

Full-Scale Crash Test of an MD-500 Helicopter with Deployable Energy Absorbers

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ABSTRACT

A new externally deployable energy absorbing system was demonstrated during a full-scale crash test of an MD-500 helicopter. The deployable system is a honeycomb structure and utilizes composite materials in its construction. A set of two Deployable Energy Absorbers (DEAs) were fitted on the MD-500 helicopter for the full-scale crash demonstration. Four anthropomorphic dummy occupants were also used to assess human survivability. A demonstration test was performed at NASA Langley's Landing and Impact Research Facility (LandIR). The test involved impacting the helicopter on a concrete surface with combined forward and vertical velocity components of 40-ft/s and 26-ft/s, respectively. The objectives of the test were to evaluate the performance of the DEA concept under realistic crash conditions and to generate test data for validation of dynamic finite element simulations. Descriptions of this test as well as other component and full-scale tests leading to the helicopter test are discussed. Acceleration data from the anthropomorphic dummies showed that dynamic loads were successfully attenuated to within non-injurious levels. Moreover, the airframe itself survived the relatively severe impact and was retested to provide baseline data for comparison for cases with and without DEAs.

1. INTRODUCTION

Externally deployable devices have long been proposed and studied for helicopter and aircraft crashworthiness. Deployable systems offer unique advantages including efficient packaging and relatively large crush stroke, which enables higher crush-load attenuation to be achieved.

External airbag systems have been utilized in many different aerospace applications including the F-111 crew-escape module that utilized passive plug-vented type airbags [1] and the Orion crew module, which utilized active plug, vented airbags [2]. Unfortunately, when used on aircraft to improve crashworthiness, the plug vented airbag has reliability issues due to delayed, partial, or no-venting caused by the multitude of possible impact orientations. Therefore, reliability issues can offset potential advantages in energy absorption.

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Porous, or automobile-type, airbags have also been considered for external use on rotorcraft to mitigate crash loads [3]. The performance of this type of airbag depends

highly on precise deployment/impact timing. Consequently, this timing requires determination of impending impact over varying terrain, which for a rotorcraft application is a very challenging problem.

In addition to reliability issues, all gas-filled airbag systems suffer from low shear stability, loading-rate sensitivity, impact/venting synchronization (especially when multiple airbags are used), and sensitivity to extreme landing-surface morphology such as water, rocks, and/or slopes. Hence, extensive testing and/or analysis are often required for system development and qualification, as was demonstrated by the F-111 program. To address the airbag shear issue, Mehaffie [4] studied a foam filled airbag system for the recovery of small pilotless aircraft. While this concept appeared to provide a viable solution to the shearing issue, time sensitive foam hardening and excess weight made it inappropriate for aerospace applications.

The Deployable Energy Absorber, DEA, was proposed and patented by Kellas [5]. This concept consists of a honeycomb structure, which can be deployed externally to provide crash-load attenuation much like an external airbag system. However, unlike airbag systems, the deployable honeycomb can be fabricated to have any shape and, because it does not require internal pressure, it is not constrained to a near spherical and/or cylindrical shape. This advantage, coupled with high specific energy absorption, efficient packaging, and superior shear stability as compared to airbags, can make the concept a better candidate for aerospace crashworthiness applications.

A study of the concept for helicopter crashworthiness was initiated under the NASA Subsonic Rotary Wing (SRW) Aeronautics Program [6]. The Rotorcraft Crashworthiness part of the program has focused, amongst other areas, attention on: customizing the DEA concept for helicopter applications and improving analytical tools for predicting rotorcraft crashworthiness at a system level [7, 8].

In the design process of the DEA for helicopter crashworthiness, the SRW team adopted the building block approach whereby a series of experiments with progressively increasing level of complexity were planned and executed. These included simple coupon and element tests to support parallel analysis efforts [6], to larger scale tests such as fuselage section tests. Fuselage section tests were used to study the effectiveness of the concept on

various impact surfaces [7, 8] during on and off-axis vertical impacts. In preliminary evaluations, which included impacts on concrete, soft soil, and water, the DEA showed great promise with reliable crush response and excellent crash load attenuation.

Early success in proof-of-concept work led to higher complexity full-scale tests with combined forward and vertical impact velocity components, which are presented in this paper. To study the interaction between the helicopter skid gear and the DEAs, a flat plate, of similar mass to the gross weight of the MD-500 was fitted with MD-500 skid gear and a set of two DEA blocks. The original MD-500 oleo-pneumatic shock struts, which were deemed unsuitable for the full-scale crash tests, were replaced with custom-made load limiting crush tubes.

Replacement of the oleo struts was necessary to meet the program's intention of using the airframe for more than one crash test and also incorporating anthropomorphic dummies in the helicopter. Previous test programs involving this aircraft [9] and analysis of actual crash events of the MD-500 and its variants indicated that under dynamic crash loads the oleo struts "lock-up" resulting in high reaction loads, leading to failure of the upper strut-fitting and allowing the front struts to penetrate the seat-pans. Consequently, simple replacement struts were designed to limit crush loads below the strength of the support fittings to prevent failure and seat-pan penetration. These struts were simply designed to meet the objectives of the test program and are therefore not suitable for flight.

Following a successful MD-500 mass simulator test, a full-scale crash test was performed using an actual MD-500 airframe. The skid gears for both the mass simulator and the MD-500 were fitted with the custom crush tubes. Dynamic finite element analysis efforts complementing these full-scale tests are presented in a separate technical publication [10].

Because the crash test of the MD-500 with DEAs was successful and the airframe sustained a minimal amount of damage, a second crash test of the MD-500 without DEAs was possible. With the exception of the DEAs, all other parameters for the two tests, including nominal impact conditions and total mass, were identical.

Other tests performed in support of the dynamic analyses and the full-scale tests presented in this paper include skid

gear friction tests on concrete and soil (sandy clay), DEA friction tests on concrete, and crush tube (replacement strut) characterization under static and dynamic loads.

2. TEST ARTICLE DESCRIPTION

Two full-scale test articles were used in a total of three full-scale crash tests and are described in detail in the sections below. These are the MD-500 mass simulator and the MD-500 airframe.

Subcomponent test articles included the MD-500 skid gear for friction measurements; the DEA assembly for friction measurements, and a number of prototype crush tubes used in static and dynamic testing. Test articles, which were used for coefficient of friction measurement, are shown in Figures 1 and 2 for the skid gear and the DEA, respectively.

2.1 Sub-Component Test Articles

The skid gear friction test article consisted of a set of skids mounted on a large aluminum mass. The test assembly was towed on various surfaces while the pull force was measured using an inline load-cell. A similar test set-up was used for the DEA friction tests, Figure 2. For this test, three DEA blocks were utilized, fabricated using the same materials and cell geometry intended for use in the subsequent full-scale tests.

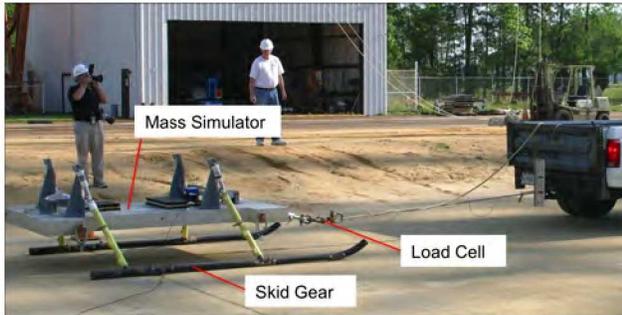


Fig. 1 Photograph of test set-up used for skid gear coefficient of friction measurements.

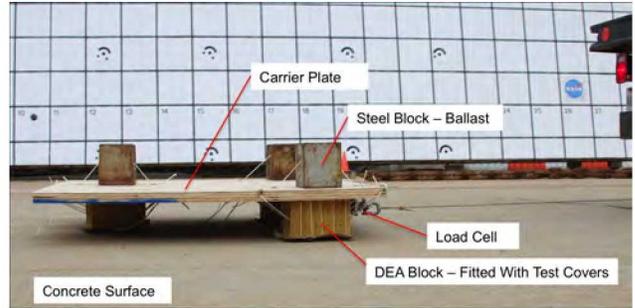


Fig. 2 Photograph of test set-up used for DEA coefficient of friction measurements.

A photograph of a partially stroked crush tube, which was used as a replacement for the oleo struts, is shown in Figure 3. Static off-axis testing of crush tube prototypes was performed using a specially designed fixture, which simulated the expected reaction forces in the airframe. The same fixture was also used for dynamic off-axis tests. For these tests the fixture was installed on a drop tower as shown in Figure 4. For the dynamic load set-up the lower platen was fixed with respect to the drop tower cross-head and the upper platen was allowed to move in the vertical direction only. The upper platen was ballasted with 40-lb lead blocks, as shown in Figure 4. Both platens contained clevis brackets to accept each end of the strut sample, which was mounted between the two platens. The clevis position was adjustable, thus allowing the struts to be tested at various off-axis angles.

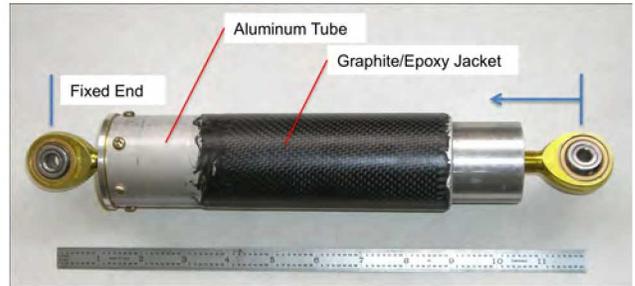


Fig. 3 Photograph of a partially stroked crush tube, which replaced the original MD-500 oleo struts.

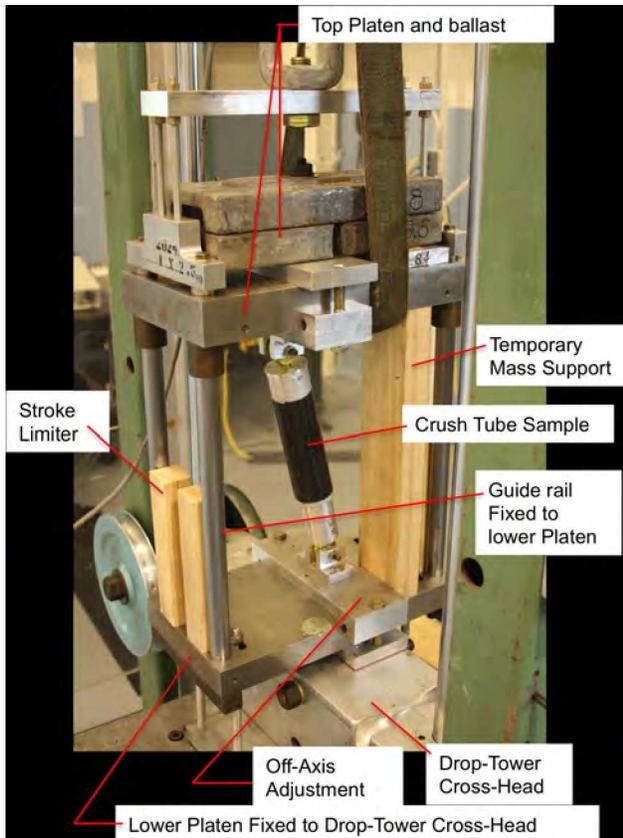


Fig. 4 Photograph of the test fixture used for dynamic off-axis strut characterization. A replacement strut sample (crush tube) is shown mounted in the fixture.

2.2 MD-500 Mass Simulator

The MD-500 mass simulator consisted of a flat aluminum plate, which served as the backbone of the test article, as shown in Figure 5. Added to this backbone were a set of custom designed brackets to allow the MD-500 skid gear to be integrated in a flight-like fashion; a set of crush tubes, which replaced the oleo struts; a set of DEAs; and data acquisition and instrumentation package. Two aluminum tubes were also added on either side of the aluminum plate to provide a convenient method for anchoring the DEA tie-down lines. The total mass of the test article was approximately equal to the MD-500 gross weight of 3000-lb.

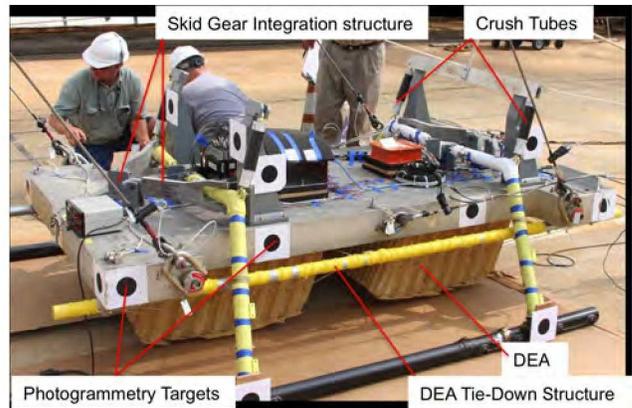


Fig. 5 Photograph of the MD-500 Mass Simulator test article being prepared for test.

For comparison purposes, the same type of DEA construction and cell geometry used in previous tests [7, 8] was chosen for these full-scale tests. Because of the forward component of velocity the cell axes were oriented 20° off vertical, pointing forward, as shown in Figure 5. The honeycomb geometry consisted of cell-wall width of 1.0-in, and cell-wall thickness of 0.01-in. The expanded density of the honeycomb was approximately 2-pcf and had a sustained crush strength along the cell axes of approximately 20-psi.

2.3 MD-500 Airframe

The MD-500 test article prepared for the first drop test is shown in Figure 6. The same airframe without the DEAs also served as the test article for the second MD-500 drop test. Standard mesh-type pilot and co-pilot seats were installed in the front crew compartment and the rear compartment was fitted with a standard mesh-type bench seat. With the exception of minor modifications, no attempt was made to tailor the seat response to that of the DEAs.

Modifications and repairs to the airframe common to both full-scale drop tests included:

- 1) Replacement of cracked, damaged or missing aluminum and/or acrylic panels.
- 2) Replacement of the four skid-gear oleo struts with crushable struts of the same initial length.
- 3) Addition of four layers of graphite/epoxy fabric (each 0.010" thick) to reinforce the belly of the airframe and

to ensure that 20-psi pressure could be reacted – the designed crush strength of the energy absorber.

- 4) Two aluminum straps (1.0-in. by 0.25-in. cross sectional area) attached to the exterior and along the side of the aircraft (shown in Figure 6) to provide a convenient tie down for the DEAs.
- 5) Three sets of steel box beams to provide six hard-points at desired locations to allow lifting and swing testing. These were secured to existing hard-points on the airframe and every care was taken not to alter the global stiffness of the aircraft.
- 6) Ballast to achieve desired total weight and to bring the CG close to the flight range.
- 7) The cantilevered portion of the bench seat was braced with three vertical struts.
- 8) One closed cell PVC foam block was inserted under the co-pilot's seat, to eliminate the 2-3 inch gap between the seat and the floor.
- 9) An aluminum plate was attached behind the rear bulkhead to attach the data acquisition system.

Items not available on the helicopter for the test were the main and tail rotors, part of the tail structure, engine and gearbox and all avionics and flight control hardware. In the test article, these items were represented by carefully arranged ballast to keep the aircraft mass and CG location within a realistic range. However, moments of inertia could not be reproduced.

Other items added to the test article included four instrumented anthropomorphic dummies and data acquisition system and instrumentation in the form of accelerometers, strain gages and miniature video cameras. One of the anthropomorphic dummies included a specially designed torso [11] and therefore represented a separate experiment in itself.

Consistent with the mass simulator test, similar DEAs were fabricated and installed on the first MD-500 test article. However, due to the aircraft's double curvature the DEA cells had a variable orientation with respect to the vertical direction. A large proportion of the cells in the front block were biased at approximately 20° forward and the majority of the cells of the rear block were oriented approximately vertical.

Reinforcement of the aircraft belly skin with graphite/epoxy was thought to be necessary to react the 20-psi honeycomb crush strength. A lower strength (larger volume) DEA could have been used but would not have

been consistent with the building block design approach that was adopted by the team. Note that the 20-psi sustained crush strength honeycomb was used in all previous demonstration tests [7, 8].

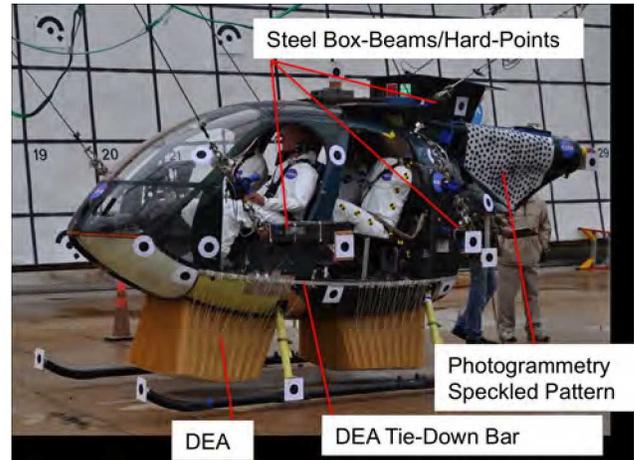


Fig. 6 Photograph of the MD-500 test article prior to test with special features labeled.

3. TEST RESULTS

The test program, presented in this paper, is an extension of previous work on the evaluation of the DEA concept and had at least three objectives with respect to the DEA for helicopter crashworthiness application. Additional goals not related directly to the DEA concept, but just as important, were related to anthropomorphic dummy response to aircraft crash loads, and the relationship of this response to human occupant survivability.

With respect to the DEA concept, the primary objectives of the full-scale test program were:

- 1) Demonstrate the capability of the DEA in a realistic crash environment, which includes an actual airframe and a representative impact velocity with relatively large forward component.
- 2) Provide test data on aircraft dynamic response for test/analysis correlation, which could eventually lead to optimization of the DEA concept through detailed dynamic analyses.
- 3) For the first MD-500 drop test, ensure aircraft survivability to enable an additional (baseline) MD-500 drop test without DEAs in order to determine a precise load attenuation contribution due to the DEAs.

Relative to human survivability the objective was to provide acceleration and spinal-load responses from HYBRID II and HYBRID III anthropomorphic dummies. In addition, the test was to provide data to assess the effectiveness of a non-standard research dummy [11] under dynamic crash loading.

3.1 Element and Subcomponent Test Results

Typical friction test results for the MD-500 skid gear are shown in Figure 7 in the form of drag force versus time for two surfaces; concrete and dry sandy clay. Based on the test vehicle mass of 2808-lb and the average drag force, the coefficients of friction were determined to be 0.38 and 0.5 for concrete and sandy clay, respectively.

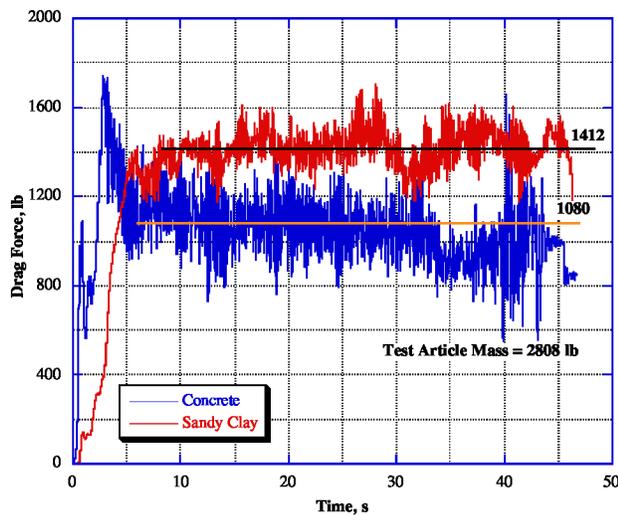


Fig. 7. MD-500 skid friction results for concrete and sandy clay.

DEA friction tests were performed only on a concrete surface for two types of covers. These results are shown in Figure 8. The measured coefficients of friction were 0.48 and 0.59 for the PTFE (Polytetrafluoroethylene) coated Kevlar and Glass impregnated with Teflon covers, respectively. Due to the lower coefficient of friction and better abrasion resistance, the PTFE coated Kevlar cover material was chosen for the subsequent full-scale drop tests.

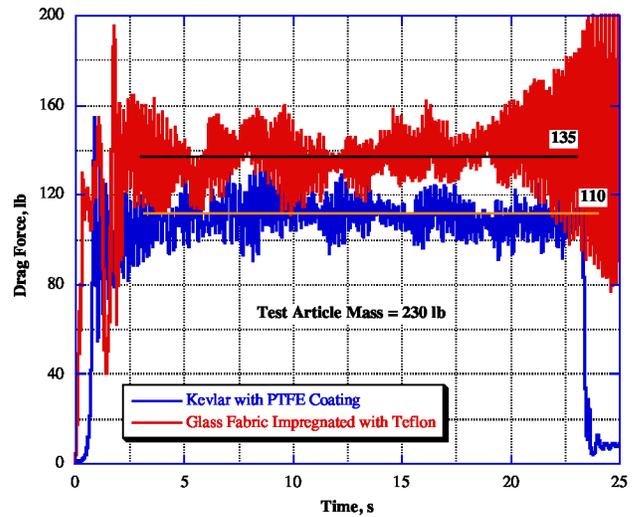


Fig. 8. DEA-cover friction results for a concrete surface.

Crush-tube prototypes were tested both axially and off-axis to assess the stability of the design to transverse loading. A typical static off-axis response for a sample initially set to 12° off the vertical is shown in Figure 9. Because the test article is constrained at its ends, the effective angle increases with vertical stroke. Consequently, the measured vertical crush force increases with vertical stroking distance as shown in Figure 9.

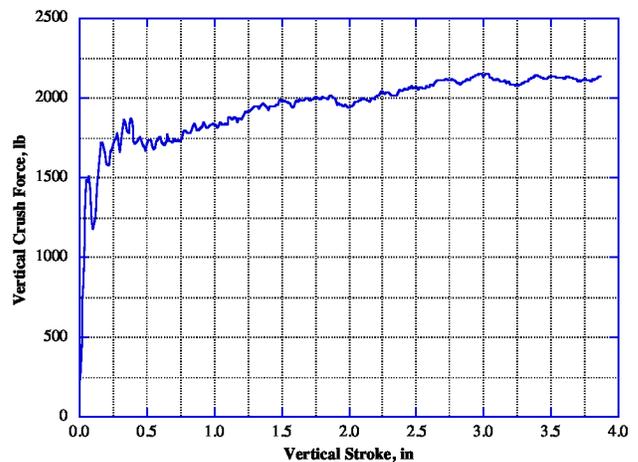


Fig. 9. Off-axis static crush response of a crush-tube (oleo strut replacement).

3.2 Full-Scale Crash-Test Results

Targeted test parameters for the full-scale crash test of the mass-simulator and the MD-500 were:

- 1) Total test article mass equal to approximately 3000-lb.
- 2) Impact velocity components were chosen to be 40-ft/s forward and 26-ft/s vertical
- 3) Impact orientation – 0° pitch, roll and yaw.

A preliminary assessment of the performance of the DEA under combined vertical and forward impact conditions was made possible with the mass simulator drop test.

3.2.1 Mass-Simulator

The mass-simulator test was performed on July 29, 2009. The objectives of the test were:

- 1) Assess the interaction between the landing gear and the DEA.
- 2) Provide dynamic DEA crush response under a realistic impact attitude to be used in analytical model verification/calibration and thus improve subsequent dynamic simulations attempting to predict the more complex MD-500 response.
- 3) Provide dynamic data to verify the interaction of the skid gear and the crush-tube concept prior to installation into the MD-500.
- 4) Provide a means to assess experimentally the DEA tie-down techniques under a realistic impact condition.
- 5) Assess the full-scale test set-up.

Measured test parameters for the mass simulator using a 3-D photogrammetry system were:

- 1) Impact velocity components were 39.6-ft/s forward and 25.8-ft/s vertical.
- 2) Impact orientation – 0.0° pitch, 1.6° roll, and 1.5° yaw. In addition, angular rates were 0.0-°/s pitch, 0.4-°/s roll, and 1.6-°/s yaw.

Total test article mass was 2900-lb.

Center of gravity acceleration responses from the mass simulator test are shown in Figure 10. Accelerations were filtered at 180 Hz.

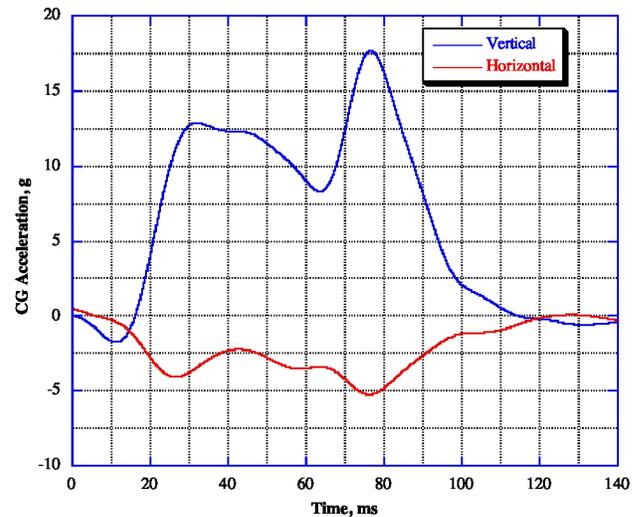


Fig. 10. Vertical and horizontal acceleration/time responses from the mass simulator drop test. Both responses were measured at the CG.

Despite the high forward impact velocity of 39.6-fps, anchoring of the DEAs to the vehicle proved sufficient to hold the honeycombs in place during the entire impact event. However, post-test inspection of the energy absorbers indicated internal cell-wall separation as shown in Figure 11. This separation likely occurred through a combination of excessive or uneven anchor-line tension and internal pressure build-up from trapped air. The load drop, which occurred at about 50 ms (Figure 10), is thought to be associated with the initiation of the internal global failures.

Following a detailed investigation of the cell-wall separation, the line tension issue was isolated and appropriate modifications were made to the tie-down technique for the DEAs, which were installed on the MD-500 test article.

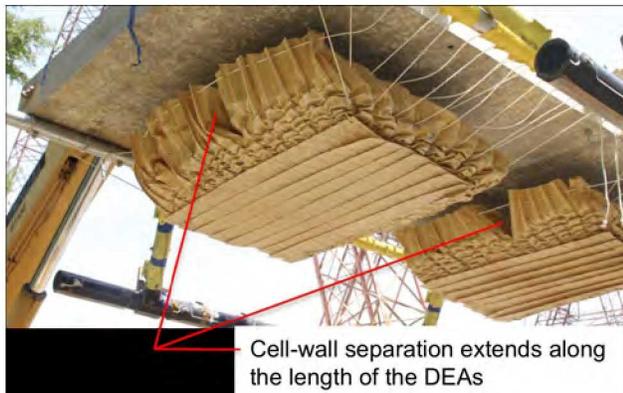


Fig. 11. Post-crash photograph of the DEAs attached to the mass simulator test article.

The dynamic response of the crush tubes was similar to that seen in laboratory tests, with progressive and uniform crushing being evident in all four replacement struts. Vehicle impact attitude and velocities at impact were well within acceptable tolerances for the intended combined velocity crash test. These overall encouraging results provided confidence for the more complex drop test involving the MD-500 fitted with DEAs.

3.2.2 MD-500 With DEA

The first MD-500 drop test (with DEAs) was performed on December 2, 2009. The second MD-500 referred to as the “baseline” test (without DEAs) was performed on March 10, 2010. The impact parameters for each test article, measured using photogrammetry, are shown in Table 1.

Table 1. Impact parameters for the MD-500 drop tests

Impact Parameters At the CG	1st MD-500 Test (With DEAs)	2nd MD-500 Test (Without DEAs)
Attitude, Deg.		
Pitch	-5.69	-6.2
Roll	7.04	1.9
Yaw	9.30	2.1
Linear Vel., fps		
Forward	38.8	39.1
Vertical	25.6	24.1
Lateral	0.5	0.64
Angular Vel., %/s		
Angular Pitch	0.44	0.54
Angular Roll	1.11	0.68
Angular Yaw	4.82	1.65
Total Mass, lb	2930	2906

Table 1 shows that both test articles were pitched down approximately 6° at impact as opposed to the desired 0° pitch condition. This off-nominal attitude was attributed to the fact that for both vehicles the CG was located slightly aft of the center of pull, which caused the vehicle to pitch down at release. Another undesirable condition occurred in the first test where excessive yaw and yaw-rate led to a more severe than planned test. While this test was intended to provide a two-dimensional impact, in reality the test article was subjected to a three-dimensional impact event. Due to the excessive yaw and yaw rate, the effective resultant component of the lateral velocity measured at the front DEA was approximately 7-ft/s.

The effect of off-nominal impact conditions for the first MD-500 drop test was also reflected in the post-crash measurement of stroke for each crush-tube. The measured crush-tube stroke for both MD-500 tests are summarized in Table 2. The crush-tubes on the right side of the aircraft stroked approximately two times as much compared to the left.

Despite the more severe impact conditions of the first test, the test article sustained minor damage and was tested again following repairs. In contrast, during the second test, the test article sustained severe structural damage in the primary subfloor structure, floor, front seat-pans, and seats. Post-test photographs highlighting the seat-frame fractures are shown in Figures 12 and 13 for the crew seats and rear bench seat, respectively.

Table 2. Summary of measured post-crash strokes for each crush tube in MD-500 drop tests.

Crush-Tube Position	1st MD-500 Test Stroke, inches	2nd MD-500 Test Stroke, inches
Front Left	3.5	6.1
Front Right	5.3	5.5
Rear Left	2.5	5.7
Rear Right	5.0	5.8

By comparing the skid stroke between the two tests, the test with DEAs had obviously less benefit from the energy absorbing capabilities of the crush tubes because the presence of the DEA prevented the tubes from stroking as much as the test without the DEA. The total stroke difference between the two tests is 6.8”, which at a constant crush load of 2000-lb (Figure 9) this difference translates to 1133 ft-lb energy between the two tests.



Fig.12. Photograph of front seats following the second MD-500 drop test.

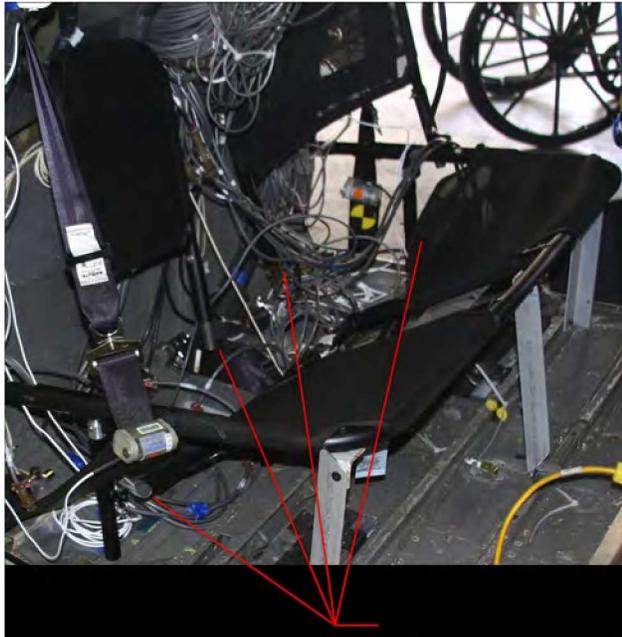


Fig.13. Photograph of rear bench following the second MD-500 drop test.

For a direct comparison of the case with and without DEAs, dynamic responses for the pilot and co-pilot are presented side-by-side. All dynamic dummy responses were filtered using a 180 Hz Butterworth filter.

Load versus time responses of the lumbar loads are shown in Figures 14 and 15 for the pilot and co-pilot, respectively. For the baseline test both occupants were subjected to a load pulse with a (filtered) maximum peak of approximately 1900-lb. The effect of the DEA was to attenuate that pulse by 67 and 60% for the pilot and co-pilot, respectively. The difference in the load attenuation can be attributed to several factors including anthropomorphic dummy difference (HYBRID III for pilot, HYBRID II for co-pilot), the foam block under the co-pilot's seat, and most importantly the difference in the impact orientation between the two tests with the first test having greater roll and yaw attitude at impact (landed on right side).

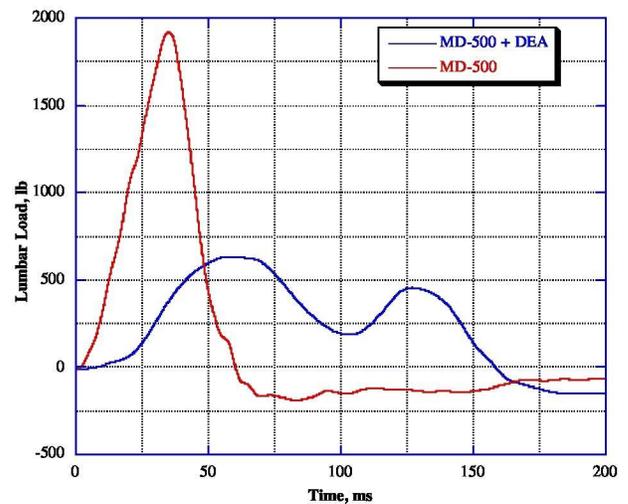


Fig. 14. Pilot lumbar load responses for both MD-500 drop tests.

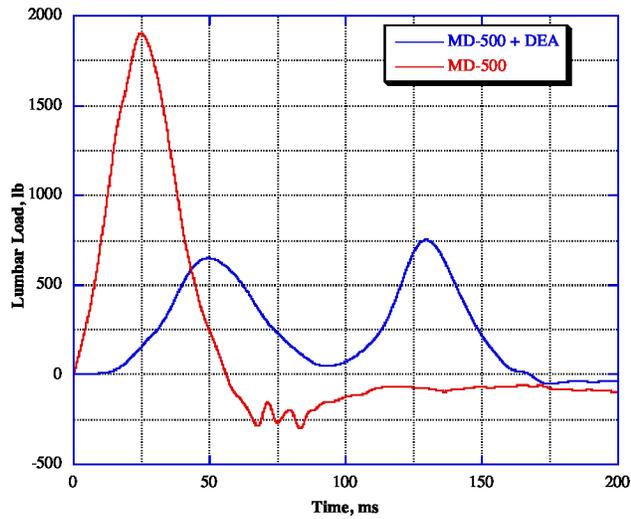


Fig. 15. Co-pilot lumbar load responses for both MD-500 drop tests

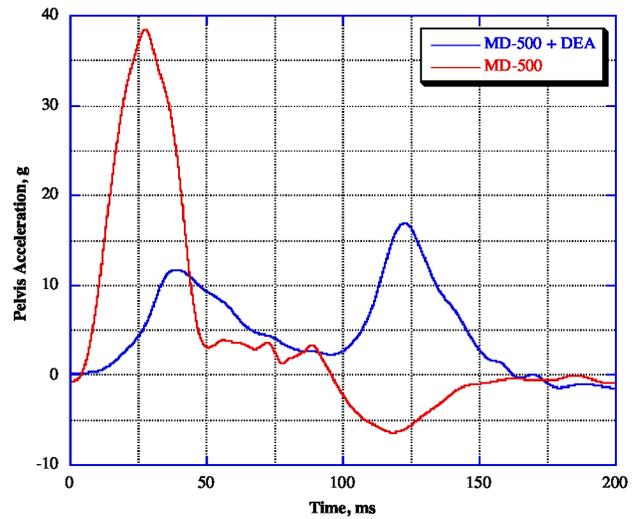


Fig. 17. Co-pilot vertical pelvis accelerations for both MD-500 drop tests.

Vertical pelvis acceleration versus time responses are shown in Figures 16 and 17 for the pilot and co-pilot, respectively.

In line with the lumbar load trends, the pelvis peak accelerations, shown in Figures 16 and 17, were also attenuated substantially due to the DEAs. Peak acceleration reductions were 74 and 56% for the pilot and co-pilot, respectively.

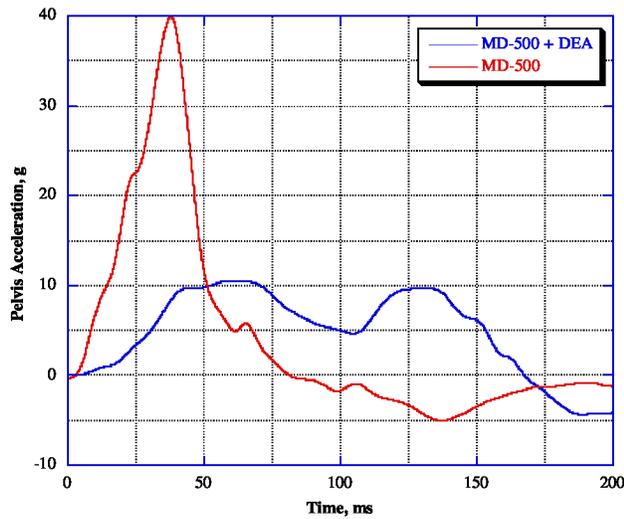


Fig. 16. Pilot vertical pelvis accelerations for both MD-500 drop tests.

Typical horizontal chest acceleration versus time response is shown for the pilot in Figure 18. Consistent with the previous results, the pilot horizontal chest accelerations were attenuated by 67% due to the DEA.

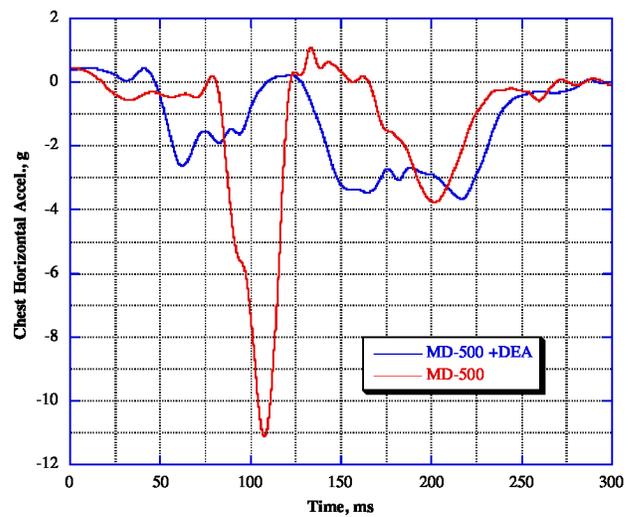


Fig. 18. Pilot horizontal chest accelerations for both MD-500 drop tests.

The biggest factor responsible for the forward acceleration attenuation is thought to be the frictional force. While the measured coefficient of friction was slightly lower for the skids (0.38) as compared to the DEA (0.48) the frictional forward resistance (and hence forward deceleration) was greater for the test article without the DEA because of the higher vertical loads.

4. DISCUSSION

For the demonstration of the DEA with respect to helicopter crashworthiness applications, the NASA team adopted the building block approach. In this approach, the effectiveness of the DEA was demonstrated in tests with progressively higher degree of complexity [7, 8]. In parallel to the test program, analytical studies followed the same path of increasing model complexity to eventually attempt to capture the DEA response as part of the overall dynamic system [10].

Based on the building block approach, the full-scale crash demonstration test was intended to provide combined forward and vertical impact velocity components. This represented a realistic level of increased complexity above what was investigated in previous tests [7 and 8], which involved purely vertical drops. Consequently, the energy absorbers for this demonstration test were designed to be as simple as possible to meet this two-dimensional impact event. A DEA more appropriate for a three-dimensional impact would have been constructed wide enough to extend over the aircrafts shoulder.

Results from the demonstration test showed significant occupant load attenuation attributed to the DEA. Despite the three-dimensional nature of the first MD-500 test, crew dynamic loads were still attenuated between 56 and 74%.

While it is not the objective of this study to assess the various crash injury criteria, it is clear based on lumbar tolerances of 1500-lb, as stated in FAR Part 27.562 (c) Reference [12], that the test article with the DEA resulted in a non-injurious crash as opposed to the second test without DEAs where lumbar loads were much greater than the 1500-lb limit. Even if a less conservative, lumbar load criterion, recommended by Desjardins [13] is used, the outcome is still the same. Desjardins' upper limit lumbar load criterion for the 50th percentile dummy is

1882 and 1752-lb for HYBRID II and III respectively, Ref. [13]. With filtered peak loads being 1907 and 1923-lb for the HYBRID II and III respectively, both pilots would have sustained spinal injuries in the test without the DEAs, and would have survived without injury in the test with the DEAs.

Because of the relatively large available stroke, most externally deployable systems can be designed to attenuate vertical impacts with good success as was demonstrated by many concepts [3, 7, and 9]. However, managing large forward components of velocity is more challenging [2], as large shear forces tend to tear deployable energy absorbers off the vehicles. Therefore, the forward component of velocity for the MD-500 demonstration test was chosen to be 40-ft/s. The choice was simply based on what was thought to be a realistic but severe (for an externally deployable device) crash landing velocity and was not based on any given standard such as, for example, MIL-STD-1290A [14].

A unique advantage of the deployable honeycomb (DEA) over any airbag system is that it offers the options of customizing the cell orientations to best accommodate the range of expected impact attitudes and velocities. Furthermore, earlier research [7] showed that for the class of honeycomb used in this study the vertical energy absorbing performance is insensitive to the cell axis orientation for up to 27° with respect to the load application. Therefore, as illustrated in the MD-500 simulator test, the honeycomb cells can be leaned forward to improve the shear stability of the DEA. Likewise, for lateral velocities the cells can be canted laterally to improve lateral stability. For optimum response, a DEA designed for omnidirectional impact load attenuation would have some cells pointing towards all orientations of expected impact velocity.

5. CONCLUSIONS

The performance of the deployable energy absorber (DEA) was demonstrated using an MD-500 airframe with replacement skid struts, total mass at impact of 2930-lb and nominal impact velocity of 40-ft forward and 26-ft/s vertical. Comparison of crew dynamic loads for tests with and without the DEA showed crew lumbar load attenuations between 60 and 67% and vertical pelvis acceleration attenuation of 56 to 74%. Results showed that

unlike the test without, the test with the DEAs would have been survivable without injuries.

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