINGLE_SURFACE command in LS-DYNA. More details of the test and modeling effort can be found in Annett (2010).

The DEA is modeled using shell elements to represent the actual geometry of the Kevlar honeycomb. The two DEA blocks consisted of 265,902 elements and 301,714 nodes. The edge length of a typical shell element is approximately 0.3-inch. The cell wall thickness is either 0.01-in. or 0.02-in. depending on whether the wall is constructed of one or two plies. The orientation of the honeycomb fiber in the cell walls is ±45° with respect to the longitudinal axis of the cell. In the original LS-DYNA model that was discussed in Annett (2010), the DEA was assigned MAT24. Although simplistic, this material proved adequate to simulate the crushing of the honeycomb. However, as an isotropic material model, MAT24 model cannot capture the orthotropic material behavior of the Kevlar fabric.



(a) Test article.



(b) Finite element model.

Figure 1. Flat plate test article with skid gear and DEA blocks.

A comparison of the LS-DYNA model predictions using the MAT24 and MAT58 material models for the DEA with acceleration time history data obtained from the flat plate is shown in Figure 2. All data were filtered with a 50-Hz low-pass Butterworth filter in LS-PrePost. Both the MAT24 and the MAT58 model show reasonable agreement with the test responses; however, the MAT58 model does a better job of predicting the horizontal acceleration. Both models used a friction coefficient of 0.3 in the RIGIDWALL card in LS-DYNA. The MAT58 model performed better at predicting the test vertical acceleration. However, both the MAT58 and the MAT24 model over predicted the test accelerations for the first 0.05 seconds. As a consequence, neither model predicted the compaction of the DEA honeycomb that occurred at approximately 0.07 seconds. It is postulated that the actual honeycomb exhibited more global buckling than seen in the simulations, which lowered the initial acceleration. Trapped air in the honeycomb plays a role that is not accounted for in the model. Although holes are drilled in the cell walls, the trapped air still alters the crushing behavior of the DEA honeycomb as it promotes internal failures and global buckling. This behavior was observed in prior drop testing of multi-cell DEA components (Kellas, 2010).

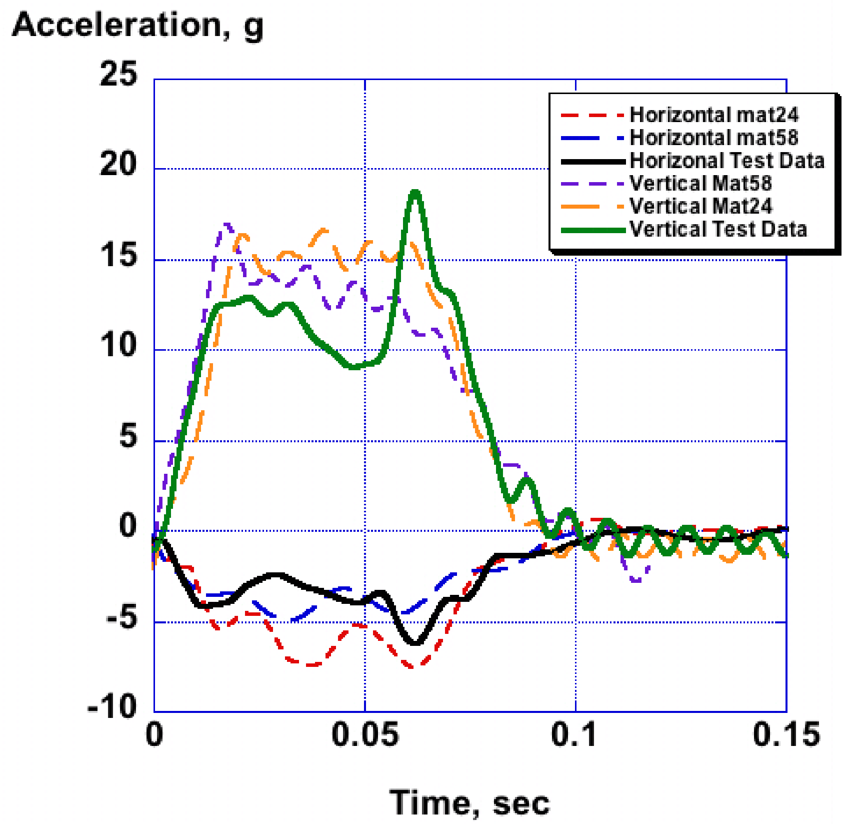
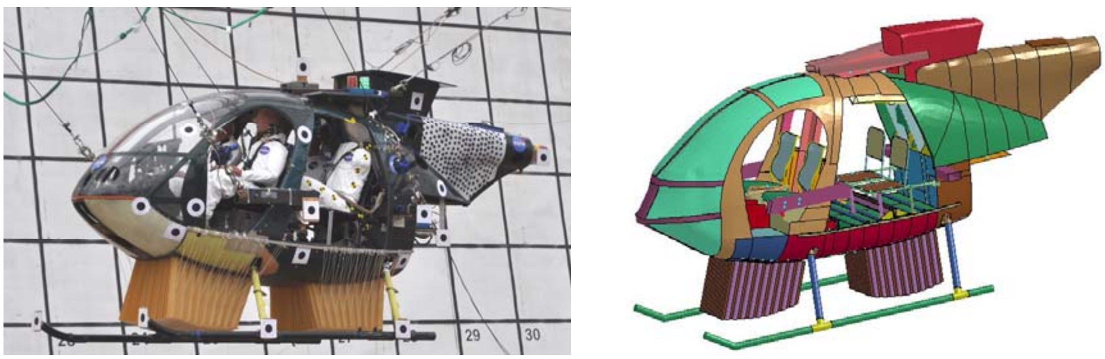


Figure 2. Comparisons of test accelerations on the mass simulator with LS-DYNA models using two DEA material models, MAT24 and MAT58.

MD-500 FULL SCALE DROP TEST AND ANALYSIS

The second full-scale impact simulation represented a crash test of an MD-500 helicopter, retrofitted with two blocks of the DEA, onto a flat concrete surface. A photograph of the test article is shown in Figure 3(a), and a picture of the system-integrated finite element model is shown in Figure 3(b). The crash test was performed at the NASA Langley Landing and Impact Research (LandIR) Facility in December 2009 to evaluate the performance of the DEA and to generate test data for comparison with the finite element predictions. The pilot was a 50th percentile male Hybrid III Anthropomorphic Test Device (ATD). The co-pilot and one passenger were 50th percentile male Hybrid II ATDs. The other passenger was a biofidelic torso developed by The Johns Hopkins University Applied Physics Laboratory (Roberts, 2007). Planned impact conditions were 26-ft/s horizontal and 40-ft/s vertical velocities. Measured impact conditions were 25.6-ft/s horizontal and 38.8-ft/s vertical velocities with an attitude of 5.7° pitch, 9.3° yaw, and 7.0° roll. Additional details of the experimental program can be found in Kellas (2010) and Littell (2010, 2011).

In the original finite element model of the MD-500 (Annett, 2010), the four occupants were simulated with finite element dummies and the DEA blocks were represented using 266,404 shell elements that were assigned isotropic MAT24 properties. In order to simplify this model, the finite element dummy occupants were replaced with lumped masses. The simplified model, shown in Figure 3(b), consists of 469,080 nodes, 77 lumped masses, 4 beam elements, 127 solid elements, and 493,537 total shell elements. The impact surface is represented using the RIGIDWALL_PLANAR feature in LS-DYNA. The simplified MD-500 model was executed with two different material models assigned to the shell elements representing the DEA blocks, the same MAT24 as in the original model and MAT58 with revised compression strength of 10,000 psi along the fiber direct ion.



(a) MD-500 test article. **(b) Simplified MD-500 Model.**

Figure 3. Crash test and simulation of the MD-500 helicopter.

Comparisons of the test acceleration time histories for the rear passenger floor and the pilot seat box in the vertical direction with the MAT24 and MAT58 DEA models are plotted in Figures 4 and 5, respectively. Note that all data were filtered in LS-PrePost with a Butterworth 60 Hz low-pass digital filter. The design goal of the DEA, to limit the floor level accelerations to 20-g or less, was achieved for both locations. The acceleration time histories predicted by the two models were close for the first 0.10 seconds. After 0.1 seconds, the accelerations predicted by the model with MAT58 material properties were below that of MAT24 for both locations. Both models over predicted the sustained crushing accelerations for the passenger floor location. The lower measured accelerations may be due to global buckling or other failures of the DEA honeycomb that occur after initial crushing. The forces on the bottom surface of the DEA due to friction probably add to instability of the honeycomb. The honeycomb in the test buckled globally in some locations and some of the seams and/or hinges failed due to the combination of forces including built-up air pressure that was not completely eliminated even though small holes were drilled in the cell walls.

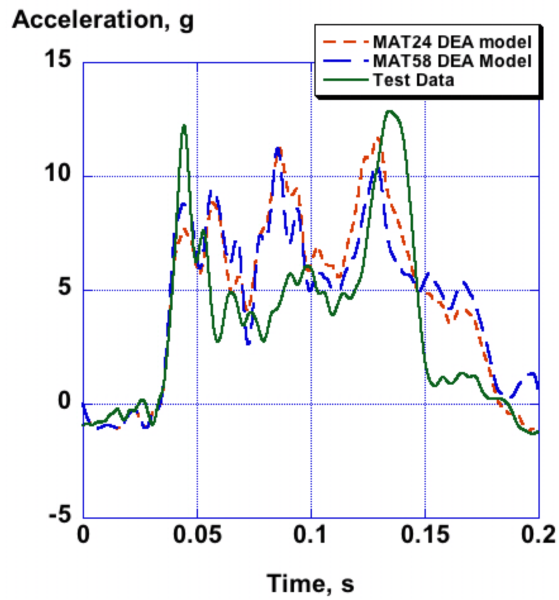


Figure 4. Comparison of model with test vertical acceleration on the passenger floor. All data were filtered with a 60-Hz low-pass Butterworth filter.

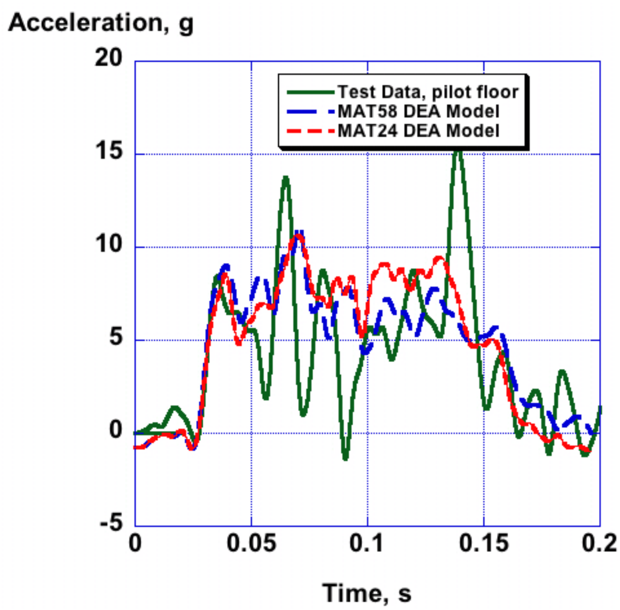


Figure 5. Comparison of model with test vertical acceleration on the pilot seat box. All data were filtered with a 60-Hz low-pass Butterworth filter.

CONCLUSIONS

This paper focused on comparing two different material models (isotropic MAT24 and composite MAT58) that were assigned to shell elements representing a composite honeycomb Deployable Energy Absorber (DEA) during two full-scale impact simulations. The DEA blocks were fabricated of a Kevlar®-129 fabric/epoxy material, that was oriented at ±45° with respect to the longitudinal axes of the hexagonal cell walls. Two material models were assigned to the shell elements used to represent the DEA, including an isotropic MAT24 (MAT_PIECEWISE_LINEAR_PLASTICITY) and a composite MAT58 (MAT_LAMINATED_COMPOSITE_FABRIC). For MAT24, a user defined stress-strain response was input to define the compressive response of the material following initial yield that was based on ±45° tensile coupon data. Alternatively, MAT58 is an orthotropic material model that takes into account nonlinear material properties in the fiber longitudinal (parallel) and transverse directions for tension, compression, and shear.

A previous MAT58 model used by the authors was accurate in predicting the failure load during 3-point bending of a single hexagonal cell of Kevlar DEA honeycomb, while the isotropic MAT24 model failed at 25% of the test load. However, the previous MAT58 model performed poorly in predicting crushing of the DEA as it had a compressive strength that was excessively high at over 60,000-psi along the fiber direction. Subsequently, the compressive strength was lowered to 10,000-psi in the current MAT58 model. The revised orthotropic MAT58 model, used in this paper, now predicts both the 3-point bending tests of a single cell and the crushing of multiple cells of Kevlar honeycomb.

Using the updated MAT58 material model with a reduced compressive strength for the Kevlar fabric, the two full-scale impact simulations were revisited. Using MAT24 and updated MAT58 material representations for the DEA, predicted acceleration time histories from models of the mass simulator and MD-500 helicopter full-scale tests were compared with measured test accelerations. The updated MAT58 material model of the DEA with reduced compressive strength is shown to accurately predict acceleration time histories for the full-scale tests. Both the MAT24 and the MAT58 material models are adequate for modeling of DEA crushing. However, for simulations in which the orthotropic aspects of the honeycomb are important, the MAT58 model is recommended.

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