CRASH SIMULATION OF A 1/5-SCALE MODEL COMPOSITE FUSELAGE CONCEPT

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ABSTRACT

This paper describes the MSC/DYTRAN crash simulation of a 1/5-scale model composite fuselage concept, which was developed to satisfy structural and flight loads requirements and to satisfy design goals for improved crashworthiness. The fuselage consists of a relatively rigid upper section which forms the passenger cabin, a stiff structural floor, and an energy absorbing subfloor which is designed to limit impact forces during a crash event. The impact design requirement for the scale model fuselage is to achieve and maintain a 125-g floor-level acceleration for a 31 ft/s vertical impact onto a rigid surface. This impact requirement corresponds to a 25-g floor-level acceleration for a geometrically-similar full-scale fuselage section. To demonstrate compliance with the impact design requirement, the scale model fuselage section was impacted at 31 ft/s vertical velocity onto a rigid surface. The experimental data demonstrate that the fuselage section with a foam-filled subfloor configuration satisfied the impact design requirement. In addition, a second drop test was performed with a 15°-roll impact attitude, which demonstrated that the fuselage concept maintained good energy absorption behavior for an off-axis impact condition. As an aid in the evaluation process, a detailed three-dimensional finite element model of the 1/5-scale model fuselage section was developed using MSC/DYTRAN. Good correlation was obtained between the experimental data and the MSC/DYTRAN analytical results for both impact conditions.

Introduction

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 [1-4]. The fuselage concept, shown in Figure 1, consists of four different structural regions, each with its own specific design objectives. The upper section of the fuselage cabin is fabricated using a stiff composite sandwich construction and is designed to provide a protective shell that encloses the occupants in the event of a crash. The outer shell is fabricated from a relatively compliant composite material that is wrapped around the entire fuselage section, enclosing the energy absorbing structure beneath the floor, and forming the lower fuselage. The outer shell is designed to provide damage tolerance, and aerodynamic shape. Upon impact, the outer shell is intended to deform and to initiate crushing of the energy absorbing subfloor. The energy absorbing subfloor is designed to dissipate kinetic energy through stable crushing, while maintaining good post-crash structural integrity. Finally, a key feature of the fuselage concept is the stiff structural floor. The structural floor is designed to react the loads generated by crushing of the subfloor, and to provide a stable platform for seat and restraint attachment.

During the first year of the research program, a one-foot-diameter, 1/5-scale model composite fuselage was designed, fabricated, and tested to verify structural and flight loads requirements [3]. During the second year of the research program, energy absorbing subfloor configurations were developed and evaluated using quasi-static testing and finite element simulation to determine the optimal design for incorporation into the 1/5-scale model fuselage concept [5, 6]. Finally, plans for the third year of the program include fabrication and testing of a full-scale version of the fuselage concept to validate the scaling process. Thus, the objectives of the research program are to demonstrate a new fuselage concept for improved crashworthiness, which can be fabricated using low-cost materials and manufacturing techniques, and to demonstrate the application of scale model testing for composite structures. The focus of the present paper is to describe the impact testing and the MSC/DYTRAN finite element simulation of the 1/5-scale model fuselage section.

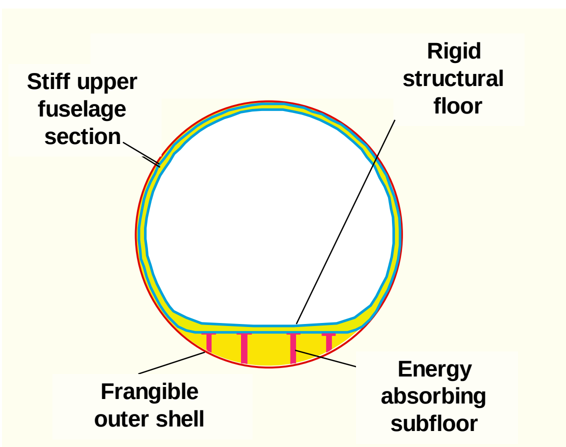


Figure 1. Schematic drawing of the proposed fuselage concept.

Design Requirements

Certain geometric and inertial parameters for the full-scale fuselage had to be selected before the scale model fuselage could be sized. For this study, the design of the 1/5-scale model fuselage is based on a full-scale aircraft with a diameter of 60 inches, and a floor load distribution of 300 pounds per linear foot of fuselage length. The geometrically- and constitutively-similar scale model fuselage has a diameter of 12 inches, and a corresponding floor load distribution of 12 pounds per linear foot of fuselage length. Due to manufacturing and testing constraints, the length of the scale model fuselage test article was approximately 12 inches. The structural design goal was to maintain floor rigidity (less than 0.1 inch of floor mid-point displacement for the 1/5-scale model fuselage) for a 10-psi internal pressure load. This goal was satisfied during the first-year of the research program [3], and the final design of the upper section and floor of the fuselage concept is shown in Figure 2.

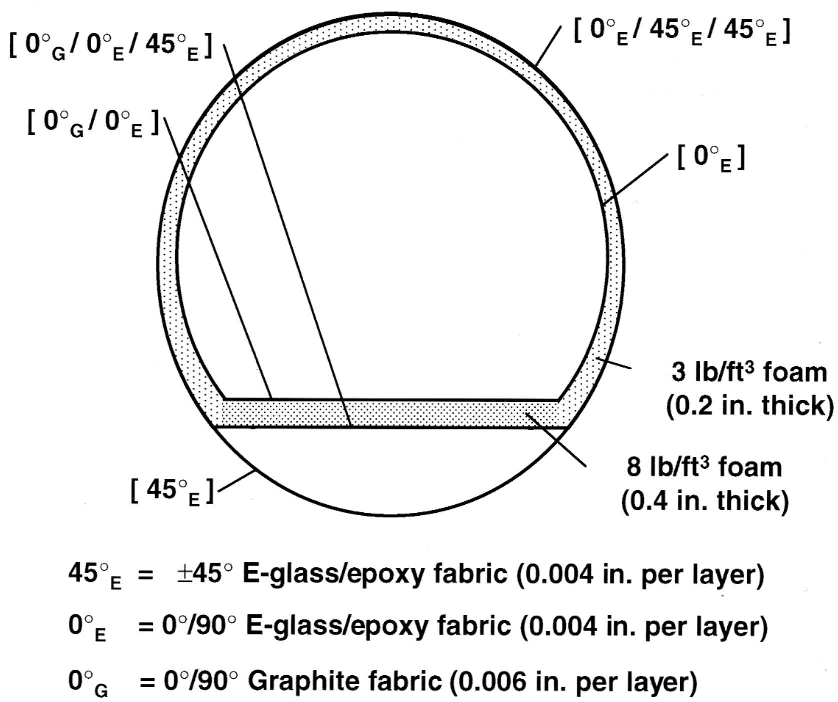


Figure 2. Schematic drawing of the final design configuration for the upper section and floor of the 1/5-scale model fuselage concept.

The upper section of the fuselage is fabricated using a composite sandwich construction with a 0.20-in.-thick, closed-cell 3-lb/ft^3 polyurethane foam core and glass-epoxy fabric face sheets which are oriented at 0°/90° with respect to the cylinder axis, as shown in Figure 2. Glass-epoxy composite material was chosen because of its lower cost and wider use by the light aircraft industry. In addition, a room temperature cure epoxy system was selected, thus eliminating the need for a more expensive autoclave cure. A custom 0.004-in.-thick E-glass plain-weave fabric was selected for the sandwich face sheets because of its efficient mechanical properties and its reduced thickness. The reduced thickness is necessary to satisfy the scaling objectives of this project. The composite sandwich construction in the floor of the fuselage consists of a 0.4-in.-thick, 8-lb/ft^3 polyurethane foam core with hybrid face sheets consisting of E-glass/epoxy and graphite-epoxy composite fabric. The layers of graphite-epoxy fabric were added for increased stiffness and improved structural rigidity.

The design goal for crash protection is to limit occupant loads to survivable levels for a 31 ft/s vertical impact onto a rigid surface. The 31 ft/s vertical impact velocity is more severe than current regulatory criteria for small aircraft, but it is a realistic, potentially survivable, impact velocity observed in actual crashes and in crash tests conducted at NASA Langley Research Center. For the 1/5-scale model fuselage, the specific impact requirement is to achieve and maintain a 125-g floor acceleration for the 31 ft/s vertical impact condition. This impact requirement corresponds to a 25-g floor acceleration for the full-scale fuselage. The subfloor is required to dissipate kinetic energy through stable crushing. For a vertical impact of a 1/5-scale model fuselage, with a length of 12 inches and weighing approximately 12 pounds, a sustained subfloor crushing load of 1,500 lb. would result in a constant 125-g deceleration. This 1500-lb. load corresponds to a subfloor crushing stress of 15 psi, given an approximate floor area of 100 in^2. From kinematics, a crushing distance of 1.43 inches is required to stop an object with an initial velocity of 31 ft/s at a constant 125-g acceleration. Since the actual crushing distance available is greater than 1.43 inches, the goal is theoretically achievable. A summary of the scaling parameters used in the design and testing of the fuselage concept is shown in Table 1 (note that the scaling factor, λ, is equal to 1/5 for this study).

Table 1. Summary of geometric and impact parameters for the full- and 1/5-scale model fuselage concepts.

Parameter	Full-Scale	1/5-Scale Model	Scale Factor
Fuselage diameter	60 in.	12 in.	λ
Length of test article	5 ft.	1 ft.	λ
Internal pressure	10 psi	10 psi	1
Impact velocity	31 ft/s	31 ft/s	1
Kinetic energy	89,500 ft-lb	716 ft-lb	λ^3
Pulse duration	38.5 ms	7.7 ms	λ
Crush force/length	7,500 lb/ft	1500 lb/ft	λ
Average crush stress	15 psi	15 psi	1
Floor-level acceleration	25 g	125 g	$1/\lambda$

<u>Quasi-static Testing of a Foam-filled Energy Absorbing Subfloor</u>

The energy absorption behavior of four different subfloor configurations was evaluated through testing and finite element analyses to determine the optimal design to incorporate into the 1/5-scale model fuselage concept [5,6]. Based on this evaluation, the chosen subfloor configuration was a geometric foam-filled design, consisting of uniformly-spaced, individual blocks of a crushable foam material surrounded by a frangible outer shell. Each block of foam is machined into a geometric shape containing a center vertical section and four diagonal sections. An end-view drawing of the subfloor geometry is shown in Figure 3. The outer shell is fabricated from a single layer of E-glass/epoxy fabric oriented at ±45° with respect to the longitudinal axis. The geometry of the foam blocks was chosen to maintain a fairly uniform cross-sectional area as the crush zone develops and progresses vertically, resulting in a fairly constant crushing force.

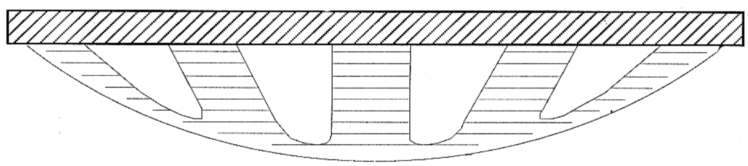


Figure 3. End-view drawing of a crushable foam subfloor configuration.

A foam-filled subfloor configuration was fabricated using a 2.8 lb/ft^3 Rohacell 31-IG foam material, which is a closed-cell, polymethylimide (PMI) foam with good high temperature properties. This material exhibits approximately a linear elastic, perfectly plastic material response for compressive loads up to 75% stroke, which makes it an ideal choice for an energy absorbing material. The subfloor consisted of five 1.5-inch-deep foam blocks, which were equally spaced under the floor. The foam blocks were overlaid with two layers of E-glass/epoxy fabric oriented at 0°/90° with respect to the longitudinal axis. The subfloor section was loaded in compression at 20 in/min in a standard universal test machine. A plot of crushing stress versus percent stroke is shown in Figure 4. The Rohacell foam-filled subfloor exhibited an excellent crushing response with an average sustained crushing stress of 15.9 psi, which is only 6% greater than the design goal. The Rohacell foam subfloor exhibited a crushing stroke of approximately 60%. Based on the promising outcome of the quasi-static test, this subfloor configuration was incorporated into the 1/5-scale model fuselage section for dynamic evaluation.

<u>Impact Testing of the Scale Model Fuselage with a Foam-Filled Subfloor</u>

Two Rohacell foam-filled subfloors were fabricated, incorporated into the 1/5-scale model fuselage, and tested under vertical impact conditions in a simple drop tower that was constructed for performing the impact tests. The first subfloor consisted of five 1.5-in.-thick blocks of foam material. This subfloor exhibited an average crushing stress of 15.9 psi, which is greater than the design goal of 15 psi. Consequently, a second subfloor was fabricated with slightly less thick foam blocks in an attempt to reduce the crushing stress to the design goal. The second subfloor consisted of five 1.3-in.-thick blocks of foam material. In each case, the Rohacell 31-IG foam blocks were overlaid with two layers of E-glass/epoxy

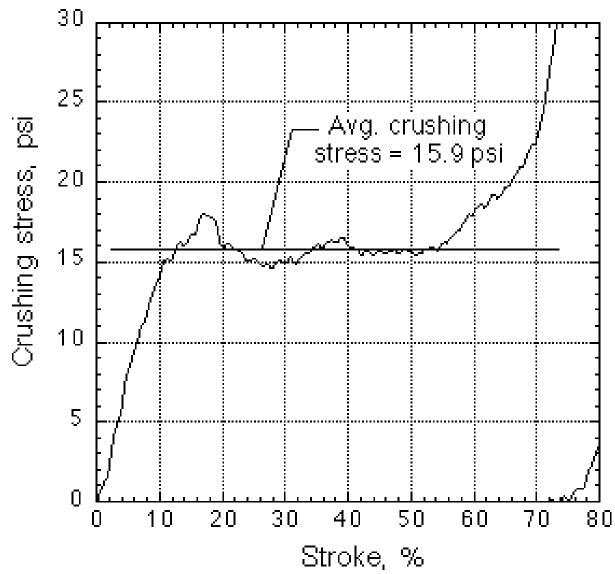


Figure 4. Crushing stress versus stroke for the Rohacell 31-IG foam-filled subfloor.

fabric material oriented at 0°/90° with respect to the longitudinal axis, and were equally spaced under the floor of the fuselage. A photograph of the subfloor region of the 1/5-scale model fuselage section with a foam-filled subfloor is shown in Figure 5.

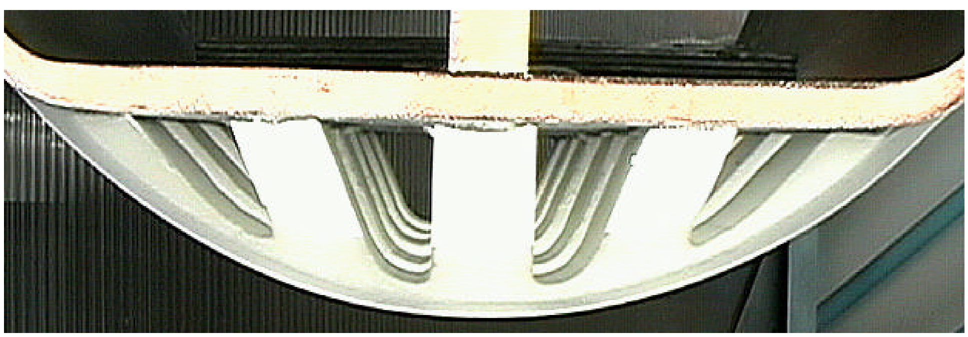
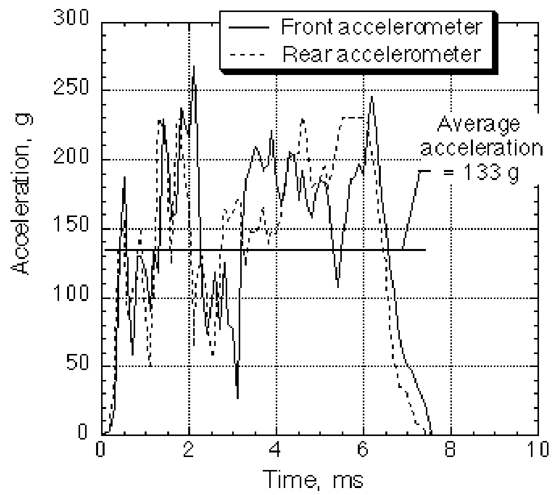
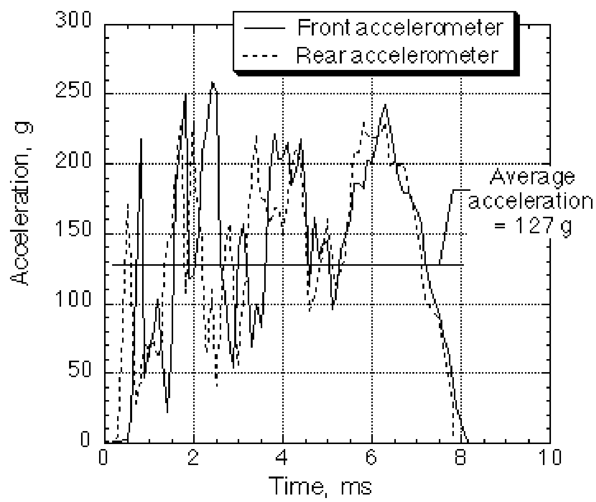


Figure 5. Photograph of the subfloor region of the 1/5-scale model fuselage section with a foam-filled subfloor configuration.

For each test, the fuselage section was dropped from a height of 15 feet to achieve a 31 ft/s vertical impact velocity. A 12-lb. lead plate was attached to the floor to represent the scaled inertia provided by seats and occupants. The sections were instrumented with front and rear accelerometers, which were secured to the lead plate along its centerline. The front and rear acceleration traces for each fuselage drop test are shown in Figure 6. As indicated in the figure, the average acceleration over the pulse duration was determined for each acceleration response. These values are 133 g for the subfloor with five 1.5-in.-thick blocks of foam, and 127 g for the subfloor with five 1.3-in.-thick blocks of foam. These values of average acceleration are close to the 125-g design goal. Also, the pulse duration for each plot is between 7.5 and 8 ms, which is close to the estimated value of 7.7 ms, which was calculated from kinematics.



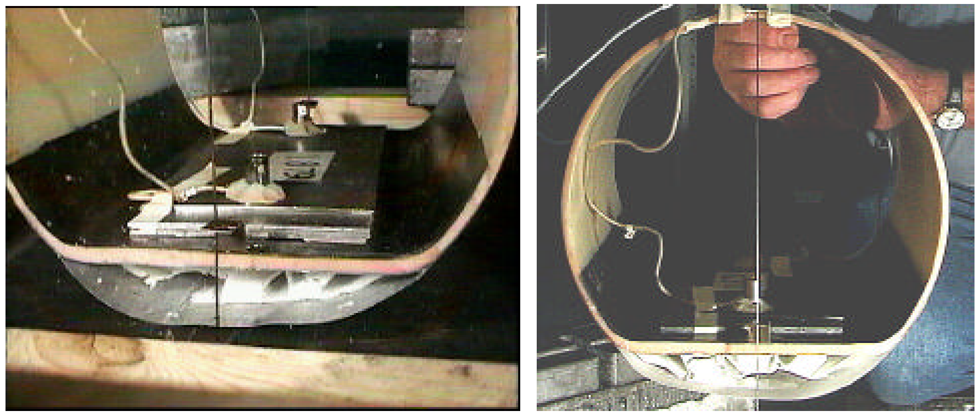
(a) Subfloor with five 1.5-in.-deep blocks of foam.



(b) Subfloor with five 1.3-in.-deep blocks of foam.

Figure 6. Experimental front and rear acceleration responses from impact tests of two 1/5-scale model fuselage sections with different foam-filled subfloor configurations.

Post-test photographs of a fuselage section with a Rohacell foam-filled subfloor are shown in Figure 7. Damage to the subfloor consisted of foam crushing and debonding of the face sheets away from the foam blocks. The upper section and floor of the fuselage were undamaged. Based on the impact test results, the final subfloor design configuration was chosen to be the foam-filled subfloor consisting of five individual 1.3-in.-thick blocks of Rohacell 31-IG foam overlaid with two layers of E-glass/epoxy fabric oriented at 0°/90° with respect to the longitudinal axis.



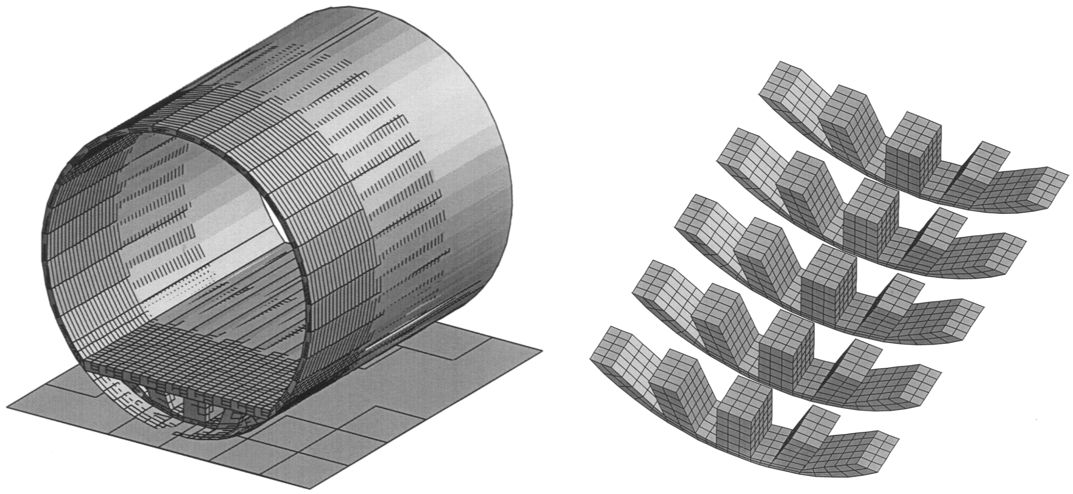
(a) Close-up photograph of subfloor damage. (b) Front-view photograph of fuselage.

Figure 7. Post-test photographs of the scale model fuselage with foam-filled subfloor.

<u>Analytical Evaluation of the Scale Model Fuselage with a Foam-Filled Subfloor</u>

As an aid in the evaluation process, a detailed three-dimensional finite element model of the 1/5-scale model fuselage section with the selected Rohacell foam-filled subfloor configuration was developed using MSC/DYTRAN [7]. MSC/ DYTRAN is a commercially available, nonlinear explicit dynamic finite element code, marketed by the MacNeal-Schwendler Corporation. The complete undeformed model, shown in Figure 8 (a), consists of 14,992 nodes, 18,240 elements, and 60 concentrated masses. The inner and outer face sheets of the upper section and floor are modeled with CQUAD4 shell elements, and the foam core in the upper section, floor, and subfloor is represented by CHEXA solid elements. The material properties of the 0°/90° and ±45° E-glass/epoxy fabric material were determined from coupon tests and are modeled using a linear elastic material model with plasticity and strain hardening. The 3- and 8-lb/ft^3 foam cores in the upper section and floor are modeled as DMATEL linear elastic solid materials. The more complicated multi-layered face sheets in the floor are modeled as laminated composite materials using the PCOMP feature in MSC/DYTRAN. The material property data for the 3- and 8-lb/ft^3 foam core materials were obtained from crushing tests of individual blocks of foam, without face sheets. The specific material properties used in the model are provided in Table 2.

The Rohacell foam blocks, which are located in the subfloor region of the MSC/ DYTRAN model, are shown in Figure 8(b). The five 1.3-in.-deep Rohacell 31-IG foam blocks are represented using DYMAT24 solid elements with properties of a linear elastic, perfectly plastic material with a modulus of 2,000 psi, a yield stress of 90 psi, and a plastic strain to failure (psf) of 80%. The 0°/90° E-glass/epoxy face sheets on the foam blocks in the subfloor are represented as DMATEP shell elements with linear elastic material properties up to a yield stress of 12,000 psi with strain hardening to ultimate failure. Sixty concentrated masses, each weighing 0.2 lb., are distributed in a centralized rectangular region on the floor to represent the inertial properties of the lead plate. The total mass of the model is 14.418 lb., which is close to the actual mass of the fuselage section of 14.42 lb. A master-surface to slave-node contact is defined between the subfloor and the impact surface. The impact surface is modeled as a 12-in.-thick plate of aluminum. All of the edge nodes on



(a) Full model. (b) Foam blocks located in the subfloor.

Figure 8. Undeformed MSC/DYTRAN model of the 1/5-scale model fuselage section.

the impact surface are fixed. An initial vertical velocity of 31 ft/s is assigned to all elements in the model except the impact surface. A transient analysis of the MSC/DYTRAN model was executed for 8 ms, which required approximately 8 hours of CPU time on a Sun Enterprise 450-4x300 workstation computer.

Table 2. Material property data used in the MSC/DYTRAN model of the 1/5-scale model fuselage section.

Material	Formulation	ρ (lb-s^2/in^4)	E (psi)	ν	G (psi)	σ_y (psi)	E_h (psi)	ε_{psf} (in/in)
Aluminum	DYMAT24	2.65e-4	10.e6	.33		55,000		
±45° E-glass	DMATEP	1.73e-4	1.5e6	.49		9,000	117,650	
0°/90° E-glass	DMATEP	1.73e-4	2.75e6	.11		12,000	117,650	
Foam 3 lb/ft^3	DMATEL	4.5e-6	1,300		650			
Foam 8 lb/ft^3	DMATEL	1.2e-5	8,000		3,200			
Graphite/epoxy	DMATEP	1.45e-4	9.1e6	.06				
Rohacell foam	DYMAT24	4.2e-6	2,000	0.3		90.		0.8
0°/90° E-glass w/failure	DMATEP	1.73e-4	2.75e6	.11		12,000	117,650	.001

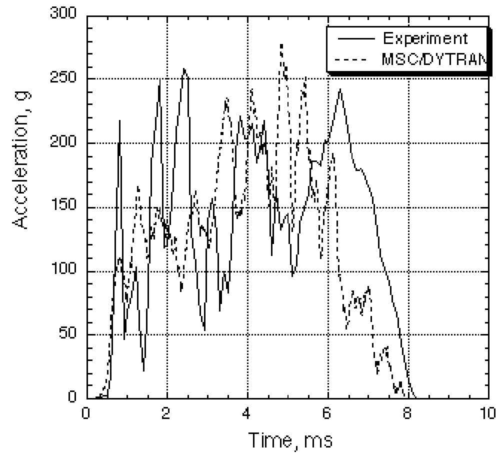
The MSC/DYTRAN-predicted acceleration, velocity and displacement responses are plotted with the experimental data from the vertical drop test of the 1/5-scale model fuselage section with the Rohacell foam-filled subfloor in Figure 9. The experimental acceleration responses obtained from the front and rear accelerometers during the impact test are nearly identical. Consequently, for clarity, only the acceleration response for the front accelerometer is shown in Figure 9 (a). The experimental velocity and displacement responses, shown in Figures 9 (b) and (c) respectively, were obtained by integrating the acceleration data.

The correlation between the MSC/DYTRAN-predicted acceleration response and the experimental data, shown in Figure 9 (a), is good. The shape of the response curve is well predicted, though the MSC/DYTRAN analysis predicted a slightly shorter pulse duration, by approximately 0.25 ms, than the experiment. The average acceleration predicted by the MSC/DYTRAN simulation is 124 g, which is 2.4% lower than the experimental value of 127 g. Good correlation between the predicted and experimental velocity and displacement responses is also obtained, as indicated in Figures 9 (b) and (c), respectively. The maximum displacement predicted by the MSC/DYTRAN analysis is 1.43 inches, compared to 1.54 and 1.51 inches for the front and rear floor locations, respectively. Given that a maximum crushing distance of 1.7 inches was available, a crushing stroke of approximately 90% was achieved in the experiment.

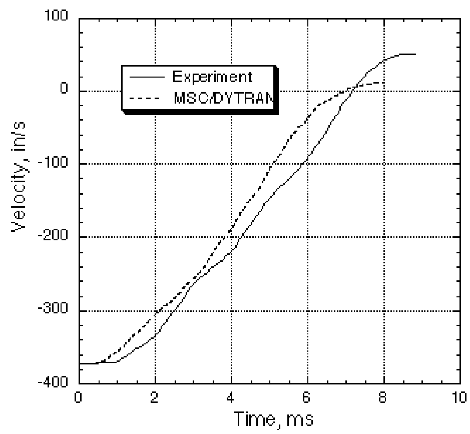
Evaluation of the Scale Model Fuselage for a 15° Off-axis Impact Condition

A final objective of the research program was to demonstrate that the fuselage concept provided a high level of crash protection during off-axis impacts. Consequently, an impact test was performed on the 1/5-scale model fuselage with the foam-filled subfloor for a +15° roll condition. The angle was achieved by rotating the support brackets located at the top and bottom on both ends of the fuselage section by 15°. The fuselage was dropped from a height of 15 feet to achieve an initial 31 ft/s vertical impact velocity. A 12-lb. lead plate was attached to the floor of the fuselage to represent the inertia provided by seats and occupants. Two accelerometers were mounted to the lead plate to measure the simulated occupant response. The accelerometers were placed at the center of the lead plate, one on the right side and one on the left side of the plate, as shown in Figure 10. The impact surface consisted of a thin lead plate covering the concrete floor. Photographs of the fuselage prior to and during impact are shown in Figure 10.

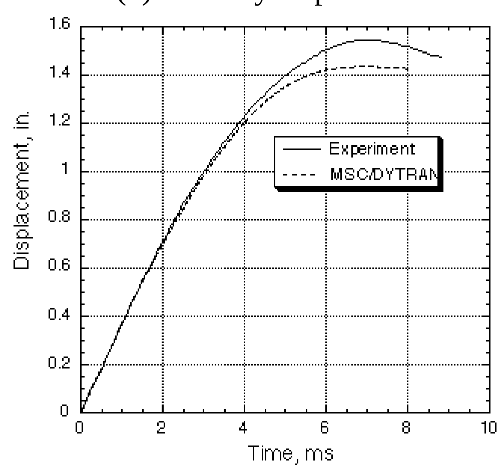
A crash simulation was performed to predict the acceleration response of the scale model fuselage during the 15° off-axis impact using MSC/DYTRAN. The undeformed MSC/DYTRAN model, shown in Figure 11, is the same model that was used to perform the 0° impact simulation. However, some modifications were made to account for the 15° roll impact attitude. In the experiment, the fuselage section was rotated by 15° and impacted at 31-ft/s vertical impact velocity. However, for the analysis, it was more expedient to rotate the impact surface by 15°, than to rotate the fuselage section model. As a result of using this approach, it was necessary to change the initial condition from a pure vertical velocity of 31 ft/s to a velocity vector with a horizontal component of 8.025 ft/s and a vertical component of 29.94 ft/s. A transient analysis of the model was executed for 10 ms, which required approximately 10 hours of CPU time on a Sun Enterprise 450-4x300 workstation computer.



(a) Acceleration response.

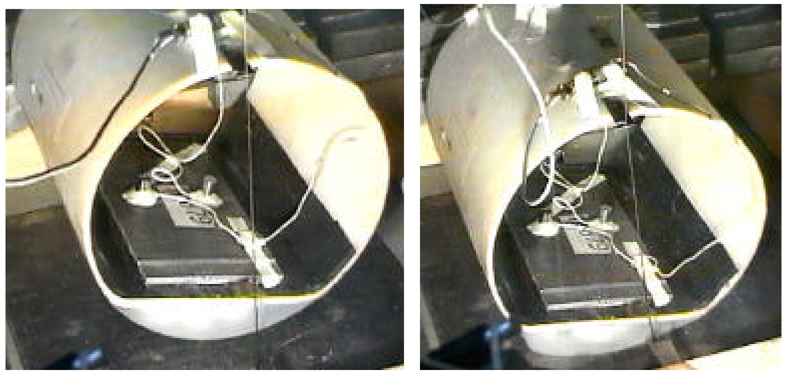


(b) Velocity response.



(c) Displacement response.

Figure 9. MSC/DYTRAN analytical predictions and experimental correlation.



(a) Prior to impact. (b) During impact.

Figure 10. Photographs of the scale model fuselage prior to and during 15° off-axis impact.

A plot of the MSC/DYTRAN-predicted and experimental acceleration responses are shown in Figure 12. The experimental responses were obtained from the accelerometers located on the right and left sides of the lead plate. The MSC/DYTRAN predictions were obtained from nodes located on the floor at the approximate locations of the two accelerometers. The acceleration responses represent the component of the acceleration that is normal to the floor, which is rotated 15° from the vertical direction. Another component parallel to the floor is also present, but was not measured in the experiment.

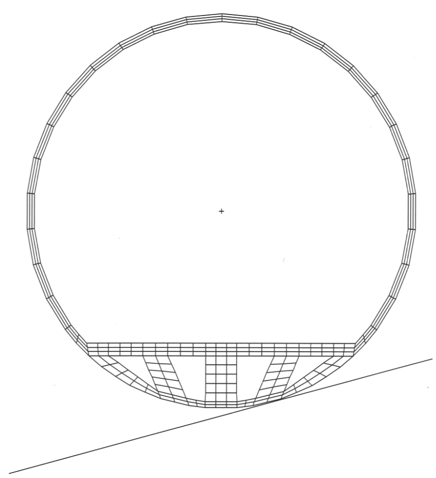
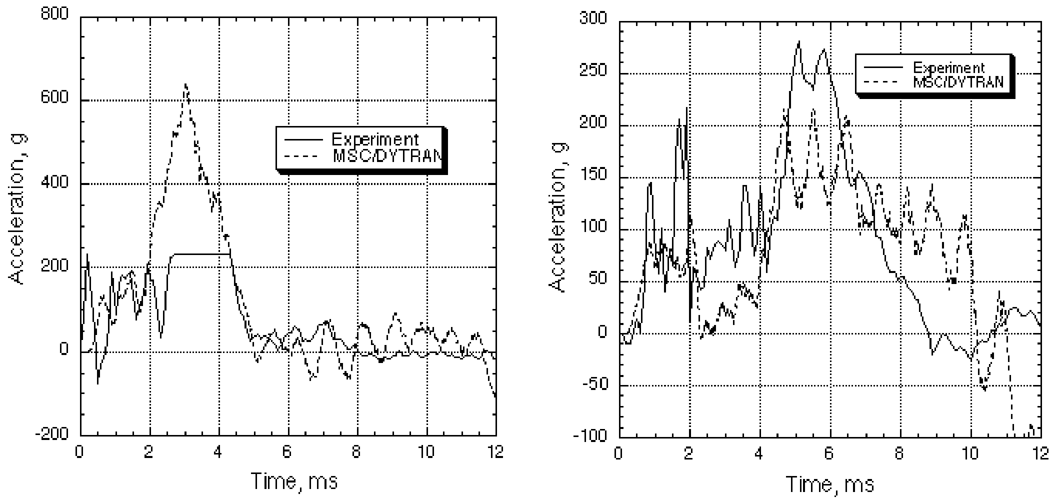


Figure 11. Front view of the MSC/DYTRAN model of the 1/5-scale model fuselage

For the right accelerometer location, the MSC/DYTRAN simulation predicted a large spike in the acceleration response, with a magnitude of about 650 g, as shown in Figure 12 (a). Unfortunately, the calibration of the accelerometer was set for a maximum of 250 g and the peak acceleration was not measured. However, the MSC/DYTRAN-predicted response correlates well with the experimental curve prior to and following the large spike. The pulse duration of the experimental acceleration response was 5.7 ms, and the MSC/DYTRAN-predicted pulse duration was 5 ms. The acceleration response measured by the right accelerometer, which is closer to the point of impact, exhibits a higher magnitude and lower pulse duration than the acceleration response measured by the left accelerometer for a 15° roll impact attitude. The acceleration response measured by the left accelerometer, shown in Figure 12 (b), has an average acceleration of 92.9 g for a pulse duration of 8.75 ms. The MSC/DYTRAN-predicted acceleration response for this location has an average acceleration of 92.5 g for a pulse duration of 10 ms. In general, the MSC/DYTRAN crash simulation correlated well with the experimental responses obtained from the 15° off-axis drop test.



(a) Right accelerometer. (b) Left accelerometer.

Figure 12. MSC/DYTRAN-predicted and experi-mental acceleration responses for the right and left accelerometers in the 15° off-axis impact test.

The good correlation obtained with the MSC/DYTRAN simulation provides a high level of confidence for future use of the code in predicting the fuselage response for other impact attitudes or velocity conditions. Such application of crash modeling and simulation could reduce the dependence on sub- and full-scale testing for validation of the crashworthy performance of airframe structures.

Concluding Remarks

A 1/5-scale model composite fuselage concept for light aircraft and rotorcraft has been developed to satisfy structural and flight loads requirements and to satisfy design goals for improved crashworthiness. The 1/5-scale model fuselage consists of a relatively rigid upper section, or passenger cabin, with a stiff structural floor and an energy absorbing subfloor. The focus of the present paper is to describe the crashworthy evaluation of the 1/5-scale model composite fuselage through impact testing and finite element simulation using the nonlinear, explicit transient dynamic code, MSC/DYTRAN. The impact design requirement for the scale model fuselage section is to achieve and maintain a 125-g floor-level acceleration for a 31 ft/s vertical impact onto a rigid surface. This impact requirement corresponds to a 25-g floor-level acceleration for a geometrically- and constitutively-similar full-scale fuselage section. The energy absorption behavior of a Rohacell 31-IG foam-filled subfloor configuration was evaluated through quasi-static crushing tests. The test results indicate that this subfloor configuration exhibited an average crushing stress of approximately 15 psi for a stroke of 60%, which is the design goal for optimal energy absorption. The foam-filled subfloor configuration was incorporated into a 1/5-scale model fuselage section, which was dropped from a height of 15 feet for an initial 31 ft/s vertical impact velocity onto a rigid surface. The experimental data demonstrate that the fuselage section exhibited an average floor-level acceleration of 127 g and, thus, satisfied the impact design requirement. A vertical drop test of the 1/5-scale model fuselage was performed for a 15° roll impact attitude, which demonstrated that the fuselage section maintained excellent energy absorption behavior for an off-axis impact condition. Good correlation was obtained between the experimental data and analytical results from a MSC/DYTRAN finite element simulation for both the 0°- and 15°-roll conditions.

References

1. Jackson, K. E., "A Comparative Analysis of Three Composite Fuselage Concepts for Crash Performance," Proceedings of the 52nd AHS Forum and Technology Display, Washington DC, June 4-6, 1996.

2. Jackson, K. E., "Analytical Crash Simulation of Three Composite Fuselage Concepts and Experimental Correlation," *Journal of the American Helicopter Society*, Vol. 42, No. 2, April 1997, pp. 116-125.

3. Jackson, K. E.; and Fasanella, E. L., "Innovative Composite Fuselage Design for Improved Crashworthiness," 54th American Helicopter Society Forum and Technology Display, Washington DC, May 20-22, 1998.

4. Jackson, K. E.; and Fasanella, E. L., "Development of a 1/5 Scale Model Fuselage Concept for Improved Crashworthiness," Symposium on Size Effects and Scaling Laws, 13th U.S. National Congress on Applied Mechanics, Gainesville, FL, June 21-26, 1998.

5. Fasanella, E. L.; and Jackson, K. E., "Analytical and Experimental Evaluation of Composite Energy Absorbing Subfloor Concepts," Proceedings of the AHS National Technical Specialists' Meeting on Rotorcraft Crashworthiness, Phoenix, AZ, September 14-17, 1998.

6. Jackson, K. E.; and Fasanella, E. L.: "Crashworthy Evaluation of a 1/5-Scale Model Composite Fuselage Concept," 55th American Helicopter Society Annual Forum and Technology Display, Montreal, Canada, May 25-27, 1999.

7. *MSC/DYTRAN User's Manual Version 4.0*, The MacNeal-Schwendler Corporation, Los Angeles, CA, November 1997.