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Development of a Scale Model Composite Fuselage Concept for Improved Crashworthiness

Karen E. Jackson* and Edwin L. Fasanella†
U.S. Army Research Laboratory, Hampton, Virginia 23681-2199
and
Sotiris Kellas‡
MRJ Technology Solutions, Hampton, Virginia 23681-2199

A composite fuselage concept for light aircraft has been developed to provide improved crashworthiness. The fuselage consists of a relatively rigid upper section, or passenger cabin, including a stiff structural floor and a frangible lower section that encloses the crash energy management structure. The crashworthy performance of the fuselage concept was evaluated through impact testing of a one-fifth-scale model fuselage section. The impact design requirement for the scale model fuselage is to achieve a 125-*g* average floor-level acceleration for a 31-ft/s vertical impact onto a rigid surface. 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 one-fifth-scale model fuselage section, which was dropped from a height of 15 ft to achieve a 31-ft/s vertical velocity at impact. The experimental data demonstrate that the fuselage section with a foam-block subfloor configuration satisfied the impact design requirement. A second drop test was performed to evaluate the energy absorption performance of the fuselage concept for an off-axis impact condition. The experimental data are correlated with analytical predictions from a finite element model developed using the nonlinear, explicit transient dynamic code MSC/DYTRAN.

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. The fuselage concept was designed to meet structural and flight loads requirements and to provide improved crash protection. The two primary design goals for crashworthiness are to limit the impact forces transmitted to the occupants and to maintain the structural integrity of the fuselage to ensure a minimum safe occupant volume.[1,2] To meet these objectives, an aircraft or rotorcraft fuselage must be designed for high stiffness and strength to prevent structural collapse during a crash. However, the fuselage design must not be so stiff that it transmits or amplifies high impact loads to the occupants. Ideally, the design should contain some crushable elements to help limit the loads transmitted to the occupant.[3]

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. During the first year of the research program, a 1-ft-diam, one-fifth-scale model composite fuselage was designed, fabricated, and tested to verify compliance with structural and flight loads requirements.[4] During the second year, energy absorbing subfloor configurations were evaluated through quasi-static testing and finite element simulation for incorporation into the one-fifth-scale model fuselage.[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. The focus of the present paper is to describe the energy absorption behavior of two different composite subfloor configurations and to evaluate the dynamic response of a one-fifth-scale model fuselage section incorporating each subfloor configuration through impact testing and finite element simulation.

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*Aerospace Engineer, NASA Langley Research Center, Vehicle Technology Directorate, Mail Stop 495. Associate Fellow AIAA.
†Aerospace Engineer, NASA Langley Research Center, Vehicle Technology Directorate, Mail Stop 495.
‡Aerospace Engineer, NASA Langley Research Center, Mail Stop 495.

Fuselage Design Concept

The fuselage concept, shown in Fig. 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. On 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. 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.

In Refs. 6 and 7, the impact response of the composite energy absorbing fuselage concept was compared analytically with the impact responses of a conventional fuselage concept and a retrofit of a conventional fuselage concept. A schematic drawing of these three fuselage concepts is shown in Fig. 2. The conventional fuselage consists of a frame-stiffened shell with stiff, noncrashworthy subfloor beams. For the retrofit fuselage, the original subfloor beams are replaced with composite energy absorbing beams.[8,9] For these two fuselage concepts, the initial impact event involves contact between a hard surface and a stiff fuselage shell. This impact event produces high-impact loads that are transmitted through the stiff fuselage structure resulting in high accelerations of the seat and occupant. For the retrofit concept, these loads may be dissipated somewhat by crushing of the energy absorbing subfloor beams. The energy absorbing fuselage incorporates crashworthy features in the preliminary structural design, thus eliminating the need for a retrofit to improve the crash performance of the airframe at some later time.

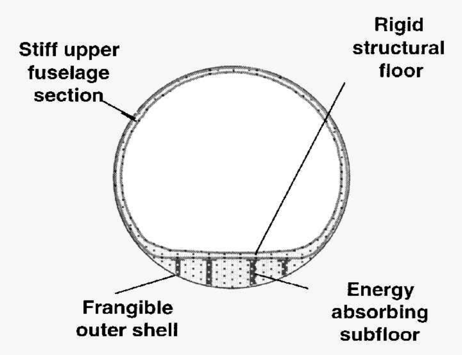


Fig. 1 Schematic drawing of the fuselage concept.

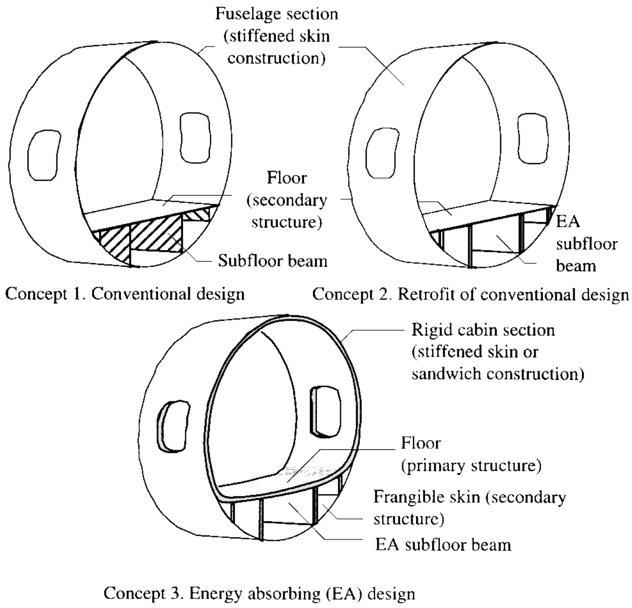


Fig. 2 Three fuselage concepts representing conventional, retrofit, and energy absorbing designs.

For this concept, the initial impact event involves contact between a hard surface and a frangible shell enclosing an energy absorbing subfloor. On impact, the energy absorbing subfloor dissipates kinetic energy through controlled crushing, resulting in lower accelerations transmitted to the seat and occupant.

An important feature of the fuselage design is the load-bearing structural floor, which provides postcrash structural integrity and maintains the seat rail and floor attachment. The conventional and retrofit fuselage concepts do not contain a stiff, load-bearing floor. Consequently, in a crash the floor may buckle or collapse, which may cause failure of the seat rails and loss of the seat attachment points. The seat and occupant can become detached from the seat rail, resulting in complete loss of motion restraint within the cabin of the aircraft. The presence of a stiff structural floor in the crashworthy fuselage concept should significantly reduce the possibility of floor buckling and seat detachment.

Another advantage of the energy absorbing fuselage concept is that its crash effectiveness is much less dependent on the mass of an individual occupant. For example, the energy absorbing subfloor beams in the retrofitted fuselage concept can provide crash protection only when loaded by an occupant of sufficient mass to initiate crushing upon impact. A child or other lightweight individual may not have sufficient mass to initiate crushing of the subfloor beams. As a result, they will not be protected from the high-impact loads. For the energy absorbing fuselage concept, the combined mass of all seats, occupants, and the upper portion of the aircraft itself are reacted by the subfloor beams during an impact. Thus, crash protection is provided to all occupants regardless of their individual mass. Finally, through the use of energy absorbing seats and landing gear, further increases in energy absorption can be attained, resulting in a truly crashworthy design configuration.

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 one-fifth-scale model fuselage is based on a full-scale aircraft with a diameter of 60 in. and a floor load distribution of 300 lb per linear foot of fuselage length. The geometrically and constitutively similar one-fifth-scale model fuselage has a diameter of 12 in. and a corresponding floor load distribution of 12 lb per linear foot of fuselage length. Because of testing constraints, the length of the scale model fuselage was limited to 12 in. The structural design goal was to maintain floor rigidity (less than 0.1 in. of floor midpoint displacement for the one-fifth-scale model fuselage) for a 10-psi internal pressure load. This goal was satisfied during the first year of the research program,[4] and the final design of the upper section and floor of the fuselage concept is shown in Fig. 3.

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 that are oriented at 0/90 deg with respect to the longitudinal axis of the fuselage, as shown in Fig. 3. 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 to improve 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 impact velocity observed in actual crashes and in crash tests conducted at NASA Langley Research Center.[10–13]

For the one-fifth-scale model fuselage, the specific impact requirement is to achieve and maintain a 125-g average floor-level acceleration for the 31-ft/s vertical impact condition. This impact requirement corresponds to a 25-g floor-level acceleration for the full-scale fuselage. The subfloor is required to dissipate kinetic energy through stable crushing. For a vertical impact of a one-fifth-scale model fuselage, with a length of 12 in. and weighing approximately

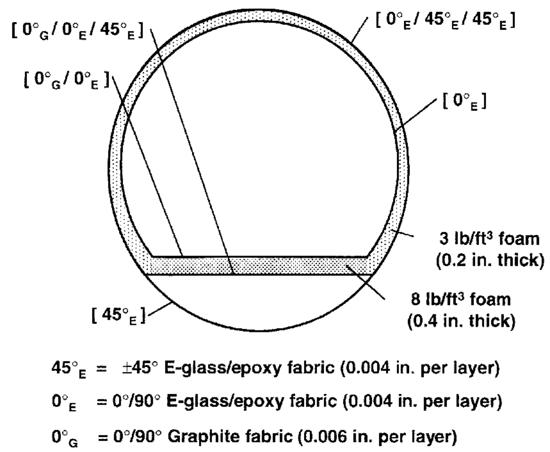


Fig. 3 Schematic drawing of the final design configuration for the upper section and floor of the one-fifth-scale model fuselage concept.

Table 1 Summary of scale factors for the full-and one-fifth-scale model fuselage concepts

Parameter	Full-scale	One-fifth-scale model	Scale factor
Diameter, in.	60	12	λ
Length, ft	5	1	λ
Internal pressure, psi	10	10	1
Impact velocity, ft/s	31	31	1
Kinetic energy, ft · lb	89,500	716	λ^3
Pulse duration, ms	38.5	7.7	λ
Subfloor crush force/length, lb/ft	7,500	1,500	λ
Average subfloor crushing stress, psi	15	15	1
Floor-level acceleration, *g*	25	125	$1/\lambda$

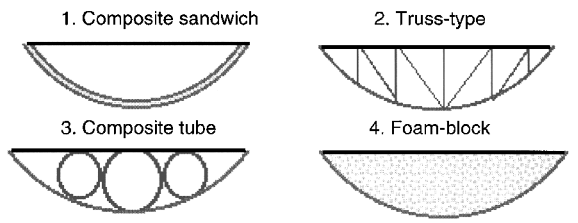


Fig. 4 Schematic drawings of four subfloor configurations.

12 lb, a sustained subfloor crushing load of 1500 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 in. is required to stop an object with an initial velocity of 31 ft/s at a constant 125-g acceleration. Because the actual crushing distance available is greater than 1.43 in., 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 one-fifth for this study).

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 one-fifth-scale model fuselage. End views of these configurations are depicted schematically in Fig. 4 and include 1) a composite sandwich for the lower subfloor surface, 2) a truss-type subfloor with interconnecting beam or sandwich segments, 3) a composite tube subfloor, and 4) a crushable foam-block subfloor. Under compressive load, the composite sandwich subfloor developed a disbond between the face sheets and the foam core, which is a relatively inefficient damage mechanism for energy absorption. The truss-type subfloor performed well, although 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 Ref. 5. In the present paper, the evaluations of the composite tube and foam-block subfloor configurations are described in the following sections.

Composite Tube Subfloor

For the composite tube subfloor, cylindrical tubes are inserted longitudinally beneath the floor and are enclosed by the outer shell. The tubes are crushed transversely under vertical impact loading to dissipate 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.

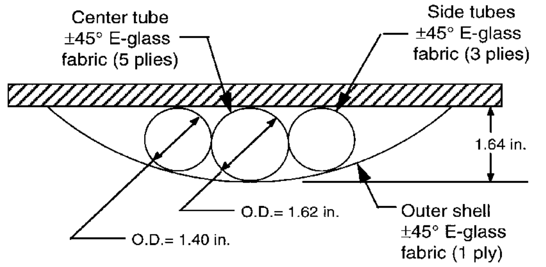


Fig. 5 Schematic drawing of the composite tube subfloor configuration.

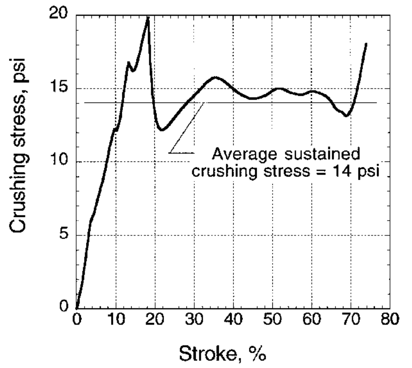


Fig. 6 Plot of crushing stress vs stroke for the composite tube subfloor.

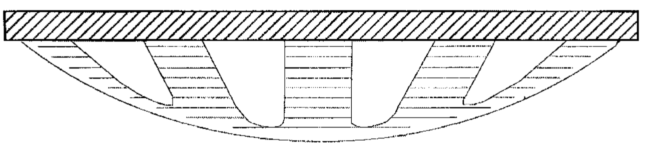


Fig. 7 End-view drawing of a crushable foam-block subfloor.

A schematic drawing of the final selected composite tube subfloor design is shown in Fig. 5. The subfloor consists of a 1.62-in.-diam center tube and two 1.4-in.-diam side tubes. The side and center tubes are fabricated from three and five layers of E-glass/epoxy fabric oriented at ±45-deg with respect to the longitudinal axis, respectively. The outer shell is formed of a single ply of ±45 deg E-glass/epoxy fabric. 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. The plot of crushing stress vs stroke, shown in Fig. 6, indicates that the subfloor exhibited an average sustained crushing stress of 14 psi and a stroke efficiency of 70%. This value of sustained crushing stress is close to the 15-psi design goal. Consequently, this composite tube subfloor was selected for incorporation into the one-fifth-scale model fuselage section for dynamic evaluation.

Foam-Block Subfloor

The foam-block subfloor consists of uniformly spaced, individual blocks of a crushable foam material surrounded by a frangible outer shell. Each block of foam is machined to the cross-sectional geometry shown in Fig. 7. The geometry of the foam blocks was chosen to maintain a fairly constant crushing force. Initially, the foam-block 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 Fig. 7. The subfloor sections were 8.375 in. wide at the floor level and 6 in. long and had a maximum height of 1.64 in. For one subfloor section, the foam blocks were overlaid with face sheets consisting of two layers of E-glass/epoxy fabric oriented at ±45 deg with respect to the longitudinal axis. For the second

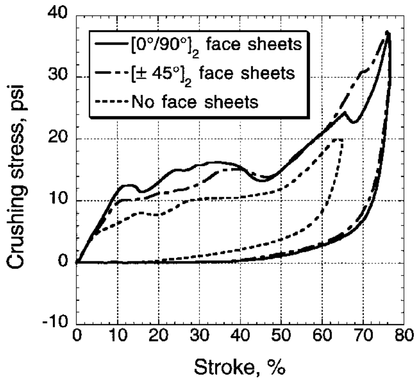


Fig. 8 Quasi-static crushing responses for three PVC foam-block subfloor configurations.

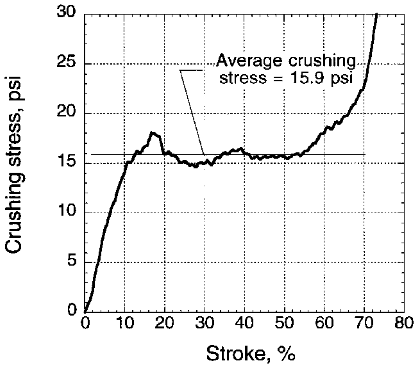


Fig. 9 Crushing stress vs stroke for the Rohacell 31-IG foam-block subfloor.

subfloor, 0/90 deg face sheets were used. The third subfloor section was fabricated without face sheets. For each subfloor, the outer shell consists of a single layer of ±45-deg E-glass/epoxy fabric.

Each of these subfloor sections was loaded in compression at 20 in./min in a standard universal test machine. A plot of crushing stress vs stroke for each of the three subfloor sections is shown in Fig. 8. The results show that adding face sheets to the foam blocks increases the crushing stress of the subfloor when compared to the subfloor without face sheets. In addition, the fuselage section with face sheets oriented at 0/90 deg exhibited a slightly higher crushing stress than did the fuselage section with face sheets oriented at ±45 deg. These results indicate that it is possible to optimize the foam-block subfloor configuration, to a certain extent, by altering the orientation of the face sheets to achieve the desired crushing stress. In general, the crushing stress of these foam-block 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 foam begins 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 Fig. 8. In general, this behavior can be undesirable for an effective energy absorbing material.

Overall, the foam-block subfloor configurations with face sheets performed well. The average sustained crushing stresses for the subfloors with face sheets oriented at 0/90 deg and ±45 deg are 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.

A foam-block subfloor was fabricated using a 2.8-lb/ft^3 Rohacell 31-IG foam material, which is a closed-cell, polymethylimide foam with good high-temperature properties. The Rohacell foam exhibits approximately a linear elastic, perfectly plastic material response under compressive load, which makes it an ideal choice for an energy absorbing material. The subfloor consisted of five 1.5-in.-deep Rohacell foam blocks, which were equally spaced under a flat, rigid surface. The foam blocks were overlaid with two layers of 0/90 deg E-glass/epoxy fabric. The section was loaded in compression at 20 in./min in a standard universal test machine. A plot of crushing stress vs percent stroke is shown in Fig. 9. The Rohacell foam-block 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 was selected for incorporation into the one-fifth-scale model fuselage section for dynamic evaluation.

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

A one-fifth-scale model fuselage section was fabricated with the final selected composite tube subfloor configuration. This fuselage section is depicted in Fig. 10. The fuselage had an outer diameter of 12.2 in. and a length of 12 in. 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. The fuselage section was instrumented with front and rear accelerometers, which were secured to the lead plate along its centerline to record the vertical acceleration response.

A simple drop tower was constructed for performing the impact tests of the one-fifth-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 ft, and a support frame that was rigidly attached to the floor. 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.

The fuselage section with the composite tube subfloor was dropped from a height of 15 ft to achieve a vertical velocity of 31 ft/s at impact. A plot of the acceleration responses obtained from the front and rear accelerometers is shown in Fig. 11. An average acceleration was calculated by determining the area under the acceleration curve and dividing by the pulse duration. From analysis of the data, an average acceleration of 147 g was determined for a pulse duration of 15 ms. This value of average acceleration is

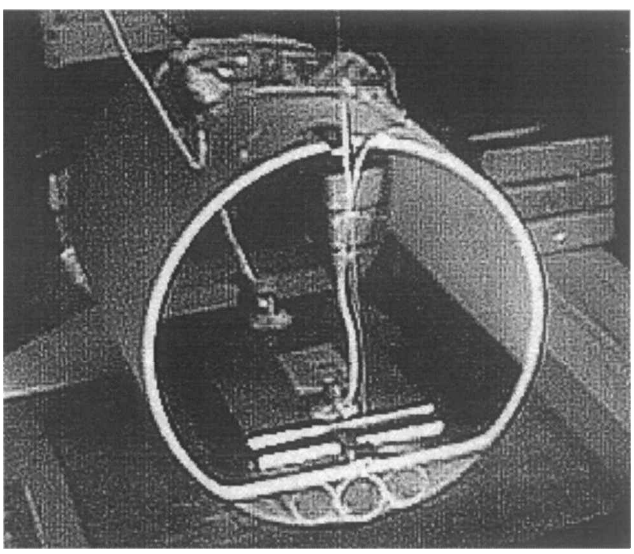


Fig. 10 Photograph of the one-fifth-scale model fuselage section with composite tube subfloor.

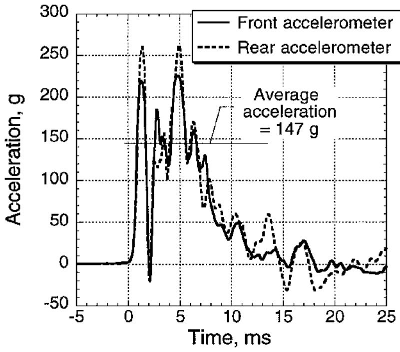


Fig. 11 Plot of acceleration vs time for the front and rear accelerometers in the scale model fuselage with the composite tube subfloor.

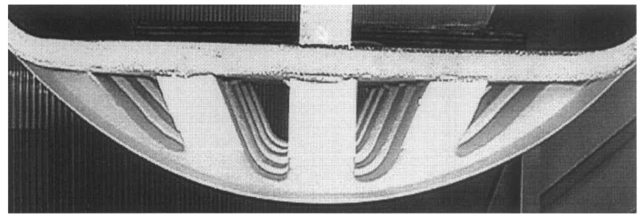
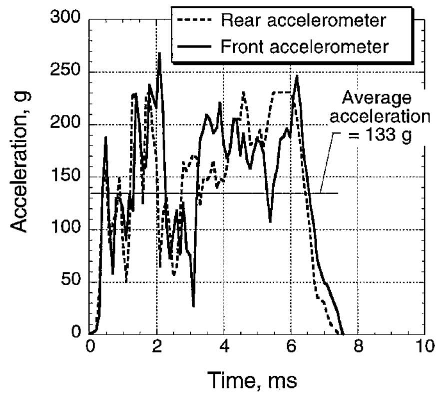
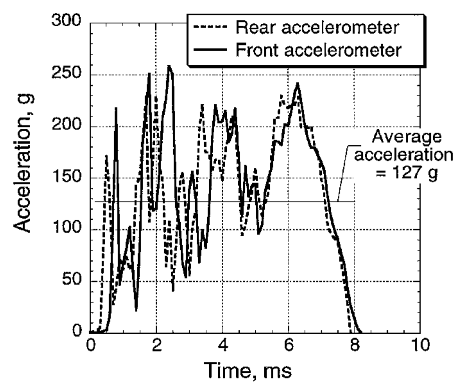


Fig. 12 Photograph of the subfloor region of the one-fifth-scale model fuselage section with a foam-block subfloor.



Subfloor with five 1.5-in.-deep blocks of foam



Subfloor with five 1.3-in.-deep blocks of foam

Fig. 13 Experimental front and rear acceleration responses from impact tests of two one-fifth-scale model fuselage sections with different foam-block subfloor configurations.

approximately 20% higher than the 125-*g* design goal. Note that the average acceleration of 147 *g* for the one-fifth-scale model fuselage corresponds to an average acceleration of 29.4 *g* for the full-scale fuselage.

After the initial impact event, the one-fifth-scale model fuselage section with the composite tube subfloor rebounded to a height of approximately 2 ft. This rebound distance appeared to be significant for the scale model fuselage, as the section rebounded a distance that was approximately twice its diameter. Given similar coefficients of restitution for the scale model and full-scale impact surfaces, the full-scale fuselage section should rebound the same distance. Given that the full-scale fuselage will be 5 ft in diameter, this amount of rebound is less significant. The reason for the large amount of rebound is due to the composite tubes storing 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 configuration 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 for this application.

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

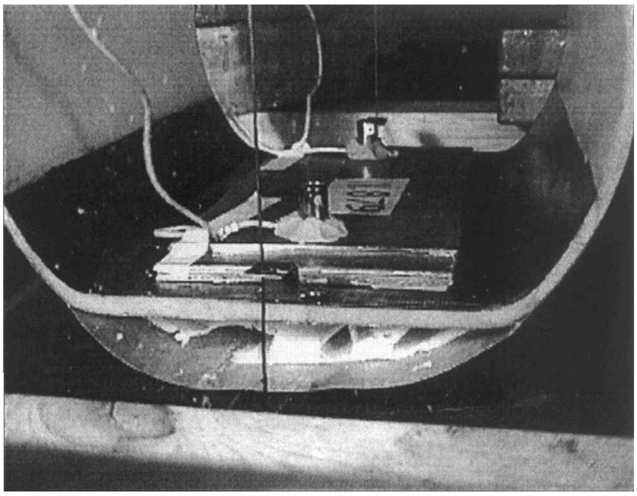
Two Rohacell foam-block subfloors were fabricated, incorporated into the one-fifth-scale model fuselage, and tested under vertical impact conditions in the simple drop tower described in the preceding section. The first subfloor consisted of five 1.5-in.-thick blocks of foam material. This subfloor exhibited 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 foam blocks having a slightly reduced thickness 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 0/90 deg E-glass/epoxy fabric and were equally spaced under the floor of the fuselage. A photograph of the subfloor region of the one-fifth-scale model fuselage section with a foam-block subfloor is shown in Fig. 12.

For each test, the fuselage section was dropped from a height of 15 ft 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 fuselage 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 Fig. 13. As indicated in Fig. 13, average accelerations of 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 were determined. These values of average acceleration are close to the 125-*g* design goal. Also, the pulse duration for each response is between 7.5 and 8 ms, which is close to the estimated value of 7.7 ms, which was calculated from kinematics.

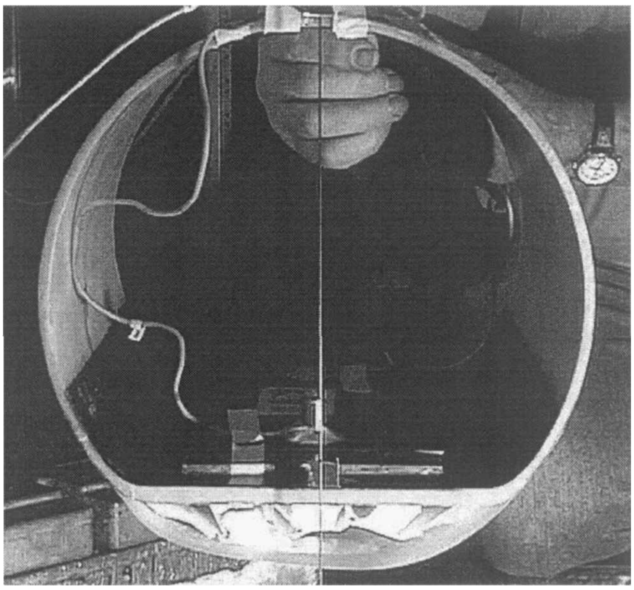
Posttest photographs of a fuselage section with a Rohacell foam-block subfloor are shown in Fig. 14. Damage to the subfloor consisted of foam crushing and debonding of the face sheets away from the foam blocks. The upper section and floor of the fuselage were undamaged. Based on the impact test results, the final subfloor configuration was chosen to be the foam-block subfloor consisting of five individual 1.3-in.-thick blocks of Rohacell 31-IG foam overlaid with two layers of E-glass/epoxy oriented at 0/90 deg with respect to the longitudinal axis.

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

An important aspect of crashworthiness research is the verification and demonstration of analytical/computational techniques for simulation of structural response to crash impacts. In fact, during the Workshop on Computational Methods for Crashworthiness that was held at NASA Langley Research Center in 1992, one of five key technology shortfalls identified was "validation of numerical simulations."[14] A detailed three-dimensional finite element model of the one-fifth-scale model fuselage section with the final selected



Closeup of subfloor damage



Frontview of subfloor damage

Fig. 14 Posttest photographs of the one-fifth-scale model fuselage section with Rohacell foam-block subfloor.

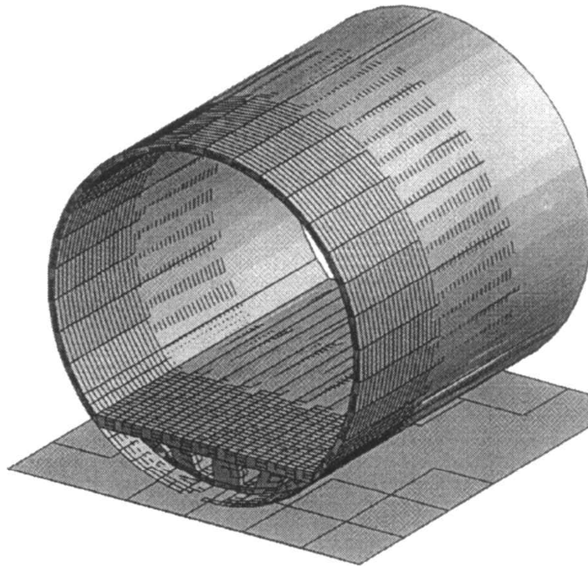


Fig. 15 Undeformed MSC/DYTRAN model of the one-fifth-scale model fuselage section.

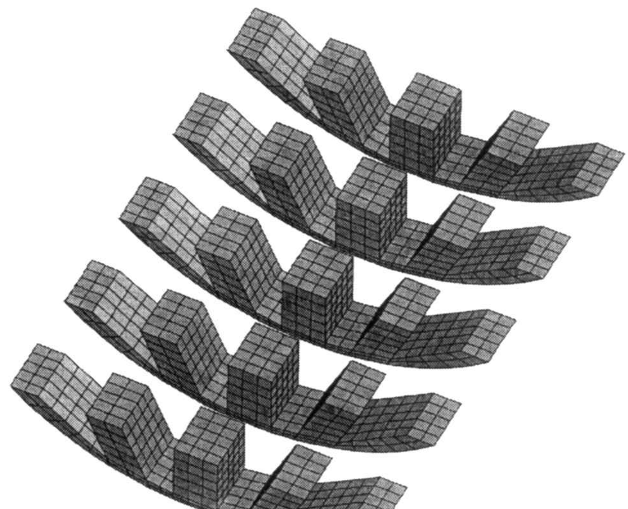


Fig. 16 MSC/DYTRAN model of the Rohacell foam blocks in the subfloor.

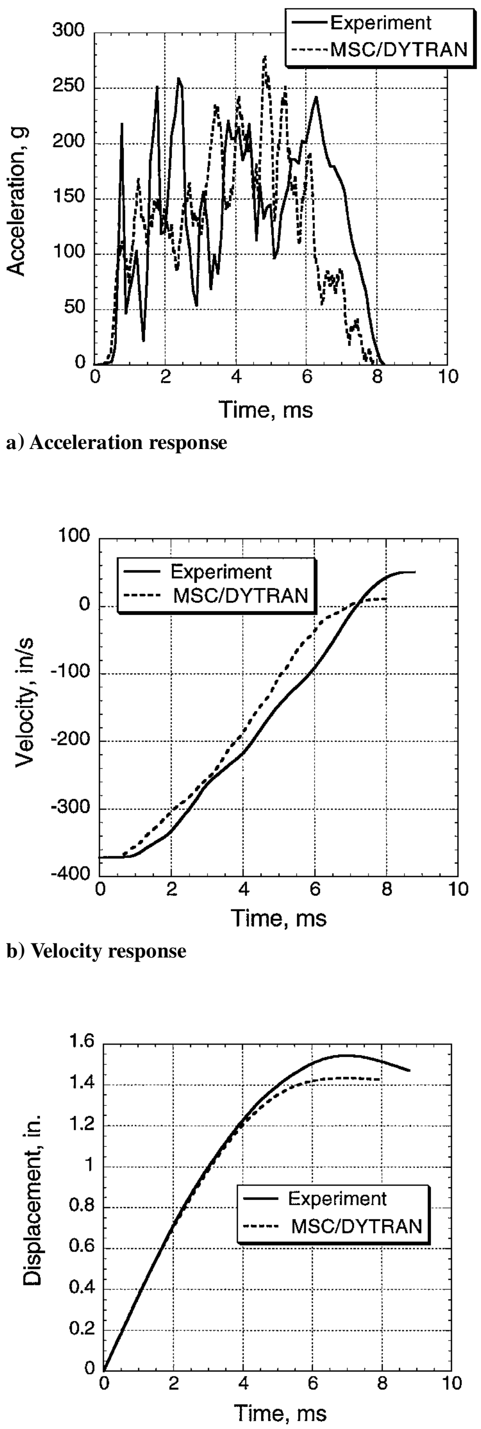
Rohacell foam-block subfloor configuration was developed using MSC/DYTRAN.[15] The purpose of the simulation was to aid in the crashworthy evaluation of the fuselage concept and to address, in a small way, the technology shortfall of numerical simulation validation. MSC/DYTRAN is a nonlinear, explicit transient dynamic finite element code, marketed by the MacNeal–Schwendler Corporation. The undeformed model, shown in Fig. 15, consists of 14,992 nodes, 18,240 elements, 89,808 degrees of freedom, 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 deg and ±45-deg E-glass/epoxy fabric layers 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 polyurethane foam cores in the upper section and floor are modeled as DMATEL linear elastic solid materials. The more complicated multilayered 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 shown in Table 2.

The Rohacell foam blocks, which are located in the subfloor region of the MSC/DYTRAN model, are shown in Fig. 16. 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 2000 psi, a yield stress of 90 psi, and a plastic strain at failure of 80%. The 0/90 deg 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. To represent the inertial properties of the lead plate, 60 concentrated masses, each weighing 0.2 lb, are distributed in a centralized rectangular region on the floor. The model weighed 14.418 lb, which is very close to the actual 14.42-lb weight of the one-fifth-scale model fuselage. 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 the impact surface are fixed. An initial vertical velocity of 31 ft/s is assigned to all elements in the model except for those elements forming the impact surface. A transient analysis of the MSC/DYTRAN model was executed for 8 ms, which required approximately 2.3 h 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 one-fifth-scale model fuselage section

Table 2 Material property data used in the MSC/DYTRAN simulation of the one-fifth-scale model fuselage section

Material	Formulation	ρ, lb-s^2/in.^{4}	E, psi	ν	G, psi	σ_y, psi	E_h, psi	$\varepsilon_{\mathrm{psf}}$, in./in.
Aluminum	DYMAT24	2.65e−4	10e06	0.33	——	55,000	——	——
±45-deg E-glass	DMATEP	1.73e−4	1.5e6	0.49	——	9,000	117,650	——
0/90 deg E-glass	DMATEP	1.73e−4	2.75e6	0.113	——	12,000	117,650	——
Foam 3 lb/ft^3	DMATEL	4.5e−6	1300	——	650	——	——	——
Foam 8 lb/ft^3	DMATEL	1.2e−5	8000	——	3,200	——	——	——
Graphite/epoxy	DMATEP	1.45e−4	9.1e6	0.061	——	——	——	——
Rohacell foam	DYMAT24	4.2e−6	2000	0.3	——	90	——	0.8
0/90 deg E-glass w/failure	DMATEP	1.73e−4	2.75e6	0.113	——	12,000	117,650	.001



a) Acceleration response

b) Velocity response

c) Displacement response

Fig. 17 MSC/DYTRAN-predicted and experimental responses.

with the Rohacell foam-block subfloor in Fig. 17. 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 Fig. 17a. The experimental velocity and displacement responses, shown in Figs. 17b and 17c, respectively, were obtained by successive integration of the acceleration data.

In general, the MSC/DYTRAN simulation predicts the overall shape and magnitude of the experimental acceleration response well, as shown in Fig. 17a. An average acceleration was determined for both responses by integrating the acceleration curve and dividing by the pulse duration. The MSC/DYTRAN-predicted response had an average acceleration of 124 g, which is only 2.4% lower than the experimental value of 127 g. However, the MSC/DYTRAN simulation did not predict the peak acceleration that occurred at 6.3 ms in the experimental response. Also, the predicted response had a slightly shorter pulse duration, by approximately 0.25 ms, than the experimental curve.

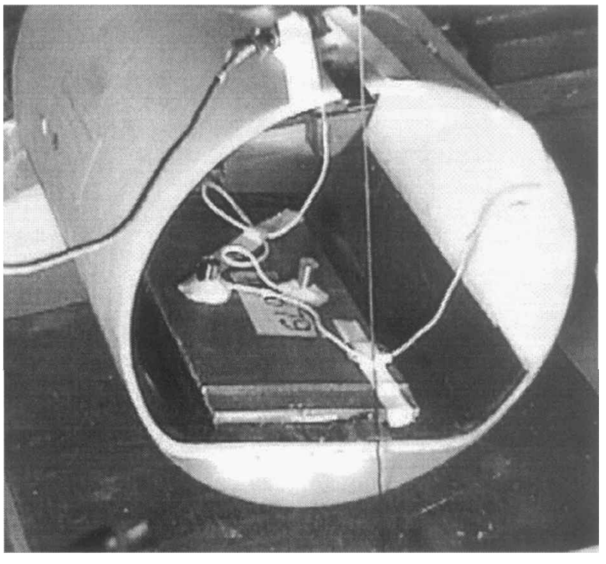
The predicted and experimental velocity time histories are plotted in Fig. 17b. The plot indicates that the MSC/DYTRAN simulation is dissipating or removing velocity at a faster rate than the experiment. For example, at any given time, the velocity of the experimental response is slightly lower (more negative) than that of the predicted response. The predicted and experimental displacement responses are shown in Fig. 17c. The maximum displacement predicted by the MSC/DYTRAN simulation is 1.43 in., compared to 1.54 and 1.51 in. for the front and rear floor locations, respectively. Given that a maximum crushing distance of 1.7 in. was available, a crushing stroke of approximately 90% was achieved in the experiment.

The small discrepancies between the measured and predicted responses may be attributed to inaccurate modeling of the subfloor crushing process in the MSC/DYTRAN simulation. The material properties of the Rohacell foam used in the model were obtained from compression tests on square blocks of foam. Consequently, the material properties represent the compressive response and failure of the material only. During the initial impact, the Rohacell foam blocks were subjected to a more complex loading scenario, including bending and shear. It is expected that the Rohacell foam would fail at much lower loads when subjected to shear and flexure. Another deficiency in the model is that it did not allow disbonding of the face sheets from the Rohacell foam in the subfloor. Because of these factors, the subfloor in the model had a relatively stiffer response than that of the actual subfloor, causing the model to dissipate more energy initially than the test. Also, the material model for the Rohacell foam in the MSC/DYTRAN simulation did not represent the stiffening effect that occurs for large compressive strains, as the foam becomes compacted. Based on the compression test results, the foam begins to compact at 70–80% stroke. Obviously, some portions of the subfloor were compacted because the one-fifth-scale model fuselage exhibited a crush stroke efficiency of about 90%. Once the subfloor became compacted near the end of the pulse, the loads reacted by the floor increased dramatically, producing the peak acceleration that was observed at 6.3 ms in the experimental response. The MSC/DYTRAN simulation did not account for the effects of foam compaction and, consequently, underpredicted the magnitude of the peak acceleration, which occurred near the end of the pulse.

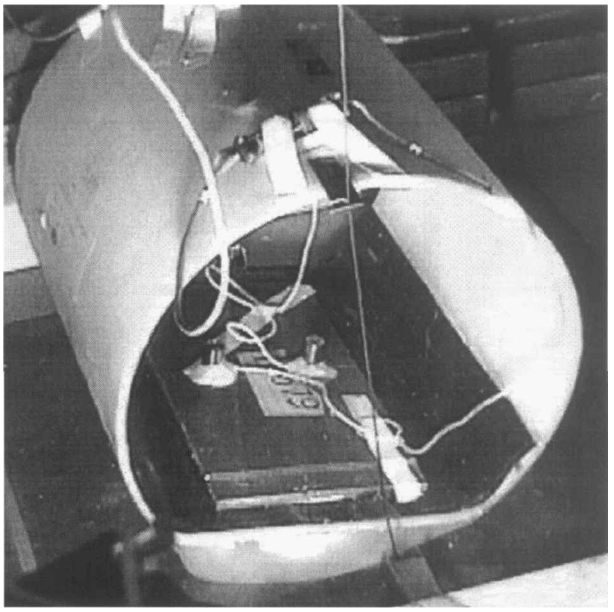
Experimental and Analytical Evaluation of the Scale Model Fuselage for a 15-Degree Off-Axis Impact Condition

A final objective of the research program was to demonstrate that the fuselage concept provided a high level of crash protection for an off-axis impact condition. Consequently, a vertical drop test of the one-fifth-scale model fuselage with the Rohacell foam-block subfloor was performed for a 15-deg-roll impact attitude. The angle was achieved by rotating the support brackets located at the top and bottom on both ends of the fuselage section by 15 deg. The fuselage was dropped from a height of 15 ft to achieve a 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 Fig. 18, one on the right side and one on the left side of the centerline. 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 Fig. 18.

A crash simulation was performed to predict the acceleration response of the one-fifth-scale model fuselage during the 15-deg off-axis impact using MSC/DYTRAN. The undeformed MSC/DYTRAN model, shown in Fig. 19, is the same model that was used to perform the earlier impact simulation. However, some modifications were made to account for the 15-deg-roll impact attitude. In the experiment, the fuselage section was rotated by 15 deg and impacted at 31-ft/s vertical impact velocity. However, for the analysis, it was more expedient to rotate the impact surface by 15 deg 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 3.5 h of CPU time on a Sun Enterprise 450-4x300 workstation computer.



Prior to impact



During impact

Fig. 18 Photographs of the one-fifth-scale model fuselage prior to and during 15-deg off-axis impact.

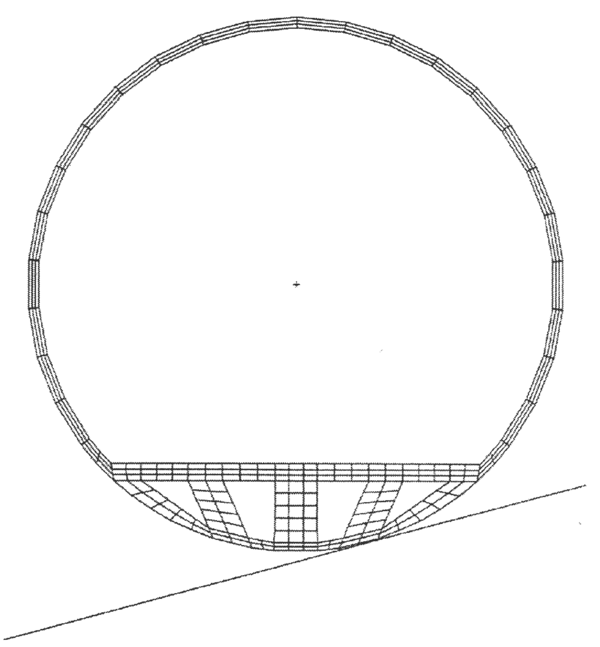
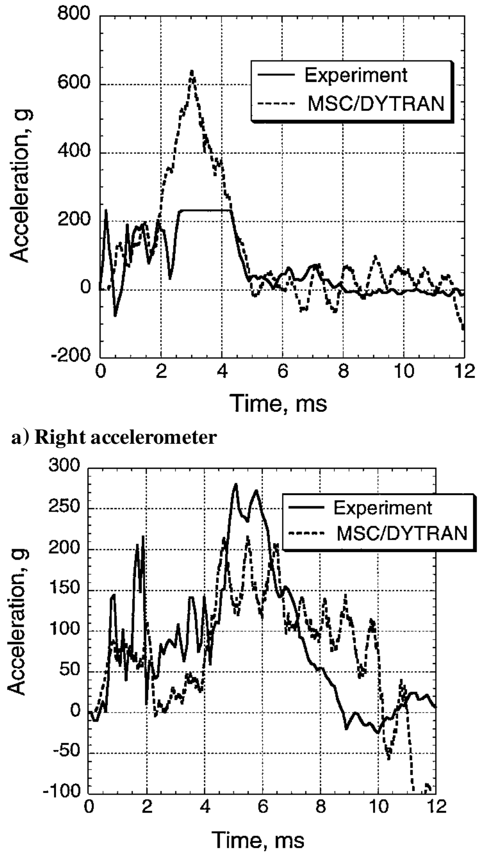


Fig. 19 Front view of the undeformed MSC/DYTRAN model for the 15-deg-roll impact condition.

Plots of the MSC/DYTRAN-predicted and experimental acceleration responses are shown in Fig. 20. 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 deg from the vertical direction. Another component parallel to the floor is also present, but was not measured in the experiment.

In general, the MSC/DYTRAN crash simulation correlated well with the experimental responses obtained from the 15-deg off-axis drop test. 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 Fig. 20a. Unfortunately, the calibration of the accelerometer was set for a maximum of 250 g and the peak acceleration was not measured. However, the predicted response correlates well with the experimental curve prior to and following the large spike. The pulse durations of the experimental and predicted acceleration responses were 5.7 and 5 ms, respectively.

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-deg-roll impact attitude. The acceleration time history recorded by the left accelerometer, shown in Fig. 20b, has an average acceleration of 92.9 g for a pulse duration of 8.75 ms. This value of average acceleration for the one-fifth-scale model fuselage corresponds to an average acceleration of 18.6 g for the full-scale fuselage. The predicted acceleration response for this



a) Right accelerometer

b) Left accelerometer

Fig. 20 MSC/DYTRAN-predicted and experimental acceleration responses in the 15-deg off-axis impact test.

location has an average acceleration of 92.5 g for a pulse duration of 10 ms.

The high level of correlation between the analytical and experimental data for both impact conditions provides increased confidence in the use of crash simulation codes to predict airframe structural response to crash. Further enhancements in the capabilities of these codes to model composite material and failure behavior will lead to improved correlation.

Conclusions

A composite fuselage concept for light aircraft has been developed to meet structural and flight loads requirements and to satisfy design goals for improved crashworthiness. The fuselage concept 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 a one-fifth-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 average 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-block 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 with a crush stroke of 60–70%, which is the design goal for optimal energy absorption. Each subfloor configuration was incorporated into a one-fifth-scale model fuselage section, which was dropped from a height of 15 ft to produce a 31-ft/s vertical velocity at impact. The experimental data demonstrate that the fuselage section with a Rohacell 31-IG foam-block subfloor exhibited an average floor-level acceleration of 127 g and, thus, satisfied the impact design requirement. A vertical drop test of the one-fifth-scale model fuselage was performed at 31-ft/s vertical velocity with a 15-deg-roll impact attitude. The test results demonstrated that the fuselage section maintained a high level of crash protection, even for this severe 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-deg-roll conditions.

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