Multi-Terrain Impact Testing and Simulation of a Composite Energy Absorbing Fuselage Section

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Abstract

Comparisons of the impact performance of a 5-ft diameter crashworthy composite fuselage section were investigated for hard surface, soft soil, and water impacts. The fuselage concept, which was originally designed for impacts onto a hard surface only, consisted of a stiff upper cabin, load bearing floor, and an energy absorbing subfloor. Vertical drop tests were performed at 25-ft/s onto concrete, soft-soil, and water at NASA Langley Research Center. Comparisons of the peak acceleration values, pulse durations, and onset rates were evaluated for each test at specific locations on the fuselage. In addition to comparisons of the experimental results, dynamic finite element models were developed to simulate each impact condition. Once validated, these models can be used to evaluate the dynamic behavior of subfloor components for improved crash protection for hard surface, soft soil, and water impacts.

Introduction

Considerable research has been performed on test and analysis of structural impacts into water, soft-soil, and hard surfaces [1-3]. This research has raised questions regarding the severity of the impacts; i.e., whether the onset rate of the acceleration pulse is greater for a water impact than for a hard surface impact, and whether an airframe designed for hard surface impact is ineffective for soft-soil and water impact. The US Navy is in the process of establishing guidelines for water impacts. Also, recent external airbag tests have shown promise for reducing the acceleration of the aircraft structure during impacts onto both hard surface and water. The focus of this paper is to address these questions by performing controlled impact tests onto three different terrains, and to assess the current capabilities of nonlinear dynamic finite element analyses for simulating multi-terrain impacts.

In 2001, a cooperative agreement was established between Bell Helicopter, the National Rotorcraft Technology Center / Rotorcraft Industry Technology Association (NRTC/RITA) and the US Army Research Lab, Vehicle Technology Directorate (ARL-VTD) to investigate the crashworthy response of a composite fuselage section for multi-terrain impact. Three 25-ft/s vertical drop tests of a 5-ft. diameter, 5-ft. long composite fuselage section were performed for nearly identical configurations onto a rigid surface in 2000 [4], soft soil in 2001 [1], and water in 2002 [5]. During each test, a new fuselage section was impacted from the same drop height and with the same floor loading provided by lead masses. In this investigation, data from accelerometers located on masses attached to the floor are compared for all tests. In conjunction with the testing program, crash simulations for each impact surface were performed and the models were validated through correlation of the analytical and experimental data. This paper summarizes the experimental data obtained during the multi-terrain tests, discusses their importance to crashworthiness applications, and presents the correlation between the test data and nonlinear finite element predictions.

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Objectives

Rigid surface impacts of airframe structures introduce concentrated loading into the stiffest part of the structure such as the keel beams and/or bulkheads. Landing gear designed to dissipate kinetic energy during an impact onto a rigid surface can significantly lower the loads transmitted to the airframe structure. In contrast, soft soil and water impacts introduce distributed loading to the fuselage skin in a rate-sensitive manner (See figure 1). Also, landing gear are ineffective for a crash into water. As a result, structures designed for hard surface impacts may not offer optimum crash performance during soft soil impacts or water impacts. Unfortunately, many otherwise survivable crashes of small aircraft and rotorcraft into water produce fatalities due to rapid water intrusion, sinking, and consequent drowning. One of the objectives of the NRTC/RITA Crashworthy and Energy Absorbing Structures project is to compare the acceleration response and specific energy absorption of structures in various impact media and to design subfloor configurations to provide improved crash protection for all impact surfaces.

Figure 1. Loading for hard surface (left) and for soft soil and water (right) impacts.

Another objective of the NRTC/RITA Crash Safety project is to improve water and soft soil crash analysis methodology through correlation of analytical and experimental data. Before attempting to design a crashworthy structure that will perform well under multi-terrain impact, it was deemed desirable to thoroughly understand the impact performance of an existing structure that was specifically designed for a hard surface impact.

TEST PROGRAM AND SUMMARY OF RESULTS

Description of the Composite Fuselage Section

The precursor to this research program was initiated at NASA Langley Research Center to develop an innovative and cost-effective crashworthy fuselage concept for light aircraft and rotorcraft [6-14]. The composite fuselage concept was designed to meet structural and flight loads requirements and to provide improved crash protection for hard-surface impacts. The composite fuselage section is approximately 5-ft. long and 5-ft. in diameter and consists of a stiff upper cabin, load bearing floor, and an energy absorbing subfloor. The structural floor produces a uniform global crushing of the energy-absorbing subfloor, which consists of five blocks of crushable Rohacell 31-IG closed-cell foam overlaid with E-glass/epoxy face-sheets. The five Rohacell blocks are uniformly spaced from front to rear with a gap in between each block. The cross-sectional geometry of the Rohacell foam blocks, shown in Figures 2 and 3, was designed to achieve a fairly uniform crushing stress. Floor loading was provided by ten 100-lb. lead weights that were mounted to the floor through the seat tracks shown in Figure 4. The total weight of the test specimen was approximately 1,200 pounds.

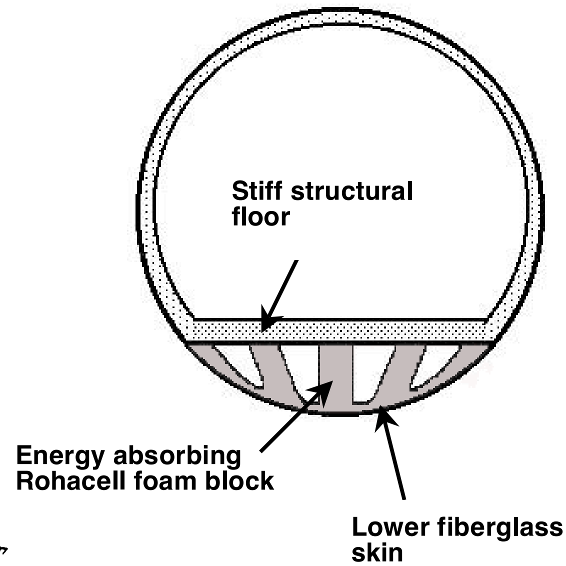


Figure. 2. Front schematic drawing of the composite fuselage section.

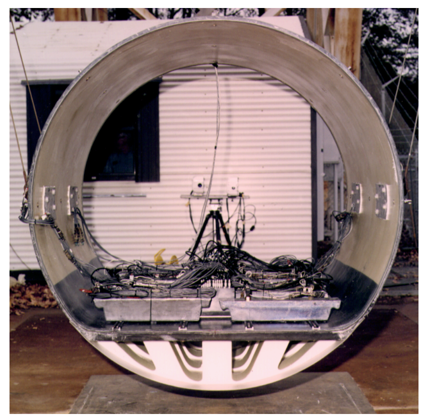


Fig. 3 Fuselage section with lead blocks and instrumentation prior to rigid surface drop test.

The crashworthy composite fuselage section was not optimized for multi-terrain impacts. The original design requirement was for crushing to initiate when the floor acceleration reached 25 g's during hard surface impacts, which translated to a 12 to 15-psi crush stress on the floor. Since the crush stress of a solid Rohacell foam energy absorber that filled the subfloor region was higher than 15-psi, five discreet blocks were used with cutouts designed to lower the pressure applied to the floor to the design level of 12- to 15-psi and to keep the crush area approximately constant during the crushing event. Since the bottom skin is unsupported between the foam blocks, the structural loading for soft soil and water impact is analogous to conventional aircraft structure with skin and stringers between bulkheads.

Drop Test Procedure, Instrumentation, Data Acquisition

All drop tests were performed using the 70-ft. drop tower located at the Impact Dynamics Research Facility at NASA Langley Research Center. Each empty fuselage had a nominal weight of approximately 200 pounds. Ten 100-pound lead

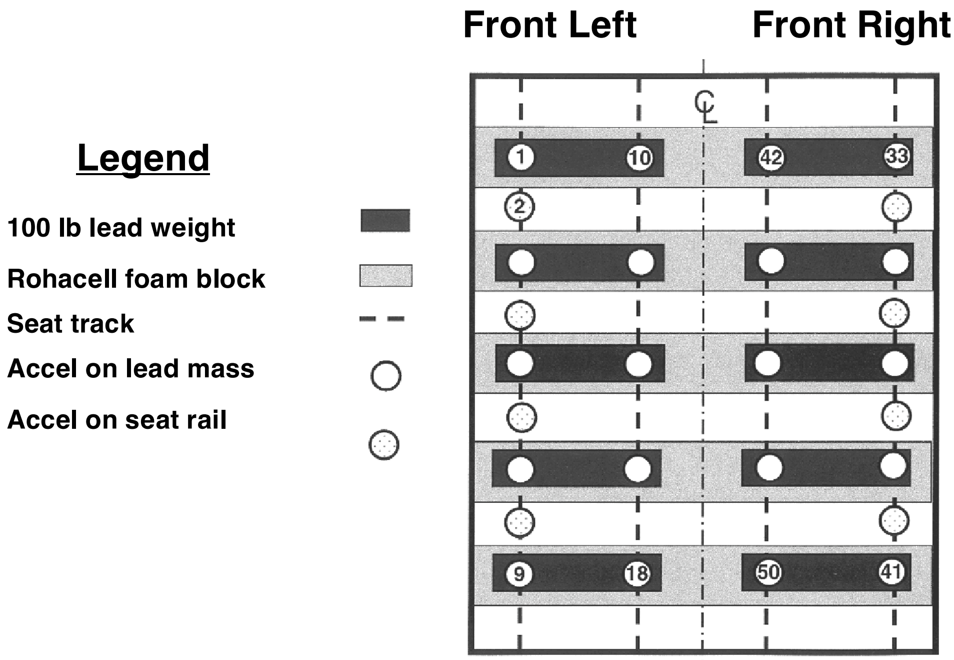


Figure. 4. Floor diagram showing placement of the ten 100-lb lead weights, channel numbers for floor-level accelerometers of interest, and placement of the 5 subfloor foam blocks. (Not to scale.)

masses brought the drop weight to a nominal value of 1,200 pounds. Each section was raised to a height of 10 feet above the impact surface to produce a vertical impact velocity of 25 ft/s. To facilitate comparisons of the test data, all of the fuselage sections were instrumented with 67 accelerometers located at the same positions on the fuselage floor, seat tracks, and lead blocks. A schematic drawing illustrating the instrumentation layout on the floor is shown in Figure 4. Note that selected accelerometer positions are numbered in Figure 4, corresponding to the original channel numbers used for the drop onto concrete. Only data for these locations will be presented in this paper. All accelerometers on the floor were oriented vertically. Accelerometers were located on the bolts securing the large lead masses to the aluminum seat rails. Some accelerometers positioned between the large masses, such as at position 2, were mounted on blocks adhered directly to the floor. Channels 1, 10, 42, and 33 are located at the front of the section. From symmetry, one would expect that data from inboard channels 10, 42, 18, and 50; and from outboard channels 1, 33, 9, and 41 would look very similar for a flat impact. However, slight offsets in the impact attitude, including small pitch and roll angles, can introduce asymmetries in the data. For example, the front end of the fuselage section was pitched down by 1 degree for the water impact. All data were collected with a digital data acquisition system (DAS) with a 10-kHz sampling rate. The DAS was onboard for the tests onto the rigid and soft-soil surfaces. The DAS was located external to the fuselage section for the water impact to avoid any water intrusion into the system. The weight of the onboard DAS was simulated by dead weight for the drop into the water. For the water impact test, seven pressure transducers were installed into the foam blocks at the bottom of the fuselage to measure the water pressure time-history.

Hard Surface Impact Test

In 2000, a drop test of a composite fuselage section was performed for the specific goal of examining test and analysis correlation approaches for detailed finite element crash simulations [4]. The data from this test were also used in this research program for comparison with data obtained from similar drop tests onto soft-soil and water. A post-test photograph of the fuselage section is shown in Figure 5. It was estimated that the subfloor foam crushed about 3.75 inches during this baseline test. The fuselage was noted to rebound, thus some of the strain energy was elastic.

Soft Soil Impact Test

A drop test of the crashworthy composite fuselage section onto sand was conducted at 25-ft/s in October 2001. The floor area of the fuselage specimen was instrumented identical to the hard surface impact test. To simulate soft soil, a large wooden "sand box" was constructed and filled with commercial grade sand. Consequently, the terms soft-soil and sand are used synonymously. A front-view photograph of the fuselage section is shown in Figure 6(a). A post-test examination of the foam subfloor indicated minimal deformation occurred, although the debonding of the face sheets from the crushable foam is obvious. The resulting impression left in the sand by the fuselage section drop is displayed in Figure 6(b). There was no observed rebound for the impact into sand.

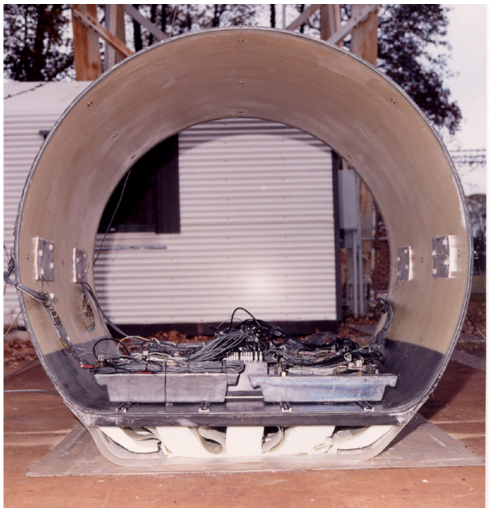
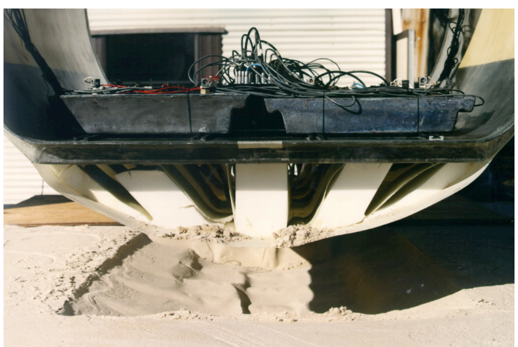


Figure 5. Post-test photo of the composite fuselage after impact onto a rigid concrete surface.



a. Fuselage section raised above sand post-test.

b. Depression of the fuselage left in the sand.

Figure. 6. Fuselage section post-test raised above sand (left) and sand depression

The material responses of soft soils are somewhat difficult to characterize and to model as the density and moisture content is quite variable. To aid in the characterization of the sand for this experiment, several small samples were obtained before the test to determine the density and moisture content of the sand. The sand was not packed except by walking on the surface. The surface was smoothed by slowly working a long board across the sandbox similar to methods used to smooth wet concrete. A hand-operated hydraulic jack was used to press a 12-inch diameter circular steel plate, approximately 1-inch thick, into the sand prior to the test to determine the load versus penetration depth. The test was performed as far from the impact area as possible. The pressure versus the non-dimensional crush factor (the change in volume divided by the original volume) curve obtained from this test is shown in Figure 7. The density of the sand was determined to be 1.36×10^{-4} lb sec^2/in^4. More details about this test can be found in reference 1.

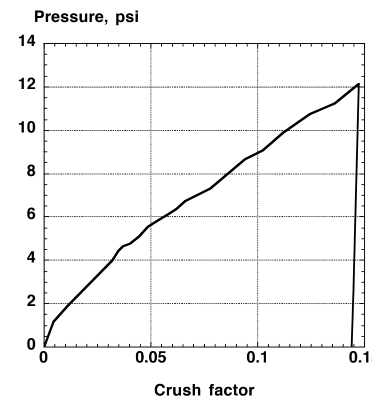


Fig. 7. Pressure-crush data for sand taken before test.

Water Impact Test

In March 2002, a vertical drop test of the composite fuselage section was conducted into a 3.5-ft. deep, 15-ft. diameter pool of water. The empty fuselage section weighed 208 pounds. The fuselage section outfitted with instrumentation, seat rails, and ten 100-lb. lead masses attached to the floor weighed approximately 1,200 pounds. A frame from a video taken during the water impact test is shown in Figure 8. The section impacted with a forward-down pitch of approximately 1 degree and a roll of 0 degree.

Figure 8. Fuselage shown shortly after water impact.

Prior to the drop test, all connectors were wrapped with plastic material and taped. To further protect the instrumentation, cables, and connectors from water intrusion; the entire floor area of the section was "vacuum-bagged." Special attention was given to sealing the instrumentation wiring. After a good vacuum was drawn, the vacuum hose was sealed. Although air leakage occurred after sealing, it was postulated that any trapped air inside the "vacuum bag" would exert a positive differential pressure within the bag that should keep water from entering. This behavior was observed after the test as air pockets did form within the bag. However, no water was observed to penetrate the sealed area after the vacuum bag was removed post-test.

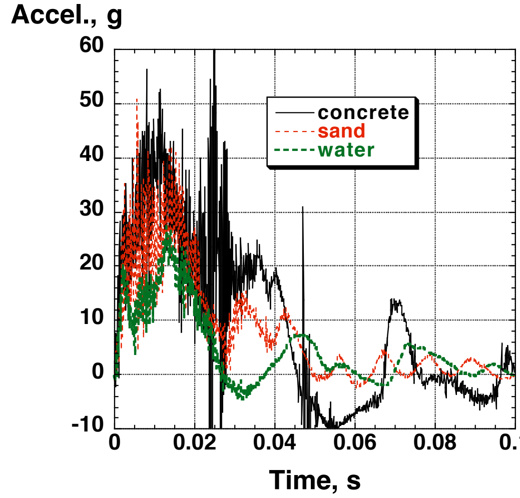
Post-test examination of the subfloor region revealed extensive damage to the outer skin. The center portion of all five foam blocks showed no sign of crushing, and there was also very little debonding of the face sheets from the foam. A post-test view of the bottom of the section taken from the front is shown in Figure 9, in which the five Rohacell foam blocks can be distinguished. The unsupported areas of the outer skin between the Rohacell blocks showed the most damage. No damage was observed to the floor and upper fuselage cabin region. Additional details can be found in reference 5.

Figure 9. Bottom of fuselage showing damage. The four dark regions are areas between the foam blocks.

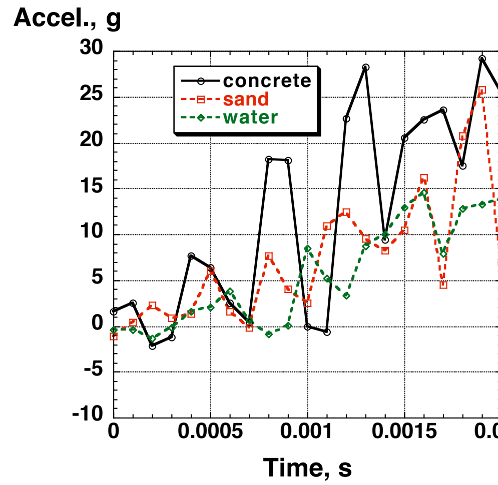
Experimental Data Comparisons

<u>Examination of typical acceleration pulses for hard surface, soft-soil, and water impacts</u>

Comparisons of hard surface (concrete), soft soil (unpacked sand), and water impact performance of the fuselage sections were conducted to examine acceleration pulse duration, peak, and onset rate. Unfiltered accelerations measured on the 100-lb lead masses at the front outboard location are shown in Figure 10(a). The onset rates appear to be approximately the same when viewed for the complete 0.1 second duration. However, when the time scale is blown up as in Figure 10(b), the concrete impact is seen to have a higher onset rate. The onset rate for both water and sand can be calculated approximately by fitting a straight line from time zero to 0.0015 seconds. Using the curve-fit, the acceleration at 0.0015 seconds for both water and sand impacts is around 10 g's. Thus the acceleration onset rate for water and sand is about 6,700 g/s. Similarly, the onset rate for the hard surface impact can be calculated to be 10,000 g/s. It is good practice that the onset rate be calculated from an accelerometer located on a reasonably large mass since the main concern is about acceleration onset rate to a seat and occupant. If the onset rate is taken from an accelerometer with very little associated mass without filtering, one is likely to only obtain the onset rate of high frequency vibrations.



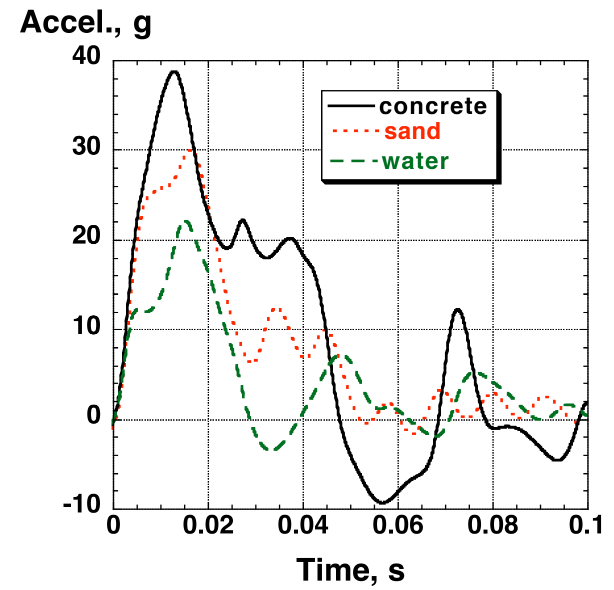
(a) Unfiltered accelerations from three section tests



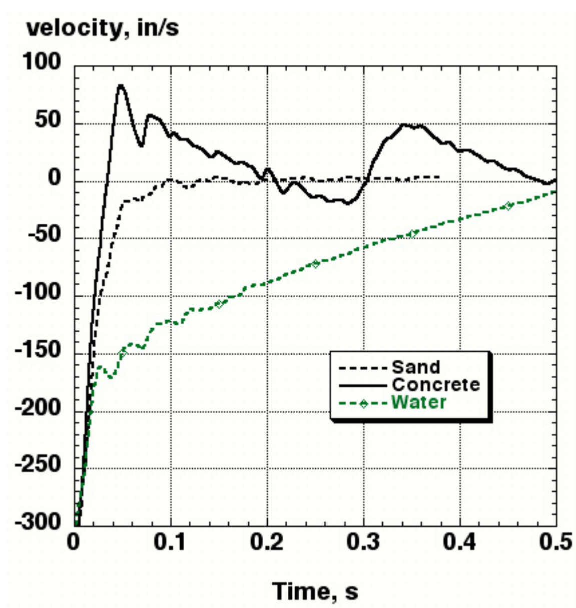
(b) Acceleration time histories for 0.002s.

Figure 10. Unfiltered accelerations for concrete, sand, and water impacts for the front outboard location. The onset rate can be computed from the right plot.

The acceleration responses in Figure 10 are filtered using an SAE CFC class 60 filter [15]. The results, shown in Figure 11(a), are easier to interpret as the high frequency vibrations have been removed. Peak acceleration levels are now apparent. The peak accelerations for the concrete, sand, and water impacts are 39, 30, and 22 g's, respectively. The accelerations are integrated to obtain the floor-level velocity of the section with respect to time as shown in Figure 11(b). The major accelerations for all impacts are over by 0.05 seconds; however, the velocity for the water impact has only been cut in half by that time, from 300 in/s to 150 in/s. Consequently, the peak acceleration and average acceleration for the water impact are reduced from those of the sand and concrete impacts. It is noted that the velocity of the section in the water has almost come to rest by 0.5 seconds. The section sinks slowly into the tank, and the velocity does not come to zero until the section strikes the bottom of the tank slightly after 0.5 second. The deceleration of the section through the water is much less than one-g and was not accurately measured with the instrumentation.



(a) Floor accelerations filtered with CFC60 digital filter.



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b) Velocities obtained from integration.

Figure 11. Comparisons of acceleration and velocity for concrete, sand, and water impacts for the front floor outboard location. The velocities were obtained from integration and were not filtered or smoothed.

The initial filtered pulse onset rates in Figure 11(a) appears comparable for the impacts onto all terrain. Thus, one needs to go to the unfiltered data to obtain the actual onset rates. In addition, from observing the test videos and from comparing the velocity traces in Figure 11b, it is evident that the drop into soft-soil and water did not exhibit any appreciable rebound. In contrast, a pronounced rebound was observed for the hard surface impact. For example, the velocity of the fuselage for the hard impact goes through zero at 0.03 seconds as shown in Figure 11(b). However, by 0.05 seconds, the velocity has reached the maximum rebound velocity of 80 in/s (6.7 ft/s) as it lifts off the ground. Thus, 0.05 seconds is the pulse duration for the rigid impact. From Figure 11(b), the total velocity change for the rigid impact is 380 in/s or 31.7 ft/s. (Recall that the impact velocity was 300 in/s or 25 ft/s.) When the velocity of the fuselage section goes through zero for the second time at 0.2 seconds, the fuselage is at its maximum rebound height. The fuselage strikes the concrete a second time at 0.29 seconds at a velocity of approximately 25 in/s.

The velocity of the fuselage into sand does not totally come to rest until 0.1 seconds (total pulse duration) and the velocity of the fuselage into water as mentioned previously does not come to rest until the bottom of the pool is struck. However, the velocity has nearly come to rest by 0.05 seconds for the sand impact. Since there is no measurable rebound, "none" of the kinetic energy was converted into elastic energy for the soft soil impact. In contrast, a portion of the kinetic energy was converted to elastic strain energy in the foam and released to produce the rebound of the fuselage for the rigid surface impact. This fact is intuitive since the concrete surface will dissipate almost no energy, while the soft soil dissipates energy by deforming plastically. Rebound is always bad since it results in a greater total velocity change and hence a larger peak acceleration. Also, as expected, the subfloor foam does not experience as much crushing in the soft soil impact as in the hard surface impact. Effectively, the soft sand and the foam are energy absorbers (springs) in series, which results in a much better energy absorber than the Rohacell foam alone. It is quite difficult to design a practical energy absorber in the subfloor of the fuselage that will produce no rebound for a rigid surface impact. The water behaves similarly to the sand by removing a major portion of the fuselage kinetic energy from the fuselage by the work performed to displace the water creating the large splash.

Discussion of Experimental Results

In a rigid surface impact, the bottom of each foam block begins to crush as soon as the contact pressure exceeds the crush stress. In the absence of friction, the contact force (and pressure) for a flat rigid surface is purely vertical. Consequently, for a vertical impact onto a rigid surface, the unsupported fiberglass skin between the foam blocks develops very little in-plane membrane forces. For the fuselage drop test onto concrete, the impact surface does not deform to remove any of the kinetic energy. Also, some of the kinetic energy is converted to elastic strain energy in the non-perfect energy absorbing foam and structure, which is released to produce rebound. Rebound increases the velocity change and generally the maximum acceleration of the fuselage. However, for soft-soil and water impacts, the impact media absorbs part of the kinetic energy of the vehicle. For the tests conducted with the composite fuselage section on non-rigid impact surfaces, the foam showed only minor crushing; hence, the major portion of the energy was absorbed by the soil and by the water. With two "energy absorbing springs in series," the resulting force is smaller than would result with either individual spring alone. In the case of the soft soil impact, the soil both compresses and displaces vertically and laterally to absorb the energy. In the case of water, which is incompressible, the collision involves momentum transfer from the fuselage to the water, which results in a large splash. For the impact onto a hard surface, the skin between the foam blocks receives only small forces. However, for both the soft-soil and water impacts, the skin between the foam blocks receives almost the same pressure wave as the supported skin. Since the skin between the blocks is unsupported, it deforms inwardly to produce large in-plane membrane forces that led to multiple failures in the water impact test. This effect is analogous to that seen in conventional metallic frame and skin aircraft structures. The fiberglass skin deformed plastically but did not fail for the soft-soil impact. Although the pressure on the unsupported skin was not measured for the sand impact test, it is apparent that the pressure was not nearly as large on the skin for the soft-soil test since the sand is compressible. Due to the incompressibility of water, the pressure was much greater for the water drop test, which led to the multiple failures observed.

This study is for a vertical impact only. For an impact with a large horizontal velocity component, both soft soil and water may produce higher longitudinal accelerations on an aircraft than a rigid surface.

Finite Element Modeling and Test/Analysis Correlation

Finite element models were constructed for all of the multi-terrain impacts. The same structural model of the fuselage section model was used for all of the simulations, while the terrain model was changed from a rigid surface for the concrete impact to deformable solid elements for the sand and water impacts. The MSC.Dytran nonlinear finite element code [16] was used to simulate the concrete and sand impacts; whereas, the LS-DYNA code [17] was used primarily to model the water impact.

The finite element composite fuselage model is shown in Figure 12. The model is comprised of approximately 30,000 elements and 30,000 nodes. The composite sandwich floor was modeled as two laminated composite face sheets with a foam core. The foam core is represented using solid elements assigned linear elastic material properties as no crushing of the foam in the floor occurred.

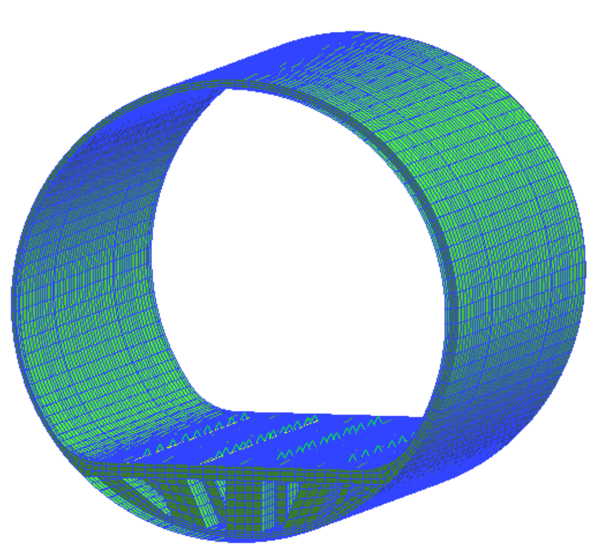


Figure 12. Schematic of fuselage finite element model.

The composite face sheets are represented with linear elastic orthotropic material properties. The upper section is also modeled with a foam core with laminated composite orthotropic face sheets. The subfloor section has solid elements with orthotropic face sheets on the interior surfaces. The accuracy of the crash simulations for this model is directly dependent on the accuracy of the subfloor Rohacel foam material properties. A stress-strain table was supplied for the MSC.Dytran FOAM2 material properties in the model. More details can be found in reference 13.

Hard Surface Analysis

A comparison of test data with the MSC.Dytran analysis for the impact onto concrete is shown in Figure 14 for four symmetric positions (see figure 3) at the front and rear of the fuselage. The four accelerometer positions (10, 42, 50, and 10) are on the 100-lb. masses located above the inboard seat track and show more oscillations than for positions above the outboard seat track (1, 33, 9, 41).

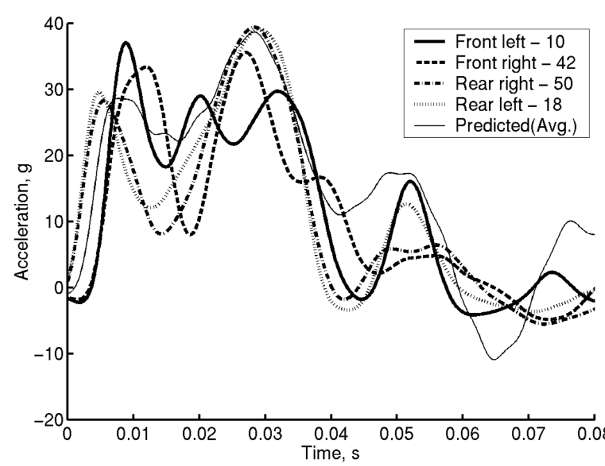


Figure 14. Measured and predicted accelerations for the impact onto concrete.

The maximum measured accelerations for the impact onto concrete peak at approximately 40-g's. In the test, the rear was pitched down slightly and impacted earlier than the front of the fuselage. The MSC.Dytran predictions were averaged for the four experimental locations. The average predicted acceleration is plotted and fits within the band of the experimental accelerations.

Soft Soil Modeling and Material Characterization

The MSC.Dytran model for the sand impact is shown in Figure 14. MSC.Dytran offers several different material models that can be used to represent soft soils. The material models that were investigated included:

a) a simple elastic-plastic soil model (DMATEP) with strain hardening was used to successfully model high-speed impacts into sand conducted in Utah by the NASA Mars Sample Return Earth Entry Program advanced development team [18],
b) the DYMAT14 soft soil and crushable foam model,
c) the FOAM2 model, which allows for user-specified unloading, a Poisson's ratio of effectively zero, strain-rate effects, and a tensile cut-off stress.

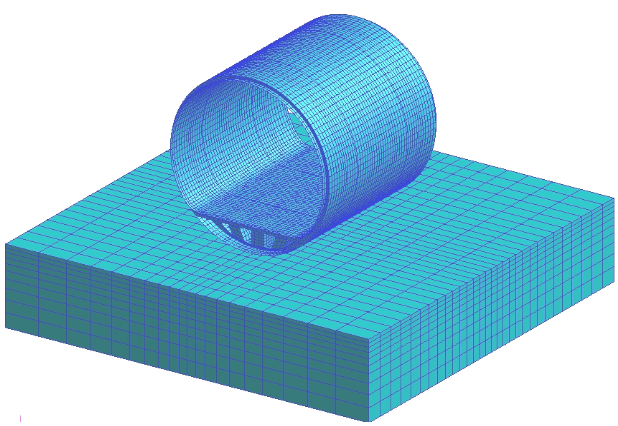


Figure. 14 MSC.Dytran analysis model for soft soil impact simulation.

Since the sand has very little shear strength, and the drop into sand showed no discernable rebound, the FOAM2 material model appears to be the best choice. Parameters used for the FOAM2 model were bulk modulus, K, equal to 533 psi, energy dissipation factor equal to 0.99, exponential unloading, a tensile cutoff stress of -0.1 psi, and a table of pressure-crush data obtained from the curve in Figure 7 corresponding to the unpacked soil material characterization.

The FOAM2 material model, which was used to represent both the Rohacell crushable foam and the sand, allows a user-specified hysteresis response curve for unloading, with strain rate dependency, and where Poisson's ratio is zero. The stress-strain (or pressure-crush) curve and a scale factor that is dependent on the strain rate determine the yield behavior.

The unloading curve is a nonlinear hysteresis response curve which is constructed such that the ratio of the dissipated energy (area between compressive loading and unloading curve) to the total energy (area under the loading curve) is equal to the energy dissipation factor, alpha. The effect of the material unloading curve on the test-analysis correlation for both the soil and Rohacell subfloor foam was investigated.

It was determined that the energy dissipation factor of 0.99 matches the test data better for the left outboard seat track acceleration (position 1). The corresponding fuselage section rebound behavior was also better for an energy dissipation factor of 0.99. This is to be expected since the experimental unloading curve of the soil, shown in figure 7 is extremely sharp, indicating a very high level of energy dissipation. Thus, the FOAM2 model in MSC.Dytran allowed an unloading curve to be generated that best matched the data for unpacked soil shown in figure 6. A typical comparison of the acceleration for test versus the analytical model is shown in Figure 15 for position 1 at the front of the fuselage. A computer generated picture of the bottom of the section after impact is shown in Figure 16. Although the bottom skin did not rupture in the test, it was noted to have a permanent set.

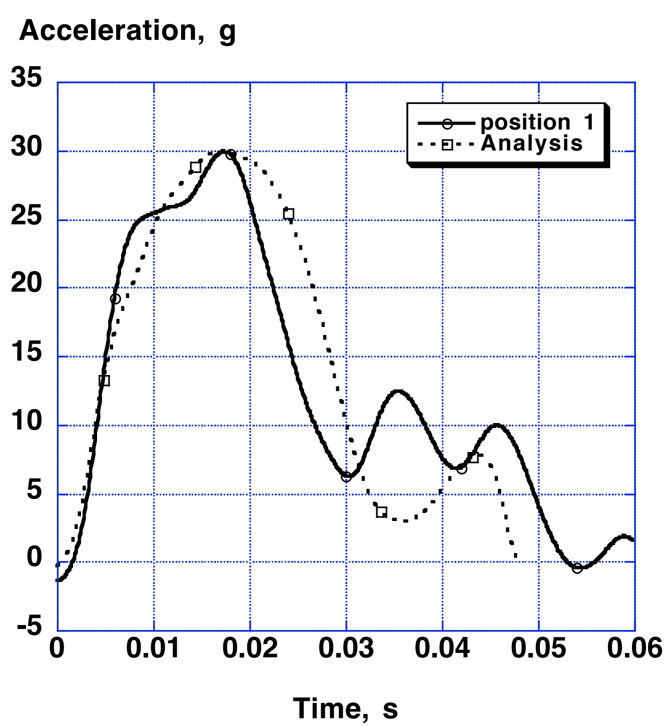


Figure 15. A comparison of the measured acceleration at the front left corner of the fuselage (position 1) versus analysis.

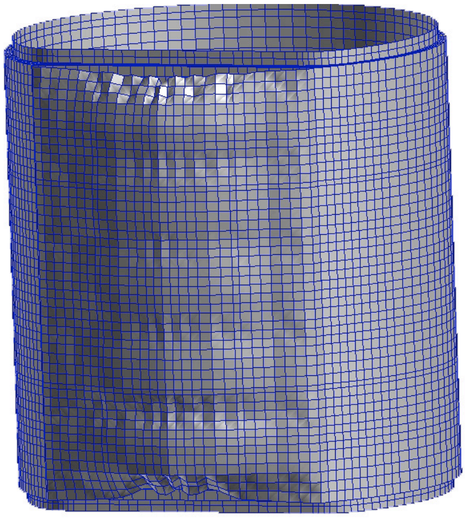


Fig. 16. Deformed view of the bottom of the fuselage section during soft soil analysis.

Water Impact Analysis

Although MSC.Dytran was used for limited water impact modeling, the LS-DYNA nonlinear finite element code was primarily used for the water impact simulation. The LS-DYNA coupled fluid structural algorithm (ALE/Euler) has the capability to allow the bottom fuselage coupling surface to fail, whereas MSC.Dytran with general coupling does not have this capability. A number of different LS-DYNA models were created to represent the air and water fluid regions. Both rectangular and cylindrical Euler meshes were created, and the size of the mesh was varied from constant 3 and 6-inch cubic meshes to a mesh with a gradient. Also, a smooth particle hydrodynamic (SPH) model of the water was developed in LS-DYNA. Although the SPH model gave good results, it was somewhat slow in execution. A description of the various water models and their resultant predictions can be found in Reference 5. A shaded three-quarter view of a typical LS-DYNA model is shown in Figure 17.

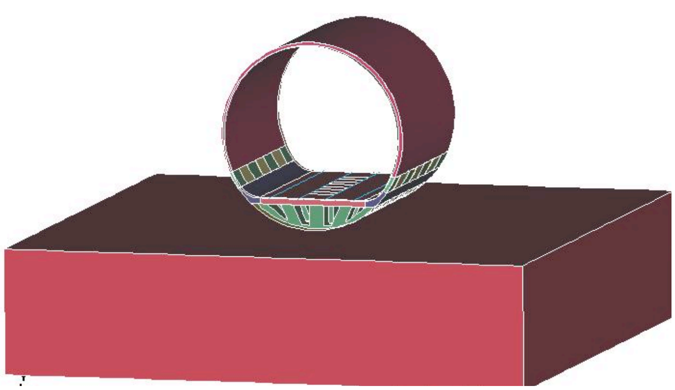


Figure 17. Shaded three-quarter view of one of the LS-Dyna water impact model.

<u>LS-DYNA 1-in. gradient mesh with and without bottom skin failure</u>

In order to study the failure of the bottom skin, a final, more detailed LS-DYNA model was created with a fine 1-in gradient fluid mesh under the section (Figure 18). The failure strain can be set on the material card for the bottom fiberglass skin to allow the elements to fail after a given strain is reached. Failed elements are deleted, thus holes are formed in the bottom surface that allow the water to flow through the failed skin. The failure of the bottom skin is shown in Figure 19 for 0.01 seconds after impact. The left half of the figure shows the bottom skin of the fuselage viewed from an angle from above. In this case, the failure strain was set to 2 percent, which is a practical value for an angle-ply fiberglass laminate. The results show that the outer skin between the foam blocks fails catastrophically allowing the water to flow through as shown in the right side of the figure. Although the failure is dramatic, the initial peak accelerations were only reduced by a small amount from the original model without failure as shown in Figure 20. Since the run times for these models are long, the model with failure was only executed long enough to capture the fundamental pulse; i.e., 0.04 seconds. The amount of damage predicted by this simulation was more severe than observed.

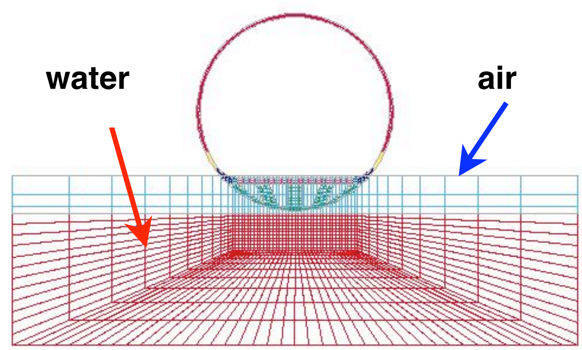
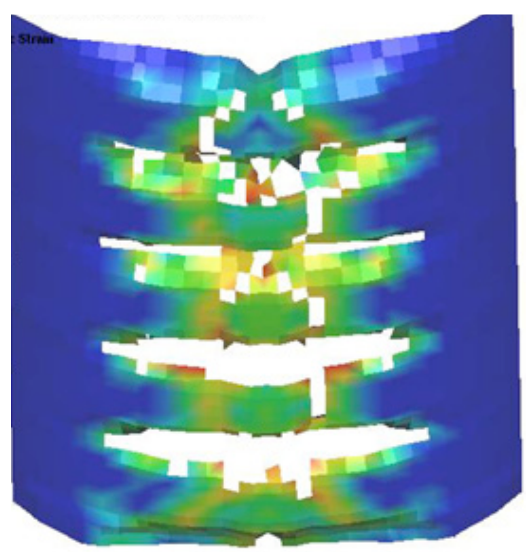
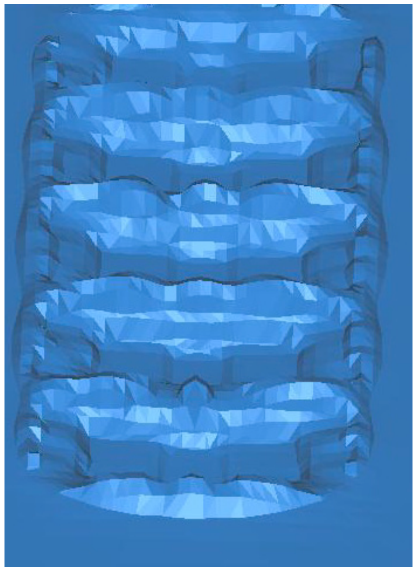


Figure 18. Front view of a slice of the gradient-mesh that becomes a refined 1-inch mesh beneath the fuselage section.

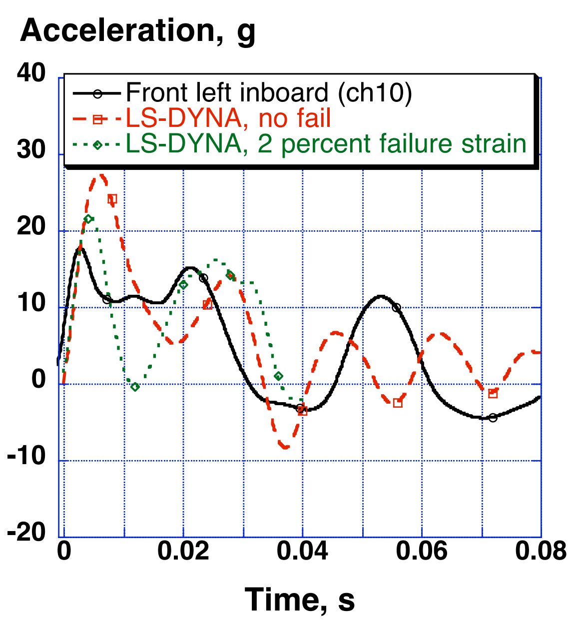


(a) Failures of the lower skin at time 0.01 seconds

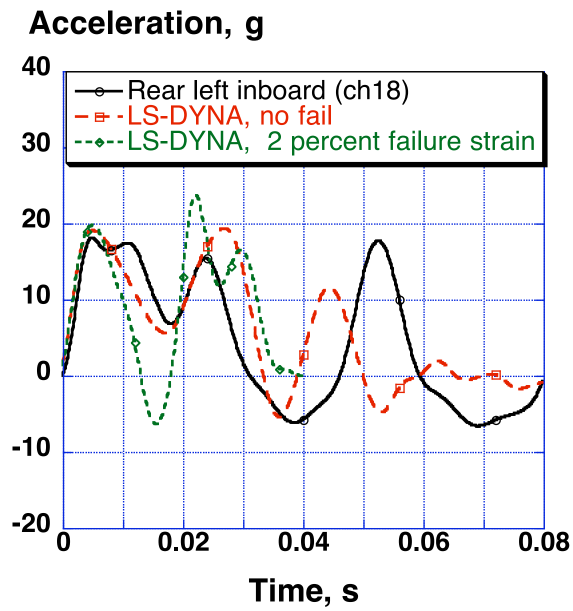


(b) Water flowing through the ruptured skin corresponding to 0.01 seconds

Figure 19. Computer graphics illustrating failures of the lower skin at time 0.01 second, which allow water to flow through the ruptured skin.



(a). Front left inboard, channel 10.



(b). Rear left inboard, channel 18.

Figure 20. Filtered experimental acceleration responses compared with LS-DYNA predicted inboard accelerations for the 1-in. gradient Euler mesh, with and without failure.

Figure 20 shows accelerations at two locations, position 10 in the front and position 18 in the rear for LS-DYNA simulations with and without failure of the bottom skin. The acceleration pulses with failure of the bottom skin drop off too quickly after the initial peak due to the excessive failure. Since the actual strain-to-failure data for the angle-ply laminate was not available, the objective of specifying a failure strain was to determine the effect of failure on the simulation. Also, note that when the failure strain criterion was met, the elements were deleted. Other failure options available in LS-DYNA such as "constrained tied nodes failure" were not evaluated, but may reduce the severity of the damage. A finer mesh would be another option; however, a mesh-density study was not performed.

Concluding Remarks

Comparisons of the impact performance of a 5-ft diameter crashworthy composite fuselage section were investigated for hard surface, soft soil, and water impacts. The fuselage concept was originally designed for impacts onto a hard surface only, and it consisted of a stiff upper cabin, load bearing floor, and an energy absorbing subfloor. Vertical drop tests were performed at 25-ft/s onto concrete, soft-soil, and water at NASA Langley Research Center. Comparisons of the peak acceleration values, pulse durations, and onset rates were evaluated for each test at specific locations on the fuselage. In addition to comparisons of the experimental results, dynamic finite element models were developed to evaluate test-analysis correlation for each impact condition.

In a rigid surface impact, the bottom of each foam block begins to crush as soon as the contact pressure exceeds the crush stress, and in the absence of friction, the contact force (and pressure) for a flat rigid surface is purely vertical. Consequently, for a vertical impact onto a rigid surface, the unsupported fiberglass skin between the foam blocks develops very little in-plane membrane forces. For the fuselage drop test onto concrete, the impact surface does not deform to remove any of the kinetic energy. However, for soft-soil and water impacts, the impact media absorbs a large part of the kinetic energy of the vehicle. For the impact onto a hard surface, the skin between the foam blocks receives only small forces. However, for both the soft-soil and water impacts, the skin between the foam blocks receives almost the same pressure wave as the supported skin. Since the skin between the blocks is unsupported from behind, it deforms inwardly to produce large in-plane membrane forces that led to failure in the water impact test. This effect is analogous to that seen in conventional metallic frame and skin aircraft structures. The fiberglass skin deformed plastically but did not fail for the soft-soil impact. However, multiple failures were observed in the outer skin between the foam blocks after the water impact. Due to the incompressibility of water, the pressure was much greater for the water drop test, which led to the multiple failures observed.

Nonlinear dynamic finite element models using both Eulerian and Lagrangian formulations were constructed with the codes MSC.Dytran and LS-DYNA. MSC.Dytran was used to model the hard surface and the sand impacts with good results. An LS-DYNA fuselage model was developed from the original MSC.Dytran mode and was used to study the impact into water. ALE coupling was used to simulate the fluid structure interaction. The LS-DYNA water model was discretized with a gradient mesh with the smallest 1-in. elements located in close proximity to the bottom of the fuselage section. When failure strains were applied to this model, water did flow though the areas formed by the deleted failed elements. However, partially due to the coarse elements in the bottom skin, the failure was more severe in the model than observed in the test.

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