COMPARISON OF HARD SURFACE AND SOFT SOIL IMPACT PERFORMANCE OF A CRASHWORTHY COMPOSITE FUSELAGE CONCEPT

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ABSTRACT

A comparison of the soft soil and hard surface impact performance of a crashworthy composite fuselage concept has been performed. Specifically, comparisons of the peak acceleration values, pulse duration, and onset rate at specific locations on the fuselage were evaluated. In a prior research program, the composite fuselage section was impacted at 25 ft/s onto concrete at the Impact Dynamics Research Facility (IDRF) at NASA Langley Research Center. A soft soil test was conducted at the same impact velocity as a part of the NRTC/RITA Crashworthy and Energy Absorbing Structures project. In addition to comparisons of soft soil and hard surface test results, an MSC.Dytran dynamic finite element model was developed to evaluate the test–analysis correlation. In addition, modeling parameters and techniques affecting test–analysis correlation are discussed. Once correlated, the analytical methodology will be used in follow-on work to evaluate the specific energy absorption of various subfloor concepts for improved crash protection during hard surface and soft soil impacts.

BACKGROUND AND OBJECTIVES

Rigid surface impacts of airframe structures introduce concentrated loading into the stiffest part of the structure, such as the keel beams. In contrast, soft soil impacts introduce distributed loading to the fuselage skin (Fig.1). As a result, structures designed for hard surface impacts may not offer optimum crash performance during soft soil impacts. One of the objectives of the National Rotorcraft Technology Center/Rotorcraft Industry Technology Association (NRTC/RITA) "Crashworthy and Energy Absorbing Structures" project is to compare the specific energy absorption of structures in various impact media and to design subfloor configurations to provide improved crash protection for all impact surfaces. Another objective is to improve water and soft soil crash analysis methodology through correlation of analytical and experimental data. An important issue in the analysis of soft soil impact performance is the characterization of soft soil material properties. Consequently, bearing pressure tests were conducted to adequately represent the soft soil used in the fuselage section crash simulation.

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DESCRIPTION OF CRASHWORTHY COMPOSITE FUSELAGE SECTION

In 1997, a three-year research program was initiated at NASA Langley Research Center to develop an innovative and cost-effective crashworthy fuselage concept for light aircraft and rotorcraft (Refs. 1–3). The composite fuselage concept, shown schematically in Fig. 2, was designed to meet structural and flight loads requirements and to provide improved crash protection. During the first year of the research program, a 1/5-scale model composite fuselage (12 inches [0.3 m] in diameter) was designed, fabricated, and tested to verify structural and flight load requirements (Ref. 3). During the second year of the research program, energy absorbing subfloor configurations were evaluated using quasi-static testing and finite-element simulation to determine the best design for use in the 1/5-scale model fuselage concept (Refs. 4–5). During the third year of the program, a full-scale version of the fuselage concept was fabricated, and

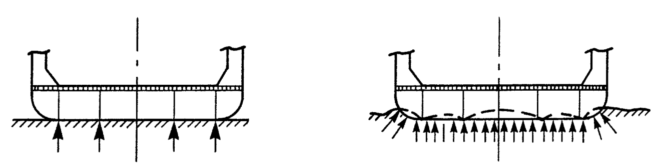


Fig. 1. Loading differences during hard surface and soft soil/water impact.

a vertical drop test was conducted to validate the scaling process (Ref. 6).

The full-scale fuselage section is 64 inches (1.63 m) long with a diameter of 60 inches (1.52 m). During impact, the stiff, load-bearing floor produces a uniform global crushing of the energy-absorbing subfloor, which consists of a geometric foam-block design with five uniformly spaced individual blocks of crushable Rohacell 31-IG closed-cell foam overlaid with E-glass/epoxy face sheets. A front view photograph of the fuselage section is shown in Fig. 3. The location of the five Rohacell foam blocks, shown in Fig. 4, was chosen to achieve a fairly uniform crushing stress based on a floor loading per unit length of 25 lb/in (43.7 N/cm). Two sets of seat-tracks spaced 11 inches (0.28 m) apart were used to support the ten 100-lb (45-kg) lead weights with associated floor-level accelerometers whose positions are shown on the floor diagram in Fig. 4. The total weight of the test specimen was approximately 1,200 lb (544 kg).

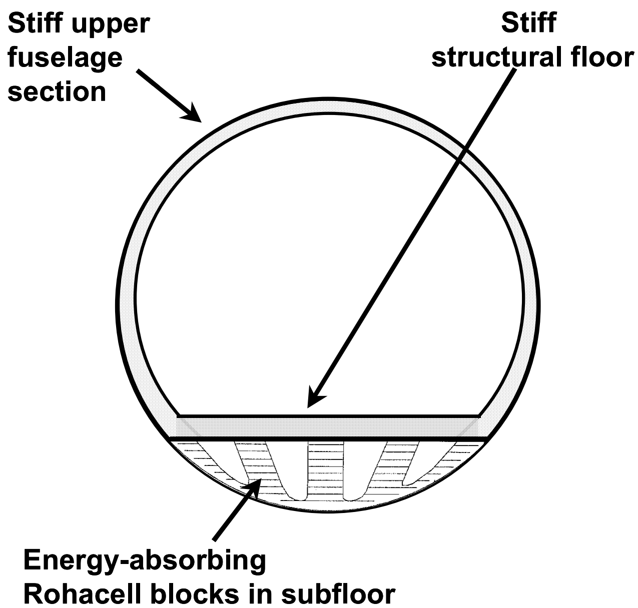


Fig. 2. Front schematic drawing of the fuselage section.

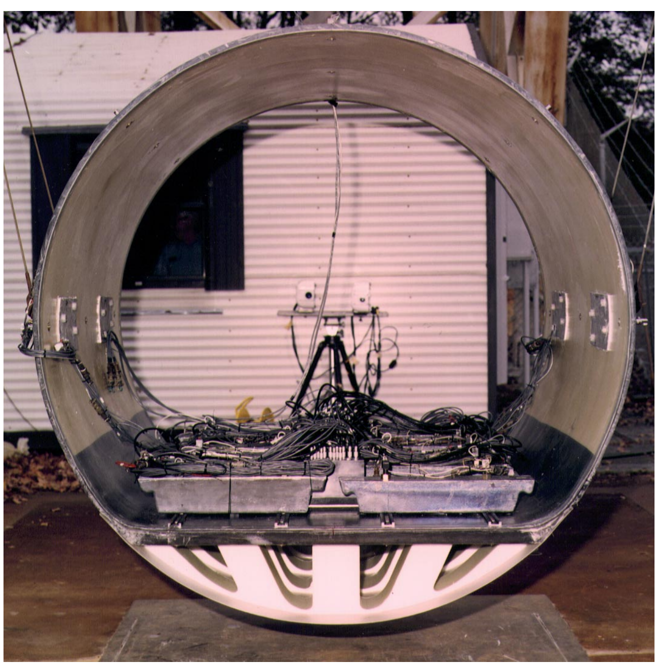


Fig. 3. Fuselage section prior to hard surface and soft soil drop test.

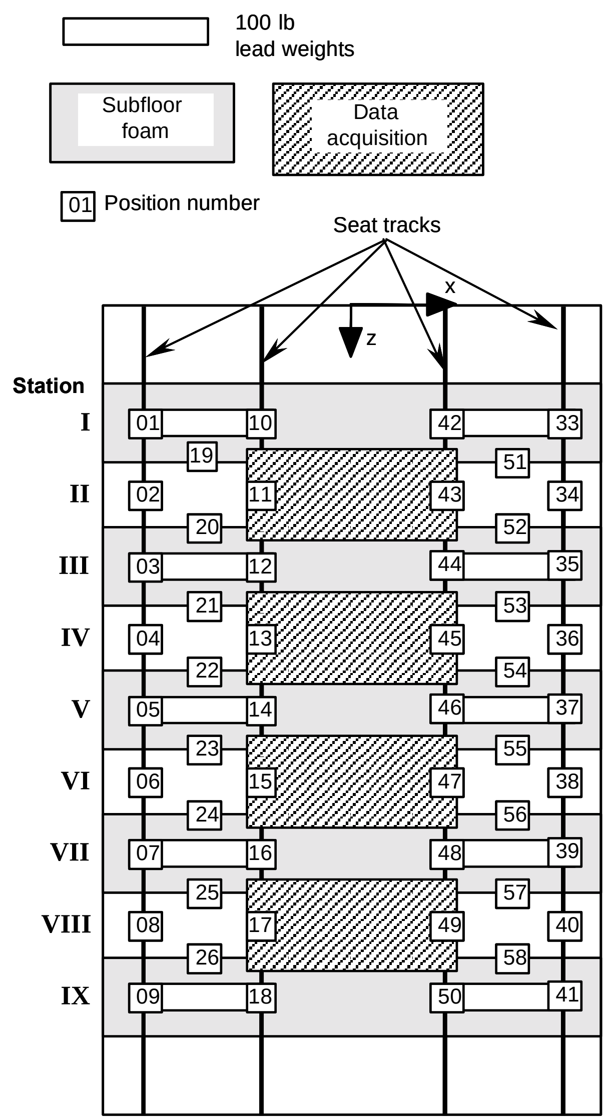


Fig. 4. Floor diagram showing placement of the ten 100-lb weights, position numbers for 52 floor-level (vertical) accelerometers, seat tracks, and placement of 5 subfloor foam blocks (NOTE: not to scale).

To date, drop tests of the composite fuselage section have been performed on rigid and soft soil (sand) surfaces. A drop test onto water is planned for Spring 2002. During each test, a new fuselage section was dropped from the same drop height and with the same floor loading provided by lead masses. In this investigation, data from accelerometers located on the floor will be compared for the hard surface test and for an identical section with the same 25 ft/s (7.6 m/s) impact velocity onto a soft soil surface.

The data from the test conducted on the hard surface are used in this investigation to evaluate the influence of impact surface on dynamic structural response. The hard surface and soft-soil impact tests are described below and the data are compared. Finally, a comparison of the soft soil finite-element model predictions will be made with test data, and modeling parameters affecting test–analysis correlation will be discussed.

HARD SURFACE IMPACT TEST

In 2000, a drop test of a composite fuselage section, 5 ft (1.5 m) in diameter, was performed at NASA Langley Research Center for the specific goal of examining test and analysis correlation approaches for detailed finite-element crash simulations (Ref. 7). The test was performed from a drop height of 10 ft (3 m) to produce an impact velocity of 25 ft/s (7.6 m/s) onto a concrete surface, and the test data were correlated with an nonlinear, transient dynamic crash simulation using MSC.Dytran[1]. For the test, the fuselage section was loaded symmetrically with ten 100-lb (45-kg) lead masses, which were attached to the floor through seat tracks (five on each side of the fuselage). Data were recorded at 10,000 samples/second from the sixty-seven accelerometers. It was estimated that the subfloor foam crushed about 3.75 inches (9.525 cm) during this test.

SOFT SOIL IMPACT TEST

A drop test of the crashworthy composite fuselage section onto soft soil was conducted at 25-ft/s (7.6 m/s) in October 2001. (The terms “soft soil” and “sand” are used interchangeably in this paper.) The soft soil used in the test was a scientific sand consisting of microglass beads of approximately 0.027 inch (0.069 cm) maximum diameter. The sand was sifted through a sieve so that the maximum size was as stated, but smaller spherical beads were present. The fuselage section was dropped on a “sandbox”—a wooden enclosure (measuring 12 ft by 12 ft, and 3 ft in height) that contained the sand. The sandbox was located under the 70-ft (21.3-m) high drop tower at the Impact Dynamics Research facility (Fig. 5). The soft soil drop test was instrumented almost identically to the hard surface impact test of Ref. 7.

The section was instrumented with sixty-seven accelerometers, with data collected using a digital data acquisition system at a 10-kHz sampling rate. The accelerometers on the floor are oriented vertically. The accelerometers at Stations I (i.e., position numbers 1, 10, 42, and 33, as shown in Fig. 4), III, V, VII, and IX were mounted to the top of the 100-lb (45-kg) lead weights on the bolts that secured those weights to the aluminum seat rails. For Stations II, IV, VI, and VIII, the outboard accelerometers were mounted on blocks attached directly to the seat rails. The inboard accelerometers were mounted to the data acquisition system support plates. The accelerometers positioned between the seat rails were

Fig. 5. Fuselage section prior to soft soil drop test at 70-ft drop tower (Impact Dynamics Research facility).

[1] MSC, MSC., and DYTRAN are registered trademarks and service marks of the MSC.Software Corporation. MSC.Dytran is a general-purpose, three-dimensional program for simulating the high-speed response of solids, structures, and fluids, developed and maintained by MSC.Software Corporation.

mounted on blocks adhered directly to the floor. The radial locations of the accelerometers located on the outer skin of the fuselage section are shown in Fig. 6.

A front view photograph of the fuselage section, shown in Fig. 7, indicated that the fuselage section displayed minimal deformation of the crushable foam after the test, 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 Fig. 8. No fuselage section rebound was visible with the unaided eye, and section ovalling was visible using high-speed video.

COMPARISON OF HARD SURFACE AND SOFT SOIL IMPACT TEST DATA

Comparisons of hard surface and soft soil impact performance of the fuselage section at different accelerometer locations were conducted to examine acceleration pulse duration, peak, and onset rate. Comparisons of the acceleration pulses and velocities at the left front outboard seat track location (Position 1, Fig. 4) between the hard surface and soft impact are displayed in Fig. 9a and 9b, respectively. Unless specified otherwise, all acceleration data in the paper were filtered with a SAE Channel Filter Class (CFC) 60 digital filter (Ref. 8).

It is clear from examining the data in Fig. 9a that the pulse onset rate is comparable for the impacts on the two media, and that the peak acceleration and pulse duration are both greater for the rigid surface impact. In addition, from observing the test videos and from comparing the velocity traces in Fig. 9b, it is evident that the drop into soft soil did not exhibit any appreciable rebound. In contrast, a pronounced rebound was observed for the hard surface impact. Effectively, all the kinetic energy was dissipated for the soft soil impact, while a portion of the kinetic energy was stored and released to produce the rebound 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. The stored elastic-energy contributes to the rebound and also results in a longer duration acceleration pulse for the hard surface impact. Also, as expected, the subfloor foam does not experience as much crushing in the soft soil impact as in the hard surface impact.

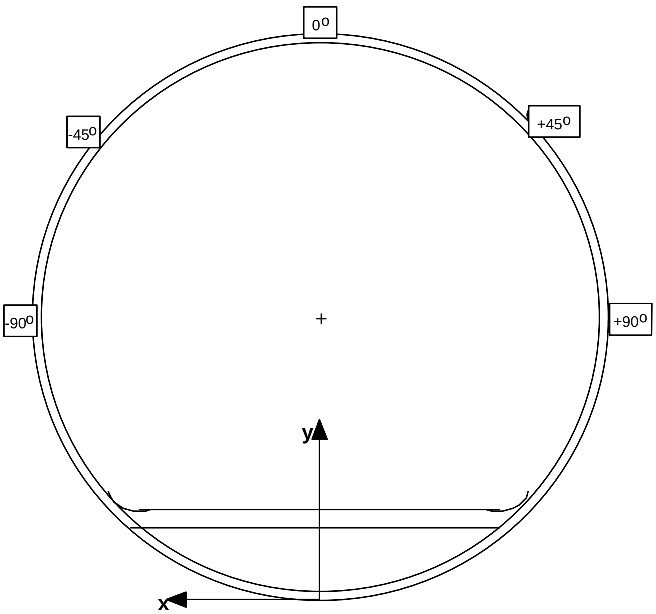


Fig. 6. Front view schematic of fuselage section with instrumentation.

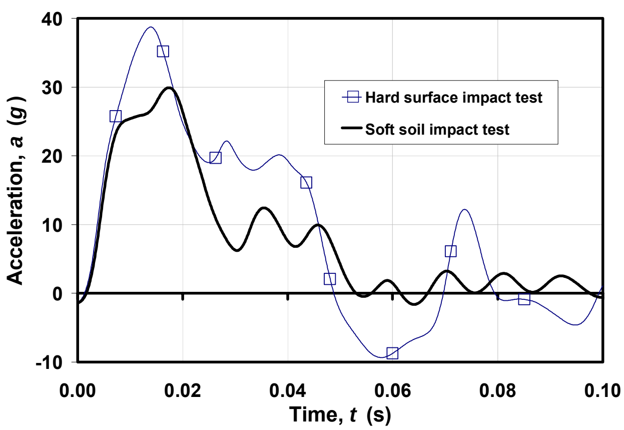
Fig. 7. Fuselage section after soft soil drop test.

Fig. 8. Soil impression after soft soil drop test.

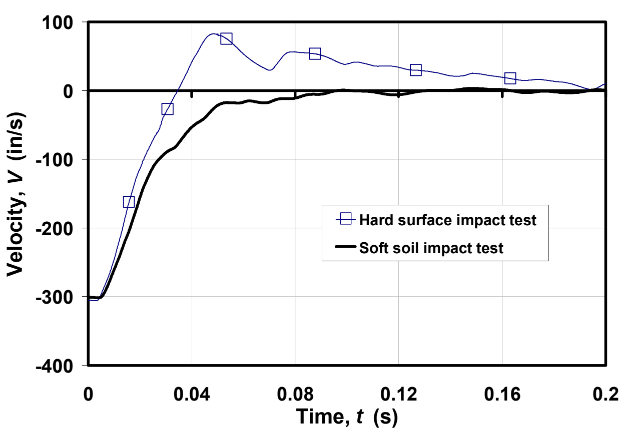
As part of the same NRTC/RITA Crashworthy Structures project, a water impact test is planned for the spring of 2002. The hard surface data will be compared with the soft soil and water impact data to determine if the compliance of the water medium offers a significantly different pulse onset rate, duration, or peak acceleration for the composite fuselage section when dropped at the same 25-ft/s (7.6-m/s) vertical velocity.

SOFT SOIL ANALYSIS

For the purpose of test–analysis correlation, a detailed three-dimensional model of the full-scale fuselage section was developed using the MSC.Dytran finite-element code. A brief description of the analysis tool and finite-element model follows, and a comparison of analysis and test data.



a. Accelerometer data during hard surface versus soft soil impact test.



b. Rebound behavior during hard surface versus soft soil impact test.

Fig. 9. Data comparisons at left front outboard (Position 1) for the hard surface and soft soil impact.

Description of MSC.Dytran Analysis Tool

MSC.Dytran (Ref. 9) is a general-purpose finite-element code that uses the explicit formulation of the finite-element method to treat transient dynamic problems with geometric and material nonlinearity. It contains both Lagrangian and Eulerian processors. The Lagrangian processor uses a control mass approach and is primarily applicable to structural problems. The Eulerian processor uses a control volume approach and is used mainly for fluid problems. The two processors can be coupled in two different ways (ALE and general coupling) to simulate a variety of fluid–structure interaction problems (Ref. 10).

The MSC.Dytran structural model can be composed of isotropic beam, isotropic or orthotropic shell and solid elements with elastic–plastic yield behavior, specific failure criteria, or composite failure models. For structural problems, a single surface or surface-to-surface contact is available. Initial or enforced velocity, nonlinear material models of various types, and output requests for a number of important variables are available in the code. For drop-test simulation problems, it is important to use the proper modeling parameters for contact including contact stiffness, the type of master and slave surfaces, and static and dynamic friction coefficients. Other modeling parameters pertinent for the soft soil impact analysis are the soil density, the soil discretization in the impact zone, the soil material characterization (experimentally determined bearing pressure data versus displacement), as well as the proper energy dissipation factor, which is determined by the unloading curve. A brief description of the MSC.Dytran finite-element model is followed by an investigation of the influence of some of these modeling parameters on the test–analysis correlation.

MSC.Dytran Analysis Model

The finite-element model used for the soft soil impact test simulation was derived from the model used for the hard-surface impact analysis described in Ref. 7. The model used for the hard surface impact simulation consisted of approximately 30,000 elements and 30,000 nodes. In the model, the rigid floor has been represented as two laminated composite face sheets with a foam core. The foam core is modeled using solid elements assigned linear elastic material properties. 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 solid elements representing the Rohacell foam blocks were modeled using a FOAM2 material with an associated pressure versus crush table.

The finite-element model was subsequently modified for soft soil analysis by replacing the rigid impact surface with a meshed soft soil region composed of solid elements. The solid elements representing soil were modeled using DYMAT14 and FOAM2 material models that use, among other parameters, a shear and bulk modulus as well as a tabular variation of pressure versus crush factor (1-relative volume) derived from soil material characterization tests. These tests were conducted for unpacked and packed soil as described in the next section of the paper. A master-surface-to-slave-node contact was defined between the soft soil surface and the subfloor nodes of the fuselage section. The resulting analysis model for soft soil simulation is shown in Fig. 10.

Soft Soil Modeling and Material Characterization

The material responses of soft soils are difficult to characterize and to model. To aid in the characterization of the soft soil for this experiment, several small samples of the soil were obtained before the test to determine the density and moisture content. However, the volume of the soil, and thus its density, can vary depending on the packing of the sand. A hand-operated hydraulic jack was used to press a 12-inch (0.3 m) diameter circular steel plate (Fig. 11), approximately 1 inch (2.54 cm) 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 crush factor curve obtained from this unpacked soil test is shown in Fig. 12a. The density of the soil was determined to be 0.000136 lb·s^2/in^4 (71.6947 kg/m^3). To further characterize the material properties of the soil, an instrumented hemispherical penetrometer, 26 inches

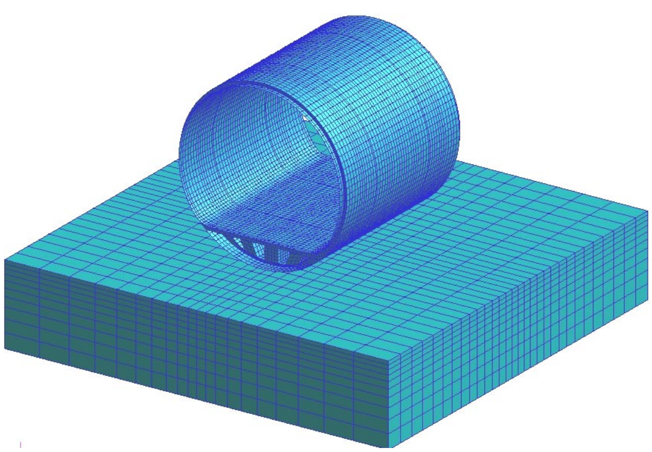
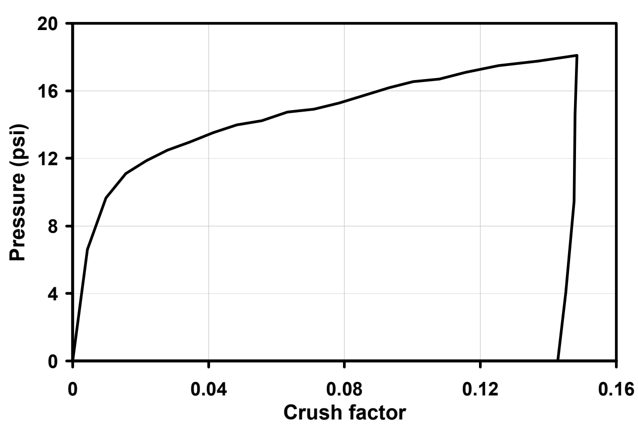


Fig. 10. MSC.Dytran analysis model for soft soil impact simulation.

Fig. 11. Soft soil bearing pressure test.

a. Unpacked soft soil.



b. Packed soft soil.

Fig. 12. Pressure-crush data.

(0.66 m) in diameter, was dropped at 25 ft/s (7.6 m/s) into the sand.

MSC.Dytran offers several different material models that can be used to represent soft soils. The material models that were investigated included the following:

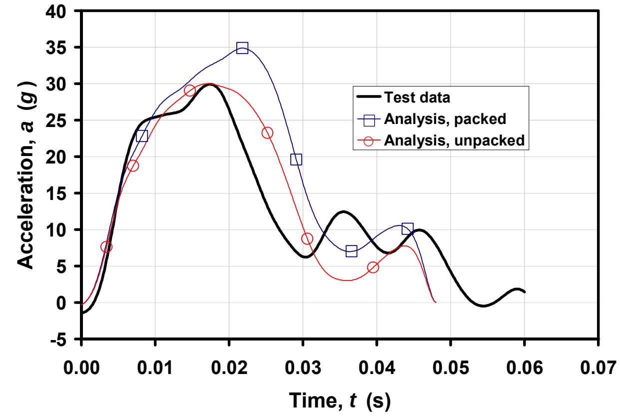
- A simple elastic–plastic soil model (DMATEP) with strain hardening that was used to successfully model high-speed impacts into sand conducted in Utah by the NASA Mars Sample Return Earth Entry Program advanced development team (Ref. 11).
- The DYMAT14 soft soil and crushable foam model.
- The FOAM2 model, which allows for user-specified unloading, a Poisson's ratio of effectively zero, strain-rate effects, and a tensile cutoff stress.

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 [3,675 kPa]), 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 Fig. 12a or Fig. 12b (corresponding to the unpacked and packed soil material characterization, respectively). Due to lack of information, the default bulk viscosity factors were used.

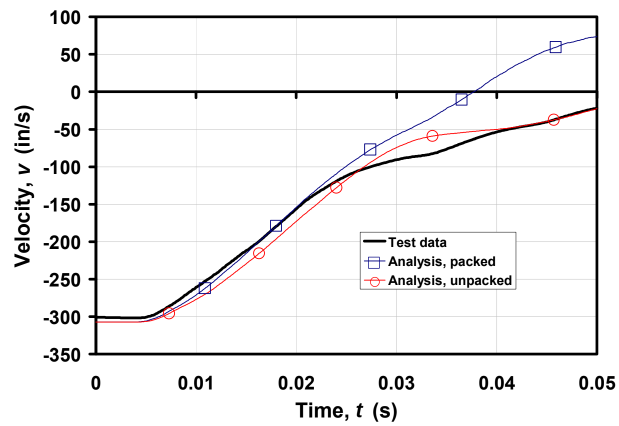
The effect of using the unpacked versus packed soil pressure-crush data on the analytical results is depicted in Figs. 13a and 13b. This figure shows a comparison of computed acceleration and velocity results with the soft soil impact test data. It is clear from the velocity data that the unpacked soil characterization better corresponds with the test results. Furthermore, velocity data shows that unpacked soil shows no rebound (a fact observed in the soft soil test), while the packed soil shows a significant rebound. This behavior is due to the better compliance offered by unpacked soil. As a result, all subsequent analyses used unpacked soil pressure versus crush-factor data.

Considerations for soft soil mesh density

The effect of soil mesh density on the accuracy of the solution was investigated as a modeling parameter. Contact forces in MSC.Dytran are generated by a contact penalty method. In particular, the nodes of the bottom of the fuselage section were designated slave nodes, and the top surface of the sand was classified as the master surface. When the contact algorithm computes that slave nodes have penetrated the master soil surface, action–reaction forces are generated to push the bodies apart. For a nondeforming



a. Acceleration comparisons, Position 1.



b. Velocity comparisons, Position 1.

Fig 13. Packed and unpacked sand material model predictions compared with test data at Position 1.

master surface, the discretization of the master surface can be very coarse in comparison with the discretization of the structure impacting the surface. However, for a surface such as soft soil, the discretization of the soil mesh has to be fine enough to conform to the deforming shape of the fuselage subfloor. In the composite fuselage section, there are five foam blocks spaced longitudinally that provide the energy dissipation for the fuselage during a hard surface impact. However, as expected, the soil was noted to deform the skin in the gaps between the foam blocks. Hence, the soil mesh must be fine enough to allow this type of behavior. Consequently, the soil volume (12 ft × 12 ft × 3 ft deep [3.66 m × 3.66 m × 0.91 m]) was meshed with a two-way bias, both in the width and length directions, with a finer mesh (about 3 inches by 3 inches [7.6 cm by 7.6 cm]) in the center region. A one-way bias was used in the vertical direction, with the mesh finer near the top and progressively coarser to the bottom of the sand. A uniformly fine mesh in the contact region is desirable. However, the number of solid elements can become extremely large if this approach is used, adversely affecting the efficiency of the simulation time.

Effect of Foam Material Characterization (Energy Dissipation Factor)

The FOAM2 material model used to represent the Rohacell crushable foam and soft soil 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 (ED) factor, α (Fig. 14). The effect of the material unloading curve on the test–analysis correlation for both the soil and Rohacell subfloor foam was investigated, and is discussed below.

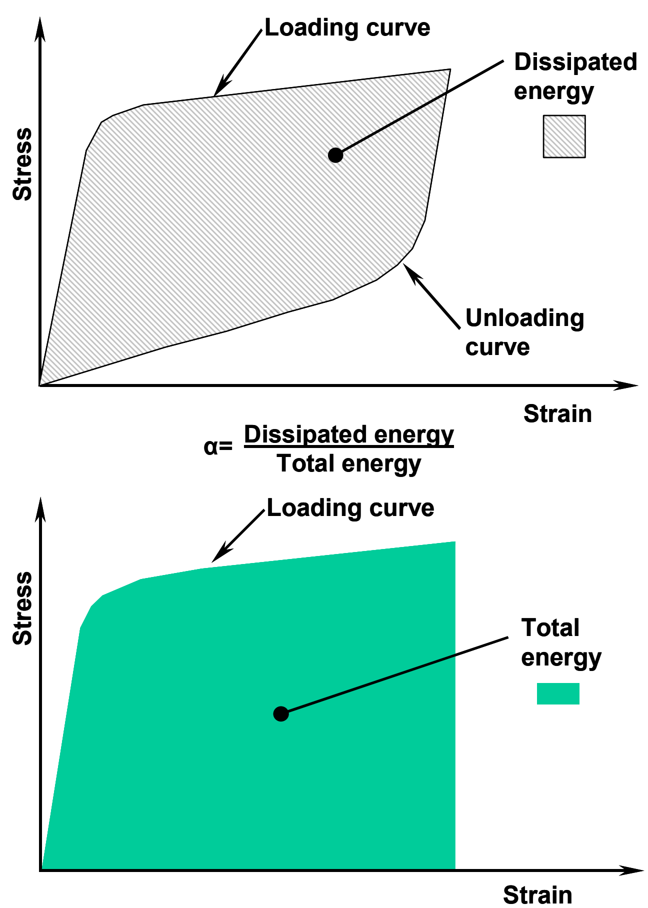
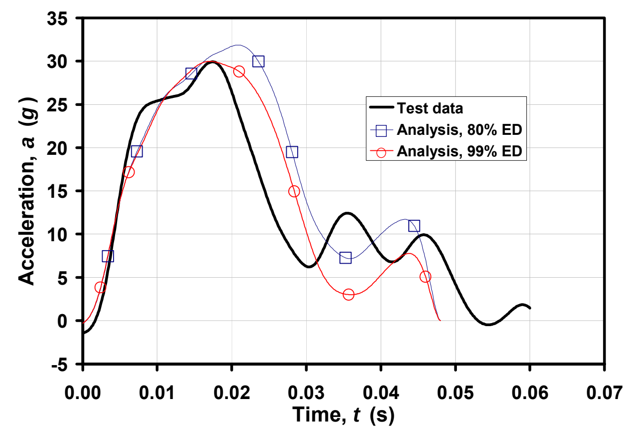
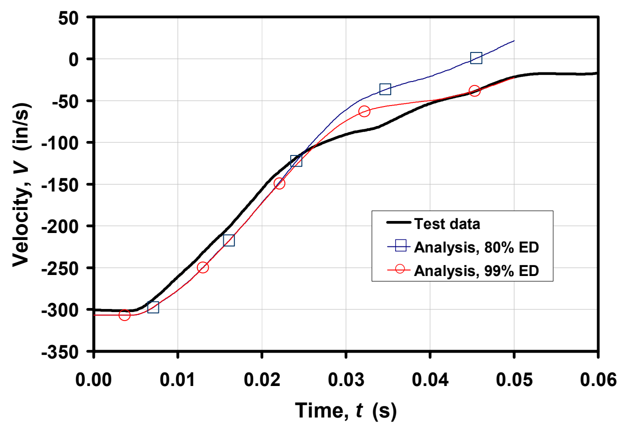


Fig. 14. Characteristic loading and unloading curve of a high-energy-absorbing foam/soil.

The baseline analyses used an energy dissipation factor of 0.8 for both the Rohacell foam and the soft soil material. The results are compared with the analysis using foam and soil energy dissipation factor, or α, of 0.99 in Fig. 15. It is clear from Fig. 15 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. Additional analysis for a foam energy dissipation factor of 0.8 and soil energy dissipation factor of 0.99 indicated results similar to the analysis for an energy dissipation factor of 0.99 for both foam and soil. This indicates that the foam energy dissipation factor has a relatively small effect on rebound behavior observed in the simulation, whereas the soil energy dissipation factor has a much greater influence, which would be expected since the soil deformed more than the Rohacell foam and did dissipate a large amount of energy. In addition, the experimental unloading



a. Acceleration comparisons for Position 1.



b. Velocity comparisons for Position 1.

Fig. 15. Effect of material energy dissipation factor (ED) on the test-analysis correlation (Position 1).

curve of the soil (see Fig. 12) is extremely sharp, indicating a very high level of energy dissipation. The FOAM2 model in MSC.Dytran allowed an unloading curve to be generated that best matched the data for unpacked soil shown in Fig. 12a.

Comparison of analysis and test data

Using the results from the modeling parameter variation study described above, a final analysis using unpacked soil material characterization and soil material energy dissipation factor of 0.99 was conducted to compare soft soil analysis and test results. The deformed state of the fuselage section is shown in Fig. 16, while the impression left in the soil by the fuselage section is shown in Fig. 17, indicating a maximum vertical penetration depth of 5.5 inches (14 cm), which compares very favorably with the measured depth of 5.5 inches (14 cm) in the center of the crater (Fig. 8). Figs. 18a and 18b show the deformed view from the front and bottom of the fuselage section, while Fig. 19 shows this test–analysis comparison at different accelerometer locations on the seat tracks. The comparison between analysis and test data was conducted at several more locations on the subfloor and circumferential locations on the fuselage section with similar results.

The velocity comparison between analysis and test is shown in Fig. 20, indicating a good prediction of fuselage section rebound by the simulation.

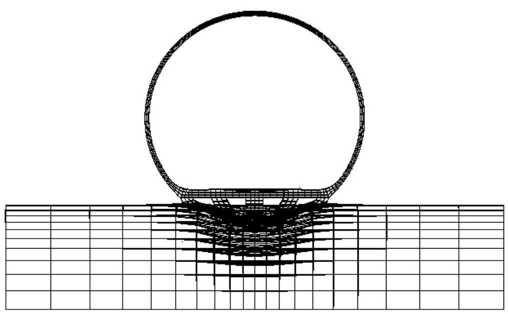


Fig. 16. Fuselage section undergoing deformation during soft soil analysis.

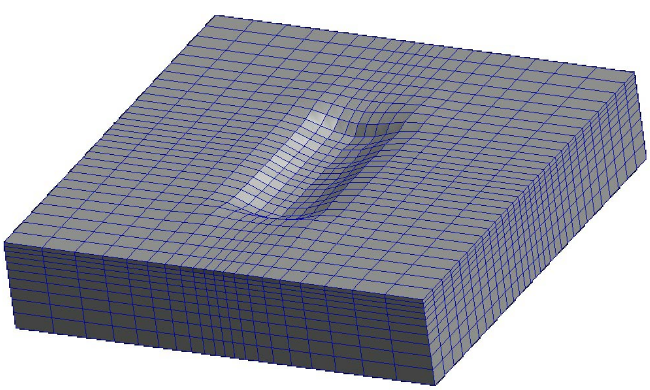
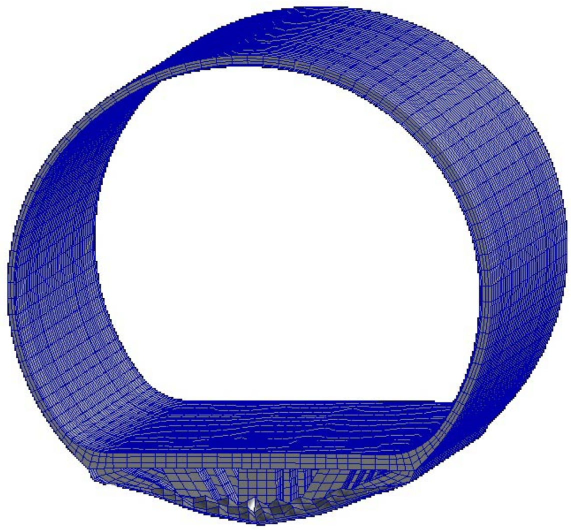
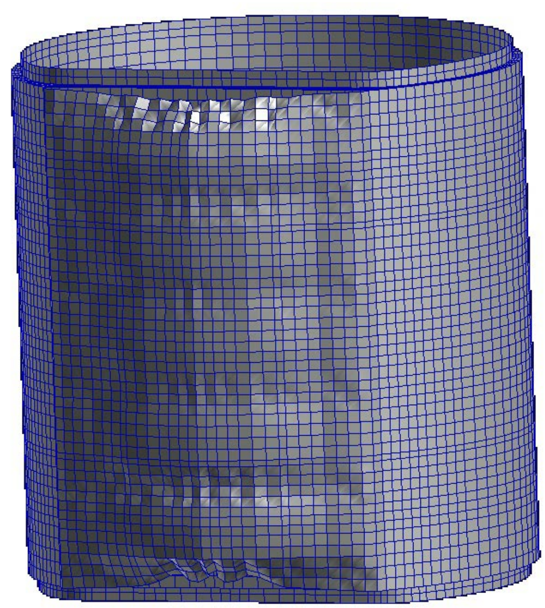


Fig. 17. Soil impression made by the fuselage section during soft soil analysis.

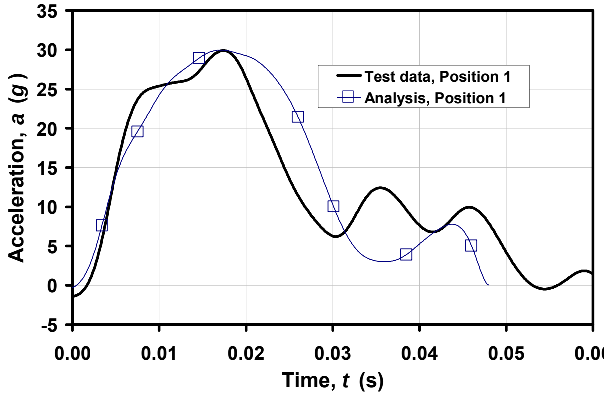


a. Front view of deformed fuselage section.

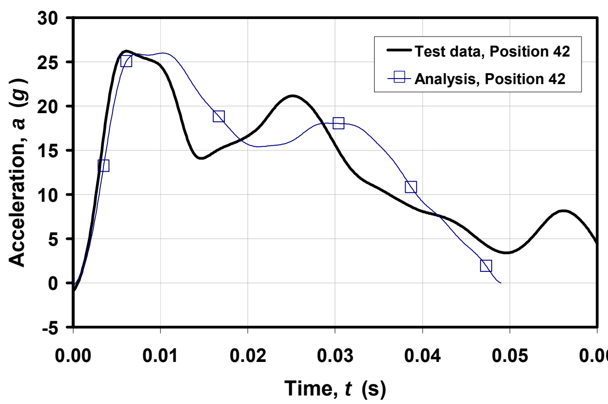


b. Bottom view of the deformed fuselage section.

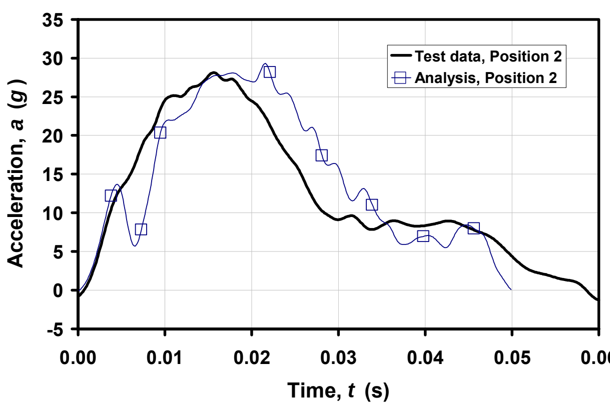
Fig. 18. Deformed view of the front and bottom of the fuselage section during soft soil analysis.



a. Comparison of test–analysis at Position 1.



b. Comparisons of test–analysis at Position 42.



c. Comparison of test–analysis at Position 2.

Fig.19. Comparison of accelerometer data for various positions (unpacked soil, α = 0.99 for both foam and soil).

CONCLUDING REMARKS

The comparison of hard surface and soft soil impact data indicates that the acceleration pulse onset rate is comparable in the two cases, while the peak loading is higher in hard surface impact due to lower compliance compared with soft soil medium.

The variation of modeling parameters for soft soil analysis yielded important information in development of predictive soft-soil analysis capability by improvement of test–analysis correlation. A similar comparison of hard surface and water impact data (and associated analyses) is planned that will provide useful acceleration pulse onset, and peak and duration comparisons, potentially leading to guidance in development of water impact criteria.

The FOAM2 material model for the sand gave the best results as it allowed for specified unloading curves, an energy absorption factor, rate effects, and a tensile cutoff value. An energy absorption factor of 0.99 in the FOAM2 model yielded good results. The resulting correlated soft soil analysis methodology will be used to analyze impact performance of candidate structural design configurations and should lead to lighter, more reliable subfloors designed for soft soil impact requirements.

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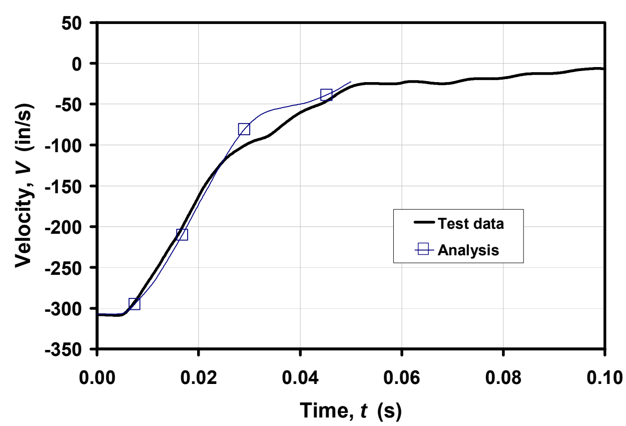

Fig. 20. Comparison of fuselage section rebound between test and analysis for Position 1 (unpacked soil, α = 0.99 for both foam and soil).

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