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Crashworthy Evaluation of a 1/5-Scale Model Composite Fuselage Concept

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Abstract

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 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 focus of the present paper is to describe the crashworthy evaluation of the fuselage concept 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 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. The energy absorption behavior of two different subfloor configurations was determined through quasi-static crushing tests. For the dynamic evaluation, each subfloor configuration was incorporated into a 1/5-scale model fuselage section, which was dropped from a height of 15 ft. to generate a 31 ft/s vertical impact 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, the fuselage section maintained excellent energy absorption behavior for a 31 ft/s vertical drop test with a 15°-roll impact attitude. Good correlation was obtained between the experimental data and 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 through quasi-static testing, and through finite element simulation for incorporation into the 1/5-scale model fuselage concept [5]. 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: (1) the energy absorption behavior of two different composite subfloor configurations and, (2) the dynamic response of a 1/5-scale model fuselage section incorporating each subfloor configuration, through impact testing and finite element simulation.

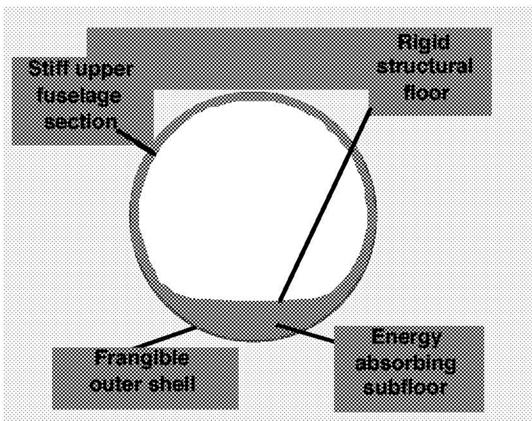


Figure 1. Schematic drawing of the proposed fuselage concept.

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.

The upper section of the fuselage is fabricated using a composite sandwich construction with an 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.

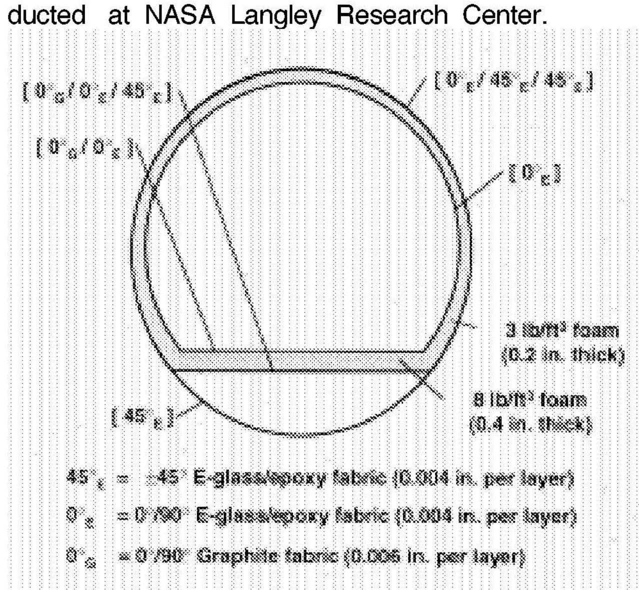


Figure 2. Schematic drawing of the final design configuration for the upper section and floor of the 1/5-scale model fuselage concept.

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 fuselage test article	5 ft.	1 ft.	λ
Floor load distribution	300 lb/ft	12 lb/ft	λ^2
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	$1/\lambda$

Quasi-static Testing of Energy Absorbing Subfloor Configurations

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. End views of these configurations are depicted schematically in Figure 3 and include: (1) a composite sandwich for the lower subfloor surface, (2) a truss-type subfloor with inter-connecting beam or sandwich segments, (3) a composite tube subfloor, and (4) a crushable foam-filled subfloor. Under compressive load, the composite sandwich subfloor exhibited a debond between the face sheets and the foam core, which is an inefficient energy absorbing damage mechanism. The truss-type subfloor performed well; however, it was difficult and expensive to manufacture. For these reasons, the composite sandwich and truss-type subfloor configurations were determined to be unacceptable concepts. Further details concerning the evaluation of these two subfloor configurations are provided in Reference 5. In the present paper, the evaluation of the composite tube and foam-filled subfloor configurations are described in the following sections.

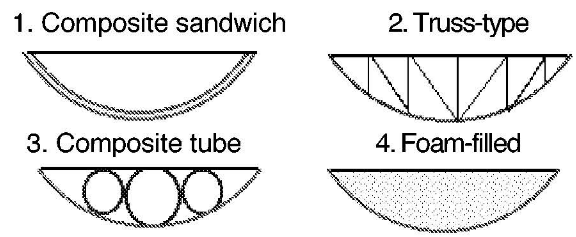


Figure 3. Schematic drawings of four subfloor design configurations.

Composite Tube Subfloor Configuration

For the composite tube subfloor configuration, cylindrical tubes are inserted longitudinally into the subfloor region. The tubes are crushed transversely under vertical impact loading to dissipate the kinetic energy. Several variations of the composite tube subfloor configuration were examined including the number of tubes, the number of layers of E-glass/epoxy fabric per tube, and the fiber orientation for the tubes. Quasi-static tests were performed to evaluate the energy absorption behavior of each configuration and to optimize the tube subfloor design for the chosen application. A schematic drawing of the final-selected composite tube subfloor design is shown in Figure 4. The subfloor consists of a 1.62-in.-diameter center tube and two 1.4-in.-diameter side tubes. The side and center tubes

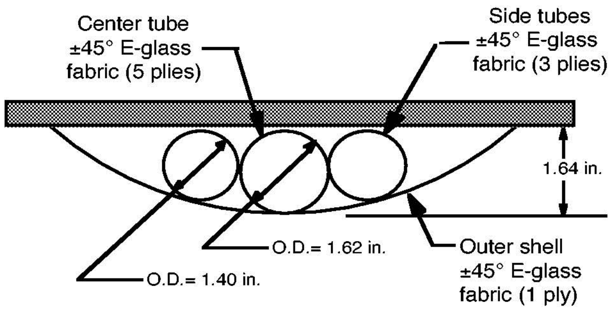


Figure 4. Schematic drawing of the composite tube subfloor configuration.

are fabricated from three and five layers of ±45° E-glass/epoxy fabric, respectively. The outer shell is formed of a single ply of E-glass/epoxy fabric oriented at ±45° with respect to the longitudinal axis. The side tubes are bonded to the center tube, floor, and outer shell using a small amount of epoxy; and the center tube is bonded to the floor and outer shell in a similar manner. The subfloor was tested quasi-statically in a universal test machine at a loading rate of 20 in/min. A plot of crushing stress versus stroke is shown in Figure 5 which indicates that the subfloor exhibited an average sustained crushing stress of 14 psi for 70 % stroke.

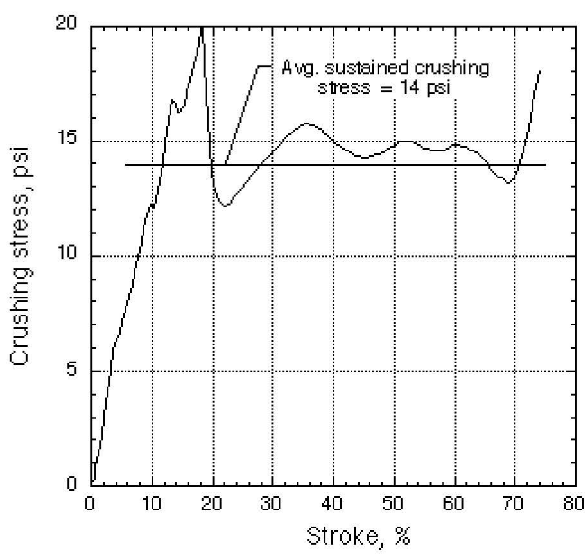


Figure 5. Plot of crushing stress versus stroke for the composite tube subfloor concept.

The quasi-static crush test results of the composite tube subfloor indicated excellent energy absorbing behavior with an average crushing stress close to the design goal of 15 psi. In addition, this subfloor configuration exhibited a fairly constant crushing stress level for up to 70% stroke. Based on the promising outcome of the quasi-static test, this subfloor concept was selected for incorporation into the 1/5-scale model fuselage section for further evaluation.

Foam-Filled Subfloor Configuration

The foam-filled subfloor configuration consists 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. A schematic drawing of this concept is shown in Figure 6. 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 for this subfloor concept 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.

Initially, the foam-filled subfloor configuration was evaluated using a 1.9-lb/ft^3 closed-cell polyvinylchloride (PVC) foam material. Three subfloor sections were fabricated by machining blocks of PVC foam to the geometry shown in Figure 6. The subfloor sections were 8.375 inches wide and 6 inches long, and had a maximum depth of 1.64 inches. For one subfloor section, the foam blocks were overlaid with face sheets consisting of two layers of E-glass/epoxy fabric oriented at ±45° with respect to the longitudinal direction. For the second subfloor, the face sheets were oriented at 0°/90° with respect to the longitudinal direction. The third subfloor section was fabricated without face sheets.

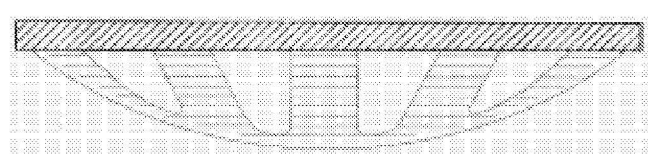


Figure 6. Schematic drawing of a crushable foam subfloor concept.

Each of these subfloor sections was loaded in compression at 20 in/min in a standard universal test machine. A plot of crushing stress versus stroke for each of the three subfloor sections is shown in Figure 7. These results indicate that adding face sheets to the foam blocks increases the crushing stress of the subfloor compared to the crushing stress of the subfloor without face sheets. In addition, the fuselage section with face sheets oriented at 0°/90° exhibited a slightly higher crushing stress than did the fuselage section with face sheets oriented at ±45° with respect to the longitudinal axis. Thus, the addition of face sheets oriented in different directions allows the subfloor design to be optimized to the desired level of average crushing stress. In general, the crushing stress of these foam-filled subfloor sections was noted to increase rapidly after approximately 50% stroke. During compressive loading, the cells within the foam material deform and collapse. Eventually, the cells begin to compact, as the air pockets within the cells are removed. Once the limit of compaction is reached, the crushing stress increases, as shown in Figure 7. In general, this behavior can be undesirable for an effective energy absorbing material.

Overall, the foam-filled subfloor concepts with overlaid face sheets performed well. The average sustained crushing stress for the subfloor concepts with face sheets oriented at 0°/90° and ±45° is 12.4 and 11.0 psi, respectively. The average crushing stress for the subfloor without face sheets is only 8.3 psi. These values of crushing stress are between 17 and 45% less than the design goal of 15 psi. Consequently, other foam materials were investigated.

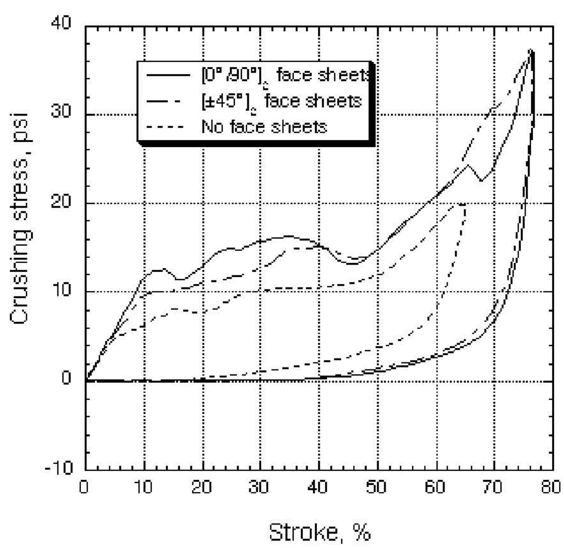


Figure 7. Crushing responses for three crushable foam-filled subfloor designs.

The 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 individual 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 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 8. The Rohacell foam-filled subfloor section exhibited an excellent crushing response with an average sustained crushing stress of 15.9 psi, which is slightly greater than the design goal. The Rohacell foam subfloor exhibited a crushing stroke of approximately 70%. Based on the promising outcome of the quasi-static test, this subfloor concept was selected for incorporation into the 1/5-scale model fuselage section for further evaluation.

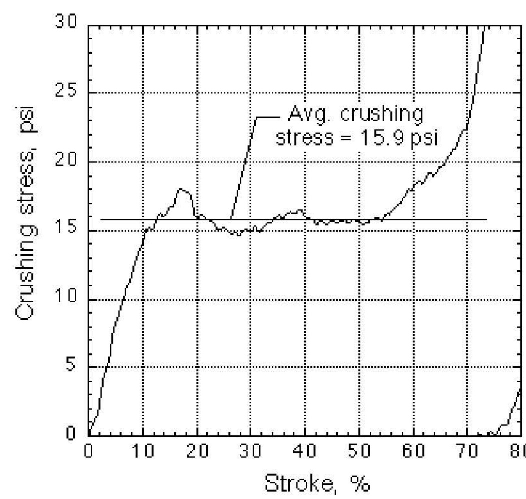


Figure 8. Crushing stress versus stroke for the Rohacell 31-IG foam-filled subfloor.

Impact Testing of the Scale Model Fuselage with a Composite Tube Subfloor

A 1/5-scale model fuselage section was fabricated with the composite tube subfloor concept. This fuselage section is depicted in Figure 9. The section had an outer diameter of 12.2 inches and a length of 12 inches. A 12-lb. lead plate was attached to the floor to represent the scaled inertia provided by the seats and occupants. The lead plate was 6-in. wide, 12-in. long, and 0.25-in. thick. Two accelerometers were attached to the lead plate to measure the floor-level impact response. Both accelerometers were located along the centerline of the plate; however, one was placed near the front edge of the lead plate, and the second was placed near the back edge.

A simple drop tower was constructed for performing the impact tests of the 1/5-scale model fuselage section. The drop tower consisted of a lateral beam, which was mounted to the interior framework in the ceiling of the testing facility at a height of approximately 20 feet, some piano wire, and a support frame which was rigidly attached to the floor. The piano wire was attached to each end of the lateral beam and suspended from the ceiling to the floor. At the floor level, the two piano wires were secured to the support frame to form guide-wires. The tension in the piano wires was adjusted by placing lead weights on the support frame. The impact surface consisted of a 0.063-in.-thick sheet of lead placed over the concrete floor. Four metal brackets were attached to the fuselage section (one at the top and bottom of the section on both ends) to guide the section during descent and to maintain the correct impact attitude. Finally, a lifting bracket was attached to the top of the fuselage to allow the section to be raised to the correct drop height.

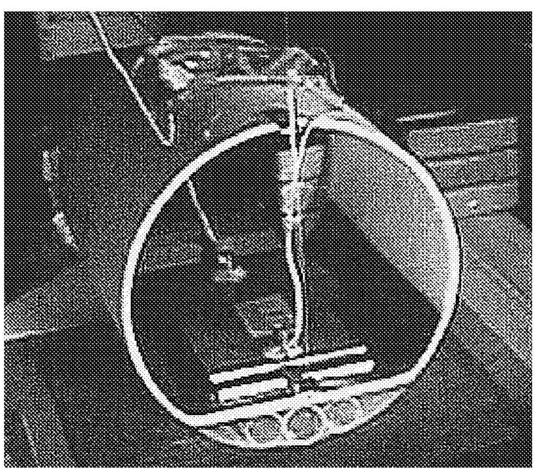


Figure 9. Photograph of the 1/5-scale model fuselage section with composite tube subfloor.

The fuselage section with the composite tube subfloor configuration was dropped from a height of 15 feet with a 0° impact attitude, to achieve an initial impact velocity of 31 ft/s. A plot of acceleration response from the front and rear accelerometers is shown in Figure 10. From analysis of the data, the average acceleration was determined to be 147 g over the pulse duration of 15 ms. This value of average acceleration is approximately 20% higher than the 125-g design goal. It should be noted that the average acceleration of 147 g for the scale model fuselage corresponds to an average acceleration of 29.4 g for the full-scale fuselage.

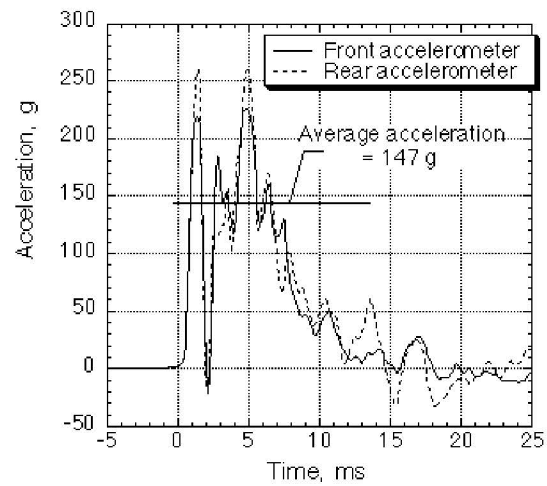


Figure 10. Plot of acceleration versus time for the front and rear accelerometers in the scale model fuselage with the composite tube subfloor.

Following the initial impact event, the 1/5-scale model fuselage section with the composite tube subfloor concept rebounded to a height of approximately 2 feet. This rebound distance appeared to be significant for the scale model fuselage; i.e., the section rebounded a distance that was approximately twice its diameter. Assuming similar coefficients of restitution for the scale model and full-scale impact surfaces, the full-scale fuselage section should rebound the same 2-ft. distance. Given that the full-scale fuselage will be 5 feet in diameter, this amount of rebound is less significant. The reason for the large amount of rebound is due to the fact that the composite tubes store energy during nonlinear elastic deformation under compressive loading. This energy is dissipated as permanent damage occurs and plastic hinges are formed. However, if the loading cycle is interrupted before damage is complete, some stored energy is returned, causing rebound. Conversely, an ideal energy absorbing material dissipates energy during compressive loading through progressive damage or plastic deformation with very little elastic energy returned on unloading. The tube concept can be designed to dissipate energy for a particular impact event, given a specified mass and velocity condition. However, for variations from the specified impact condition, the tube design would prove ineffective. For this reason, the composite tube subfloor configuration was determined to be an unacceptable concept.

Impact Testing of the Scale Model Fuselage with a Foam-Filled Subfloor

Two Rohacell foam-filled subfloors were fabricated, incorporated into the 1/5-scale model fuselage, and tested under vertical impact conditions in the simple drop tower described in the previous section. 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 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 configuration is shown in Figure 11.

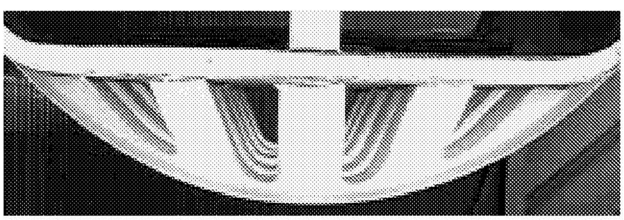
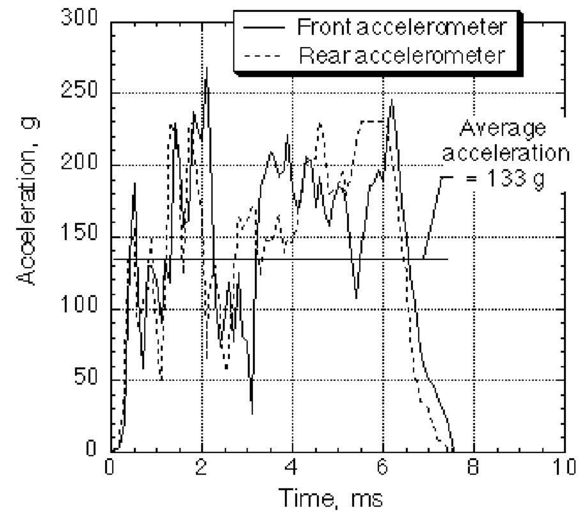
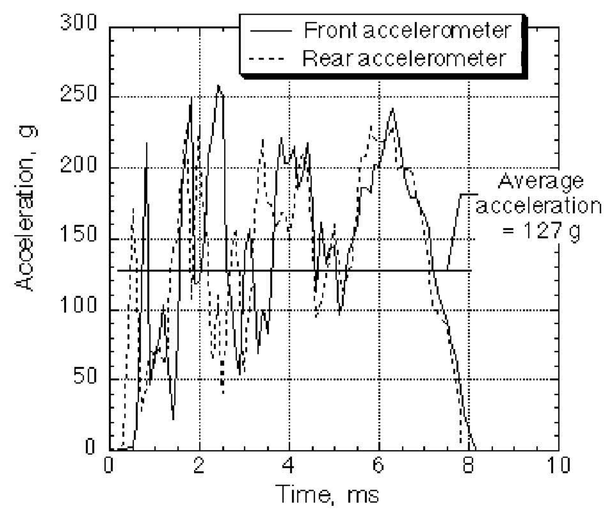


Figure 11. Photograph of the subfloor region of the 1/5-scale model fuselage section with a foam-filled subfloor configuration.

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 12. As indicated in the figure, the average acceleration over the pulse duration was determined for each acceleration response. These values are127 g for the subfloor with five 1.3-in.-thick blocks of foam, and 133 g for the subfloor with five 1.5-in.-thick blocks of foam.



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

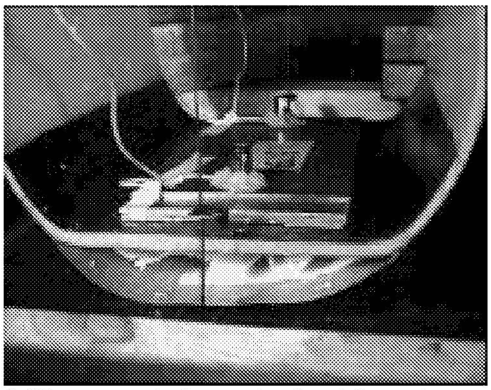


(b) Subfloor with five 1.3-in.-deep blocks of foam.

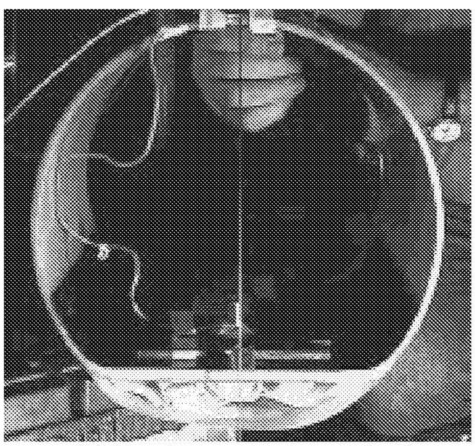
Figure 12. Experimental front and rear acceleration responses from impact tests of two 1/5-scale model fuselage sections with different foam-filled subfloor configurations.

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.

Post-test photographs of a fuselage section with a Rohacell foam-filled subfloor are shown in Figure 13. 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

Figure 13. Post-test photographs of the 1/5-scale model fuselage section with Rohacell foam-filled subfloor.

Analytical Evaluation of the Scale Model Fuselage with a Foam-Filled Subfloor

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 [6,7]. MSC/DYTRAN is a commercially available, nonlinear explicit dynamic finite element code, marketed by the MacNeal-Schwendler Corporation. The undeformed model, shown in Figure 14, 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 and floor 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 specific material properties used in the model are shown in Table 2. 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.

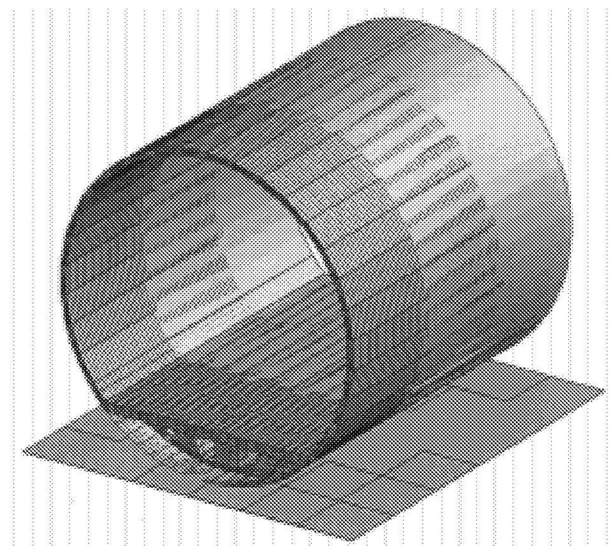


Figure 14. Undeformed MSC/DYTRAN model of the 1/5-scale model fuselage section.

The Rohacell foam blocks, which are located in the subfloor region of the MSC/DYTRAN model, are shown in Figure 15. 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 an ultimate plastic failure strain 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., compared with the total mass of the fuselage section which was 14.42 lb. A master surface-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 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.

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 16. 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 16 (a). The experimental velocity and displacement responses, shown in Figures 16 (b) and (c) respectively, were obtained by integrating the acceleration data.

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_{ult} (in/in)
Aluminum	DYMAT24	2.65e-4	10.e6	.33		55,000		
±45° E-glass	DMATEP	2.2e-5	1.5e6	.49		9,000	117,650	
0°/90° E-glass	DMATEP	2.2e-5	2.75e6	.113		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	DMATEP	2.2e-6	9.1e6	.061				
Rohacell 31-IG foam	DYMAT24	4.2e-6	2,000	0.3		90.		0.8
0°/90° E-glass w/failure	DMATEP	2.2e-5	2.75e6	.113		12,000	117,650	.001

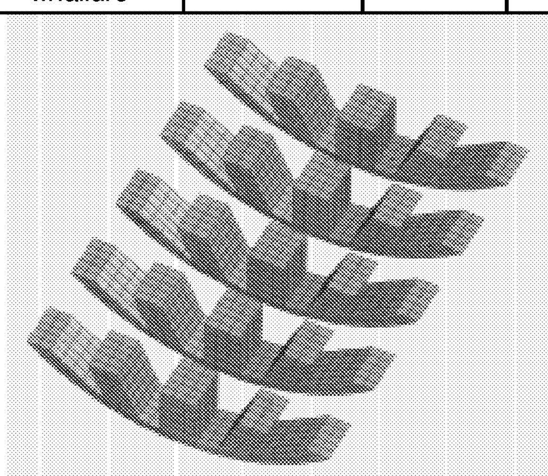


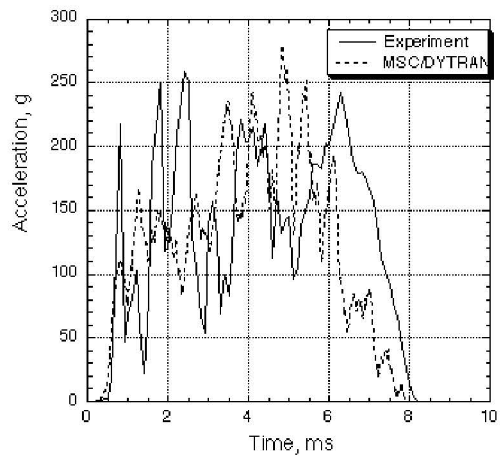
Figure 15. MSC/DYTRAN model of the Rohacell foam blocks in the subfloor.

The correlation between the MSC/DYTRAN-predicted acceleration response and the experimental data, shown in Figure 16(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 16 (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.

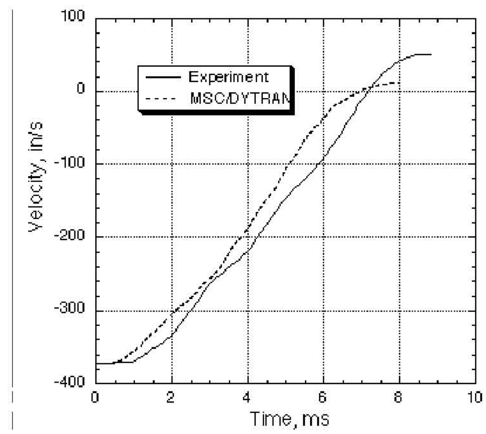
Experimental and Analytical Evaluation of the Scale Model Fuselage for a 15° Off-axis Impact Condition

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 concept 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 of15 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, as shown in Figure 17, one on the right side and one on the left side of the plate. 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 17.

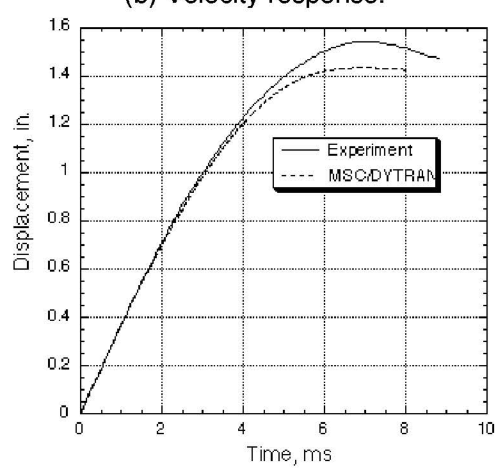
A crash simulation was performed to predict the acceleration response of the scale model fuselage during the 15° off-axis impact using MSC/DYTRAN. The undeformed MSC/DYTRAN model, shown in Figure 18, is the same model that was used to perform the 0° impact simulation. However, some modifications were 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.

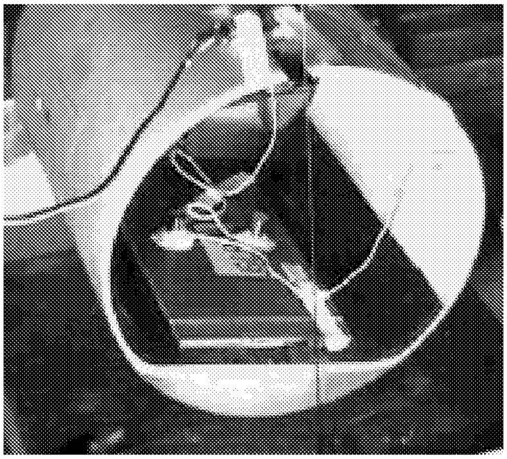


(b) Velocity response.

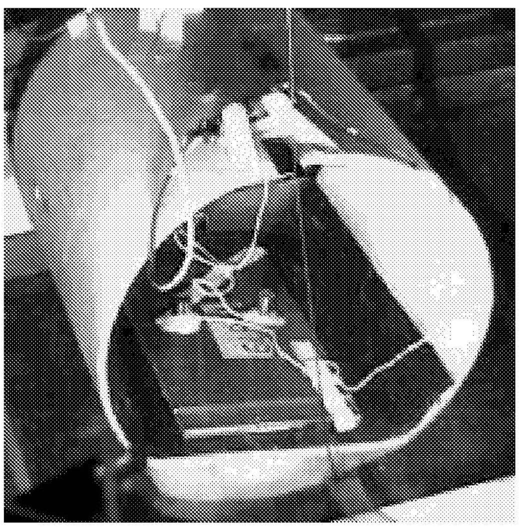


(c) Displacement response.

Figure 16. MSC/DYTRAN-predicted and experimental acceleration, velocity, and displacement responses.



(a) Prior to impact.



(b) During impact.

Figure 17. Photographs of the 1/5-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 19. The experimental responses were obtained from the accelerometers located on the right side and the left side 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.

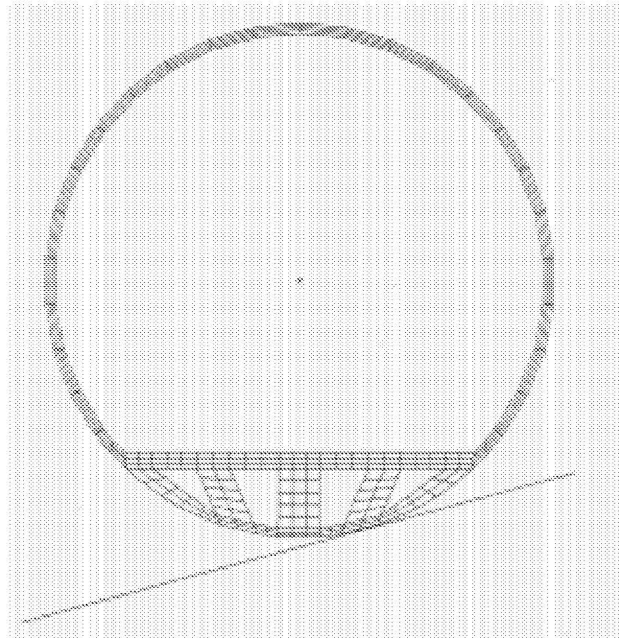
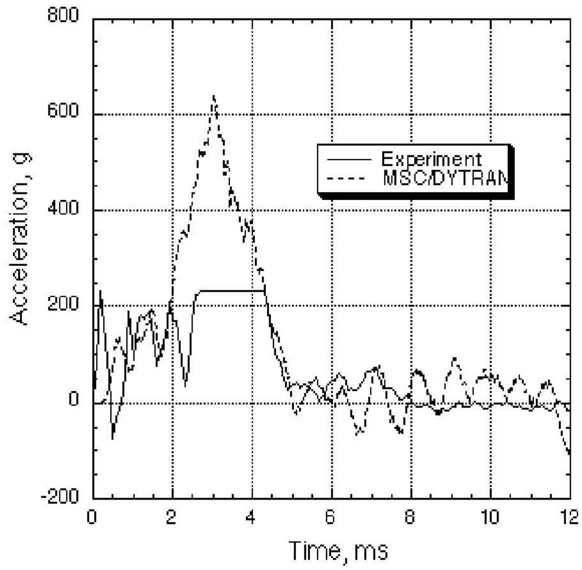
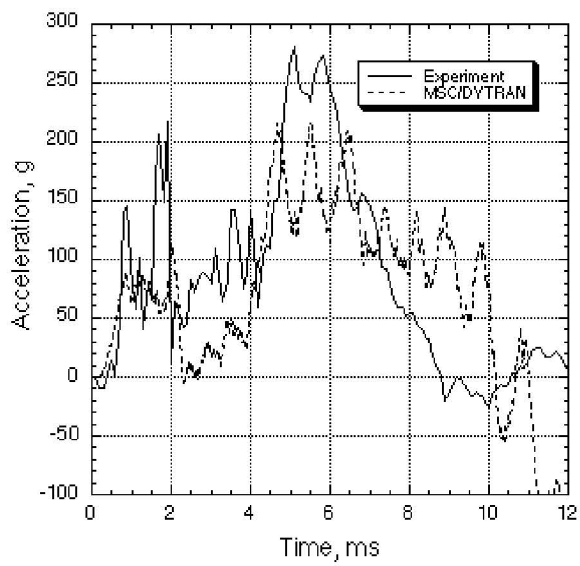


Figure 18. Front view of the undeformed MSC/DYTRAN model of the 1/5-scale model fuselage prior to 15° off-axis impact.

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 19 (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 19 (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 form the 15° off-axis drop test.



(a) Right accelerometer.



(b) Left accelerometer.

Figure 19. MSC/DYTRAN-predicted and experimental 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 two different subfloor configurations, including a composite tube design and a geometric foam-filled design, was evaluated through quasi-static crushing tests. The test results indicate that both subfloor configurations exhibited an average crushing stress of approximately 15 psi for a stroke of 70%, which is the design goal for optimal energy absorption. Each subfloor configuration was incorporated into a 1/5-scale model fuselage section, which was dropped from a height of 15 ft. for an initial 31 ft/s vertical impact velocity onto a rigid surface. The experimental data demonstrate that the fuselage section with a Rohacell 31-IG foam-filled subfloor configuration 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.

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13. ABSTRACT (Maximum 200 words)

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