

Comparisons of the Impact Responses of a 1/5-Scale Model and a Full-Scale Crashworthy Composite Fuselage Section

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Abstract

A 25-fps vertical drop test of a 1/5-scale model composite fuselage section was conducted to replicate a previous test of a full-scale fuselage section. The purpose of the test was to obtain experimental data characterizing the impact response of the 1/5-scale model fuselage section for comparison with the corresponding full-scale data. This comparison is performed to assess the scaling procedures and to determine if scaling effects are present. For the drop test, the 1/5-scale model fuselage section was configured in a similar manner as the full-scale section, with lead masses attached to the floor through simulated seat rails. Scaled acceleration and velocity responses are compared and a general assessment of structural damage is made. To further quantify the data correlation, comparisons of the average acceleration data are made as a function of floor location and longitudinal position. Also, the percentage differences in the velocity change (area under the acceleration curve) and the velocity change squared (proportional to kinetic energy) are compared as a function of floor location. Finally, correlation coefficients are calculated for corresponding 1/5- and full-scale data channels and these values are plotted versus floor location. From a scaling perspective, the differences between the 1/5- and full-scale tests are relatively small, indicating that appropriate scaling procedures were used in fabricating the test specimens and in conducting the experiments. The small differences in the scaled test data are attributed to minor scaling anomalies in mass, potential energy, and impact attitude.

Introduction

In 1997, a three-year research program was initiated to develop and demonstrate an innovative and cost-effective composite fuselage concept for light aircraft. The fuselage concept was designed to meet structural and flight loads requirements and to provide improved crash protection [1]. The fuselage concept, shown schematically in Figure 1, consists of a stiff fuselage cabin, a load-bearing floor, and an energy absorbing subfloor. The fuselage cabin is fabricated of a composite sandwich construction and is designed to provide a protective shell enclosing the occupants in the event of a crash. The energy absorbing subfloor consists of five blocks of a closed-cell Rohacell foam that are uniformly spaced beneath the floor. The subfloor is designed to dissipate kinetic energy through crushing. A key feature of the fuselage concept is the load-bearing structural floor, which is designed to react the loads generated by crushing of the subfloor while also providing a stable platform for seat and restraint attachment. The motivation for the fuselage concept and a comparative analysis with more conventional and retrofit designs is provided in Reference 1.

During the first two years of the research program, the fuselage concept was designed and evaluated through fabrication and testing of a 1/5-scale model [2-5]. This test article was 12-inches in diameter and approximately

12-inches in length. In 1998, a small drop tower was built and tests of the 1/5-scale model fuselage section were performed at 31-fps velocity for 0°- and 15°-roll attitudes. For these tests, a single 12-lb. lead weight was used to provide a uniform floor loading. During the third year, a full-scale prototype was fabricated by "scaling up" the geometry and constitutive properties of the 1/5-scale model [6-8]. The full-scale test article was 60-inches in diameter and approximately 60-inches in length. Drop tests were performed at 31-fps vertical velocity for 0°- and 15°-roll impact attitudes using the 70-ft. drop tower at the Impact Dynamics Research Facility located at NASA Langley Research Center in Hampton, Virginia. For these tests, a single 1,500-lb. lead weight was used to provide a uniform floor loading.

For the 0°-roll impact tests, the 1/5- and full-scale fuselage sections were instrumented with two accelerometers attached to the lead mass on the floor and located on the centerline, at an equal distance in front of and behind the mid-plane. For the 15°-roll impact tests, the two accelerometers were located on the lead mass at the mid-plane, an equal distance to the right and left of the centerline. During the 15°-roll impact test of the 1/5-scale model fuselage section, one of the accelerometers over-ranged. Thus, for these four impact tests, a total of seven channels of data were collected. Consequently, a comparison of the scaled test data yielded only three plots. Differences in the 1/5- and full-scale experimental results were attributed to slight variations in the test articles and the impact conditions, as discussed in Reference 6. However, insufficient data were available to make a thorough assessment of the scaling procedure or to determine if scaling effects were present.

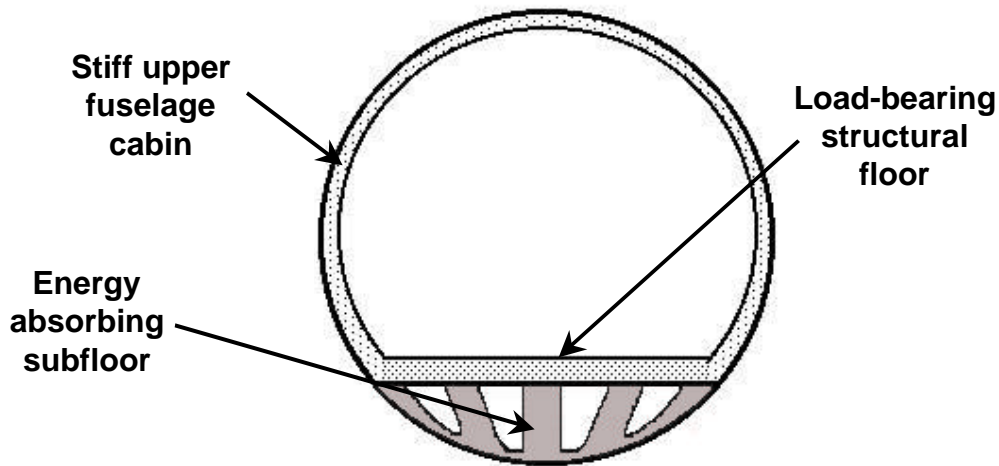


Figure 1. Schematic drawing of the fuselage concept.

In November 2000, a 25-fps drop test of a full-scale fuselage section was conducted in which the section was configured with seat rails and ten 100-lb. lead blocks on the floor. Data from this drop test were previously documented in References 9-11. In September 2002, a vertical drop test of the 1/5-scale model fuselage section was conducted to replicate this full-scale test. The 1/5-scale model fuselage section was configured in a similar manner with ten 0.8-lb. lead blocks attached to the floor through simulated seat rails, and the drop test was performed under scaled conditions.

In this paper, the experimental data obtained from the drop test of the 1/5-scale model fuselage section are compared with the full-scale drop test data to provide a more comprehensive assessment of the scaling technology. In particular, the scaled floor-level acceleration and velocity responses are compared and a general assessment of structural damage is made. To further quantify the correlation accuracy, comparisons of the average acceleration data are made as a function of floor location and longitudinal position. Also, the percentage differences in the velocity change (area under the acceleration curve) and the velocity change squared (proportional to kinetic energy) are compared as a function of floor location. Finally, correlation coefficients were calculated for corresponding 1/5- and full-scale data channels and these values are plotted versus floor location. A brief description of the experimental program, a comparison of the 1/5- and full-scale test results, and the data correlation studies are presented in the following sections of the paper.

Experimental Program

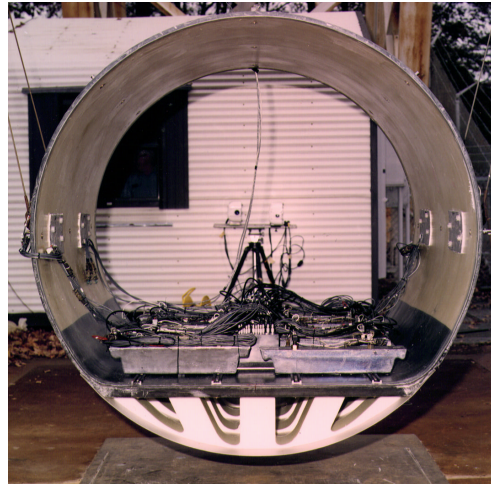
Pre-test photographs of the 1/5- and full-scale fuselage sections are shown in Figure 2. The full-scale fuselage section, which weighed 200 lbs. empty, was configured with ten 100-lb. lead masses, five per side, that were attached to seat rails on the floor. The total weight of the fuselage section, lead masses, and instrumentation boxes

was 1,243 lbs. The 1/5-scale model fuselage section was configured in a similar manner with ten 0.8-lb. lead masses attached to simulated seat rails on the floor. The total weight of the 1/5-scale model fuselage section, lead masses, and accelerometers was 10.74 lbs. From a scaling perspective, the weight of the 1/5-scale fuselage section should equal the weight of the full-scale fuselage section (1,243 lbs.) divided by 5^3 , or 125, which is 9.94 lbs. Thus, the 1/5-scale model fuselage section is 0.8 lbs. heavier than desired. This difference is attributed to the empty weight of the 1/5-scale fuselage section, which should have weighed 1.6 lbs. or the empty weight of the full-scale fuselage section (200 lbs.) divided by 125. However, the actual empty weight was 2.4 lbs., accounting for the 0.8-lb. difference.

The original purpose of the 25-fps vertical drop test of the full-scale fuselage section was to obtain experimental data with which to perform a detailed test-analysis correlation study, as described in References 9-11. Consequently, the full-scale fuselage section and lead masses were heavily instrumented. A schematic drawing showing the instrumentation layout on the floor of the full-scale fuselage section is shown in Figure 3. Data were recorded from 73 accelerometers at a 10-kHz sampling rate by an on-board digital data acquisition system (DAS). The accelerometers on the floor were oriented vertically. Inboard and outboard accelerometers were located on the bolts securing the large lead masses to the aluminum seat rails. In addition, some outboard accelerometers were mounted on blocks to the seat rails and several inboard accelerometers were mounted on blocks to the DAS support plates. The accelerometers positioned between the seat rails were mounted on blocks adhered directly to the floor. In addition, several accelerometers were mounted to the outer surface of the fuselage cabin to measure the radial acceleration; however, these accelerometers are not shown in Figure 3. The accelerometers to be compared with the data from the drop test of the 1/5-scale fuselage are numbered 1 through 16 in Figure 3. These accelerometers were mounted to the bolts used to attach the lead masses to the seat rails on the floor.



(a) 1/5-scale model fuselage section.



(b) Full-scale fuselage section.

Figure 2. Pre-test photographs of the 1/5- and full-scale fuselage sections.

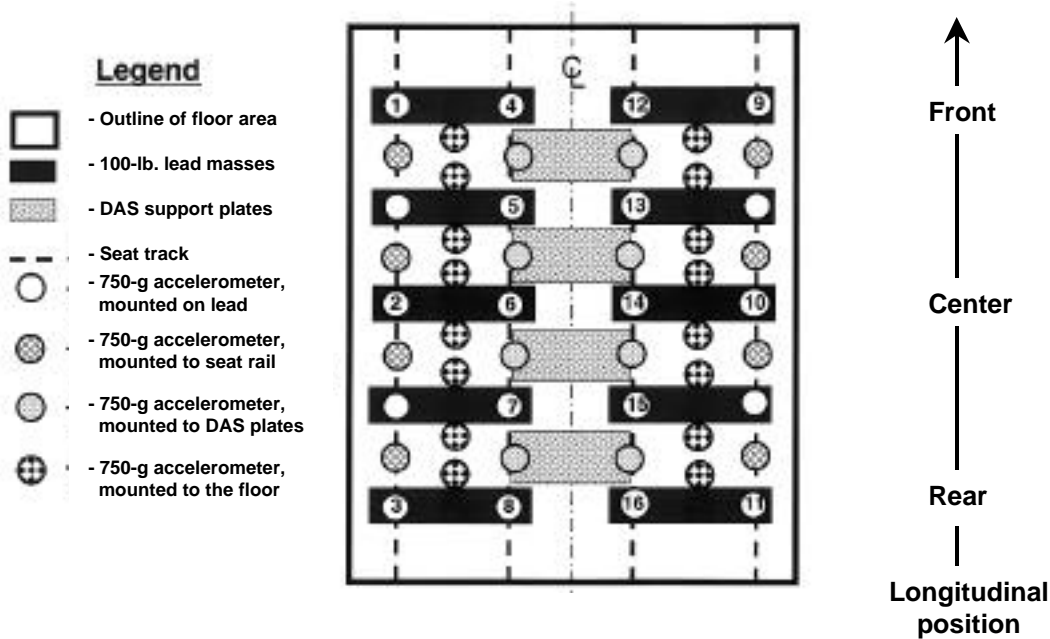


Figure 3. Instrumentation layout on the floor of the full-scale fuselage section.

The instrumentation layout on the floor of the 1/5-scale model fuselage section is shown in Figure 4. A total of 16 accelerometers were used to record the vertical acceleration responses of the lead masses on the floor. These accelerometers were attached directly onto the lead masses and were placed in similar locations relative to the full-scale fuselage to permit direct comparison of the 1/5- and full-scale responses. The locations of these accelerometers, numbered 1 through 16, are depicted in Figure 4. Four of the sixteen accelerometers had a maximum range of $\pm 2,000$ -g, while the remaining accelerometers had a range of ± 500 -g. These ranges were necessary since the acceleration levels in the 1/5-scale test are expected to be

five times higher than those seen in the full-scale test. The accelerometers used in the drop test of the 1/5-scale model fuselage section were especially small, weighing only 0.0022 lbs., or approximately 1 gram. This feature was needed to achieve mass scaling between the 1/5-scale and full-scale fuselage sections. A limited number of these small accelerometers were available for this test, which explains why the 1/5-scale model fuselage section was less heavily instrumented than the full-scale test article. Test data were collected at 10-kHz sampling rate using a digital DAS that was located external to the fuselage section.

The drop test of the full-scale fuselage section was performed using the 70-ft. drop tower located at the Impact Dynamics

Research Facility. Four lifting brackets were mounted to the upper section of the fuselage, two on either side, and four cables of equal length were attached between the lifting brackets and an A-frame support on the drop tower. The fuselage section was raised to a height of 10 ft. and dropped onto a concrete surface to achieve a 25.4-fps (304.5-in/s) vertical velocity at impact.

The drop test of the 1/5-scale model fuselage section was performed using a specially constructed indoor drop tower. 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, and a support frame, which 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. Four metal brackets were attached to the 1/5-scale model fuselage section (one at the top and one on the floor of the section at both ends) to guide the section during descent and to maintain the correct impact attitude. Finally, a lifting bracket was attached to the center of the top of the fuselage section. The 1/5-scale model fuselage section was raised to a height of 10 ft. and dropped onto the concrete floor of the test facility to achieve a 25.4-fps (304.5-in/s) vertical velocity at impact. The instrumentation cables leading from the accelerometers on the fuselage floor to the external DAS were supported in a sling to prevent them from interfering with free fall of the test article and to ensure that they were not loaded in tension during the test.

Comparison of 1/5- and Full-Scale Test Results

Structural Damage Assessment

Based on post-test visual inspection, the floor and upper portion of the fuselage cabin were undamaged in both the 1/5- and full-scale drop tests. However, as shown in Figure 5, the sub-floor regions of the 1/5- and full-scale fuselage sections exhibited several failure modes. Both subfloor sections exhibited debonding of the face sheets from the foam core and fracturing or brittle failure of the foam material. In addition, the central region of the subfloor showed crushing and compaction. In general, the same failure modes were observed in both fuselage subfloor sections; however, the relative amount of damage was greater for the full-scale subfloor. It should be noted that the full-scale fuselage section was subjected to a 1.75-in. vertical drop test prior to the 10-ft. drop test, as described in References 9-11. This drop test was performed to excite the linear response of the fuselage without causing significant damage and to generate test data for correlation with a modal analysis. The subfloor crushed approximately 0.25-in. during the initial drop test. An additional 3.5-inches of subfloor crush was measured following the 10-ft. drop test for a total crush distance of 3.75 inches. For the 1/5-scale model fuselage, a maximum crush distance of 0.55-in. was measured post-test which, when multiplied by 5, gives a predicted full-scale crush distance of 2.75 inches. This value is 21% lower than the total 3.5 inches of crush attributed to the 10-ft. drop test of the full-scale section. As will be described more fully in the Discussion of Results section of the paper, it is believed that the prior 1.75-in. drop test of the full-scale fuselage section did not contribute to the differences between the 1/5- and full-scale subfloor crushing response.

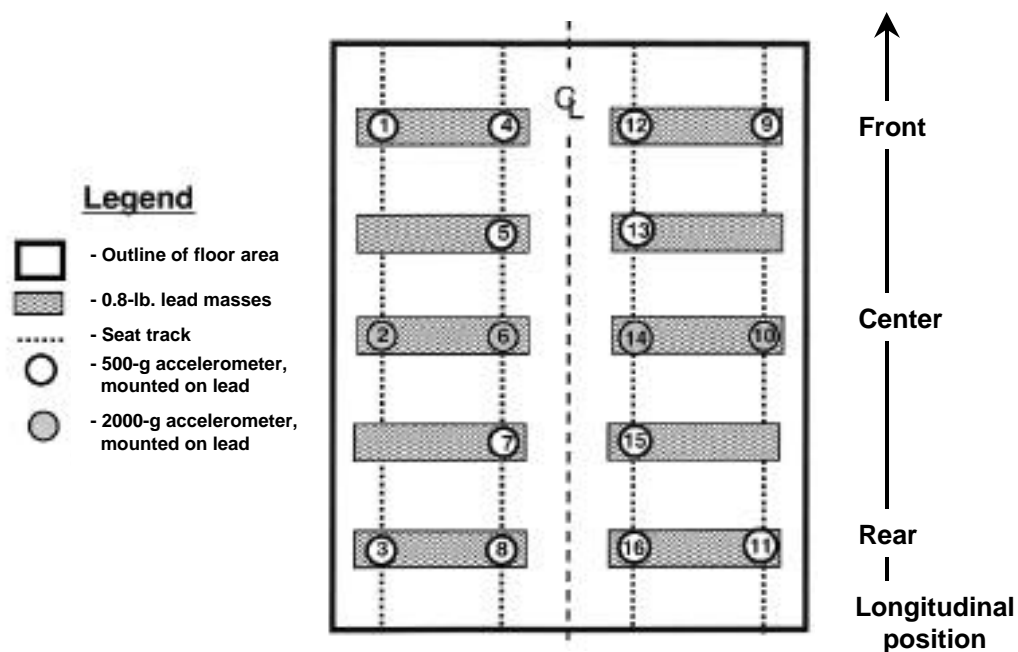


Figure 4. Instrumentation layout on the floor of the 1/5-scale model fuselage section.



(a) 1/5-scale model fuselage section.



(b) Full-scale fuselage section.

Figure 5. Post-test photographs of the subfloor regions of the two fuselage sections.

Floor-Level Acceleration Responses

Several quality checks were performed on the acceleration data obtained from the drop test of the 1/5-scale model fuselage section. The data were zeroed in time initially and inspected to ensure that $-1-g$ was recorded during free fall and that the data eventually returned to $0-g$ after impact. Also, the acceleration responses were integrated to obtain the velocity time histories. For each channel, the change in velocity, which is equal to the maximum rebound velocity minus the initial value, was calculated and compared with the known impact velocity determined from the drop height. The pulse duration was calculated for each channel, which is equal to the difference in the time of maximum rebound velocity minus the initial time. Also, average acceleration values were calculated for each of the 1/5- and full-scale acceleration responses by integrating the raw acceleration data and dividing by the pulse duration determined for each channel. In order to show the 1/5- and full-scale acceleration traces on the same plot, the data from the 1/5-scale model test were scaled up by dividing the acceleration values by 5 and by multiplying the time values by 5. Finally, the 1/5- and full-scale acceleration data were filtered using a digital low-pass zero-phase filter with a cut-off frequency of 180-Hz.

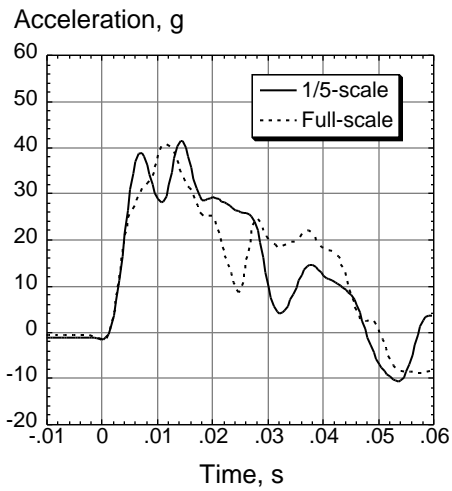
Comparisons of the filtered acceleration responses recorded by the left and right outboard accelerometers are shown in Figure 6. These plots illustrate the variations in acceleration with both lateral (left versus right) and longitudinal (front, center, and rear) position. For three of the six outboard locations, the peak accelerations of the 1/5-scale data are higher in magnitude than the full-scale

values. For the other three locations, the peak accelerations of both curves are similar. The pulse durations of the 1/5- and full-scale acceleration responses are approximately equal, with the exception of the left center outboard location (position 2) where the 1/5-scale acceleration response is longer in duration than the full-scale response by approximately 0.01 seconds. The average accelerations for these responses range from 21- to 22-g for the full-scale data and from 17- to 21.6-g for the 1/5-scale data.

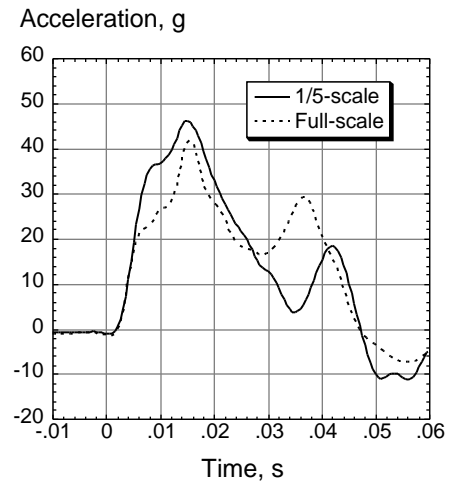
Comparisons of the filtered acceleration responses recorded by the left and right inboard accelerometers are shown in Figure 7. In general, the acceleration curves are somewhat saddle-shaped, exhibiting two peaks. For the 1/5-scale data, the first peak is higher in magnitude than the second peak. However, for six of the ten full-scale responses, the second peak is higher in magnitude than the first. For all inboard locations, the 1/5-scale responses are higher in magnitude than the full-scale values and the pulse durations are shorter. The average accelerations for the inboard responses range from 14- to 18.7-g for the full-scale data and from 14.9- to 17.7-g for the 1/5-scale data.

Floor-Level Velocity Responses

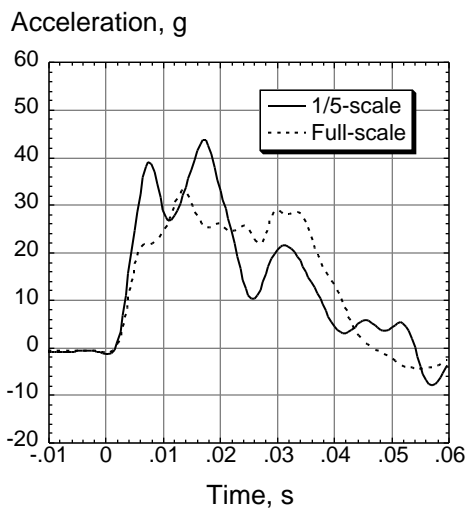
The 1/5- and full-scale velocity time histories for the left center outboard and inboard locations (positions 2 and 6, respectively) are shown in Figure 8. The velocity time histories were obtained by integrating the unfiltered acceleration data. To show the 1/5- and full-scale velocity responses on the same plot, the 1/5-scale data were scaled up by multiplying the time values by 5. The 1/5-scale velocity data were not modified since the scale factor for velocity is 1. The velocity responses shown in Figure 8 are typical of all of the inboard and outboard locations.



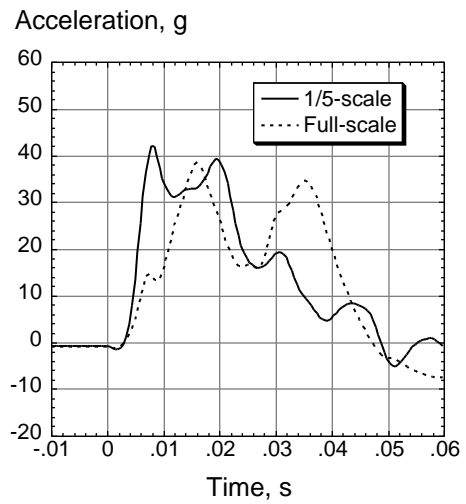
(a) Left front outboard position 1.



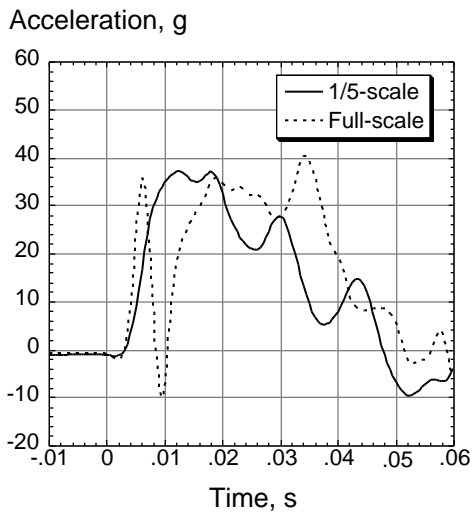
(b) Right front outboard position 9.



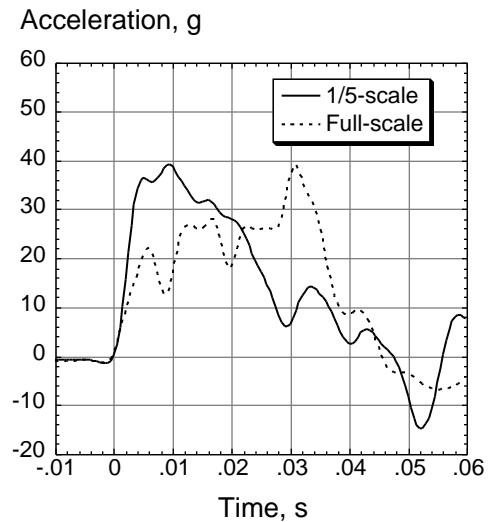
(c) Left center outboard position 2.



(d) Right center outboard position 10.

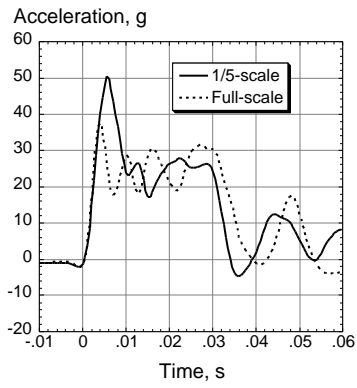


(e) Left rear outboard position 3.

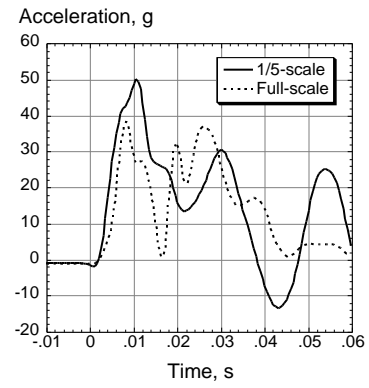


(f) Right rear outboard position 11.

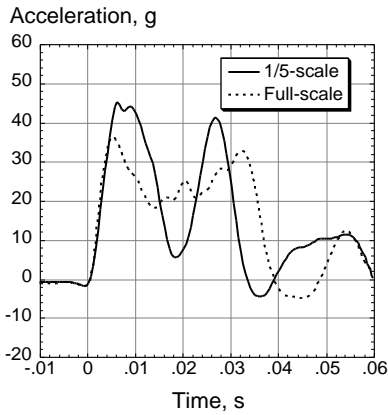
Figure 6. Comparisons of the 1/5- and full-scale left and right outboard acceleration responses.



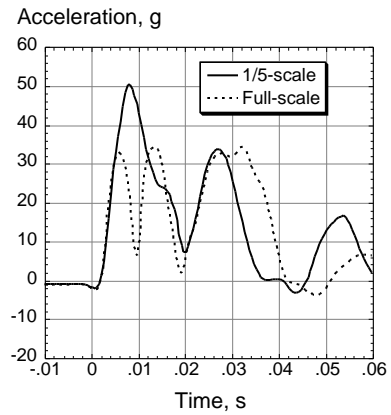
(a) Left front inboard position 4.



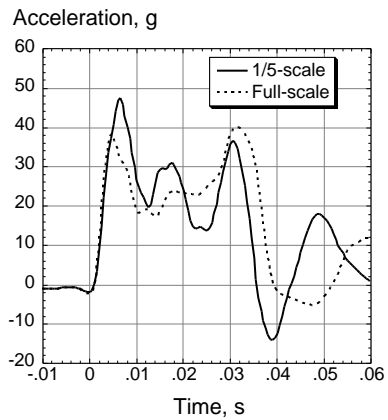
(b) Right front inboard position 12.



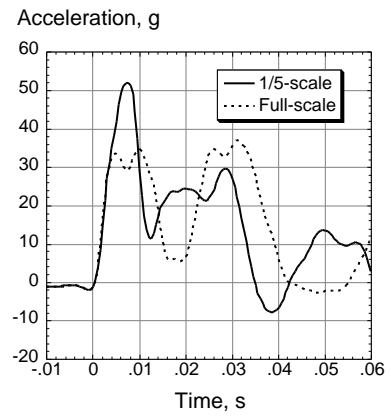
(c) Left inboard position 5.



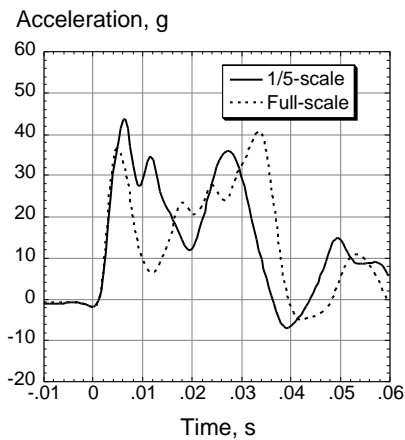
(d) Right inboard position 13.



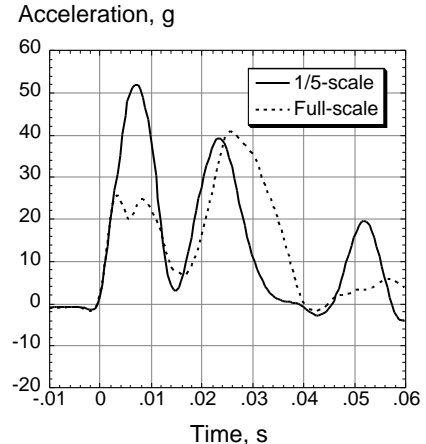
(e) Left center inboard position 6.



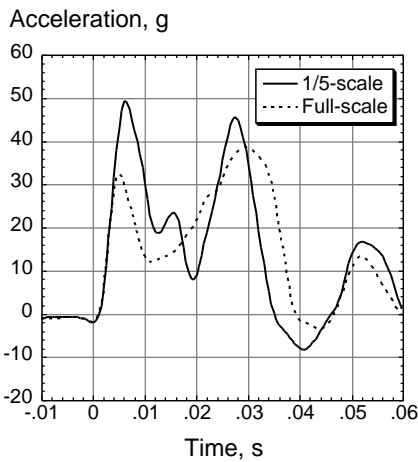
(f) Right center inboard position 14.



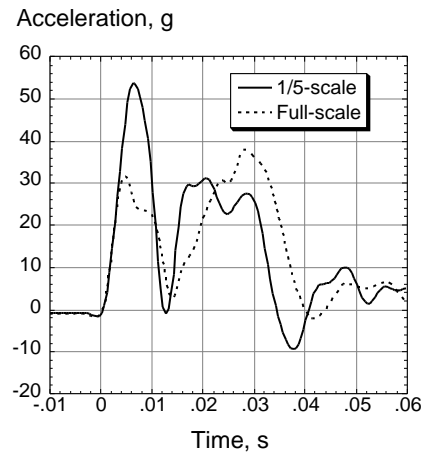
(g) Left inboard position 7.



(h) Right inboard position 15.

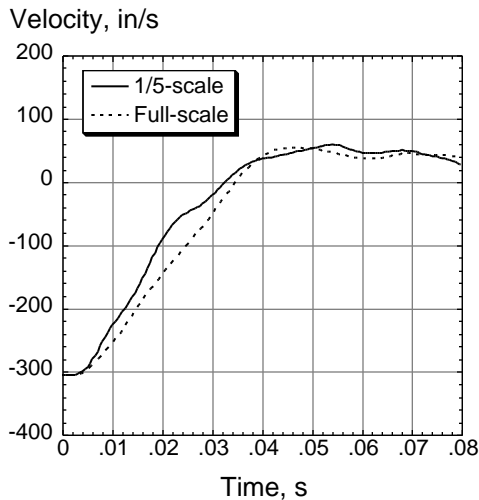


(i) Left rear inboard position 8.

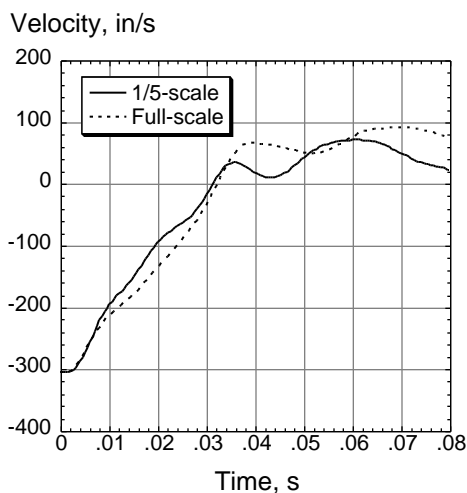


(j) Right rear inboard position 16.

Figure 7. Comparisons of filtered inboard acceleration responses.



(a) Left center outboard position 2.



(b) Left center inboard position 6.

Figure 8. Left center velocity responses from the 1/5- and full-scale impact tests.

The comparisons shown in Figure 8 indicate that velocity is removed more quickly during the 1/5-scale drop test than for the full-scale experiment. For example, at 0.02 seconds the velocity of the left center outboard location (position 2) is -145 in/s for the full-scale test and -90 in/s for the 1/5-scale model test. Also, the 1/5-scale responses cross zero velocity slightly earlier in time than do the full-scale responses. However, after crossing zero, significant differences are seen in the outboard and inboard velocity responses. At the outboard location, the velocity responses increase to a maximum rebound velocity of approximately 60 in/s and begin to drop off as time continues. Conversely, after crossing zero, the velocity responses at the inboard location exhibit two maxima with the second being higher in magnitude than the first. The maximum rebound velocities are 70 and 90-in/s for the 1/5- and full-scale responses, respectively. The time of occurrence of the maximum rebound velocity is delayed for the inboard locations, as compared with the outboard locations. This delay causes the pulse durations for the inboard channels to be approximately 20% longer than the pulse durations of the outboard channels. The differences between the inboard and outboard velocity responses are attributed to a greater upward deflection of the center of the floor as compared with the floor-wall intersection. The center region of the floor, where the inboard accelerometers are located, is more flexible than the edges, where the outboard accelerometers are located. During the design phase, the intersection region between the floor and the upper fuselage cabin was reinforced to limit deformation during internal pressurization of the fuselage section [2, 4-6].

Data Correlation Studies

Several approaches were used to quantify the correlation between the 1/5- and full-scale test data including comparisons of the average acceleration responses, the percentage differences in the velocity change and the velocity change squared, and comparisons of the correlation coefficients as a function of floor location. Each of these comparisons provides a measure of global correlation between the two sets of test data.

The average acceleration values were calculated for each of the 1/5- and full-scale acceleration responses by integrating the raw acceleration data and dividing by the pulse duration determined for each channel. These values are plotted versus floor location in Figure 9, which provides a point-to-point comparison of the 1/5- and full-scale data. Note that the floor location numbers are identified in Figures 3 and 4. The average accelerations range in magnitude from 14- to 22-g. Generally, the full-scale data show greater variation in average acceleration than do the 1/5-scale data, i.e. the full-scale average acceleration data are higher for the outboard locations (positions 1-3 and 9-11) and lower for the inboard locations (positions 4-8 and 12-16) than the corresponding 1/5-scale data. The location with the greatest difference is position 2, the right front inboard location, where the 1/5-scale average acceleration is lower than the corresponding full-scale value by 22%.

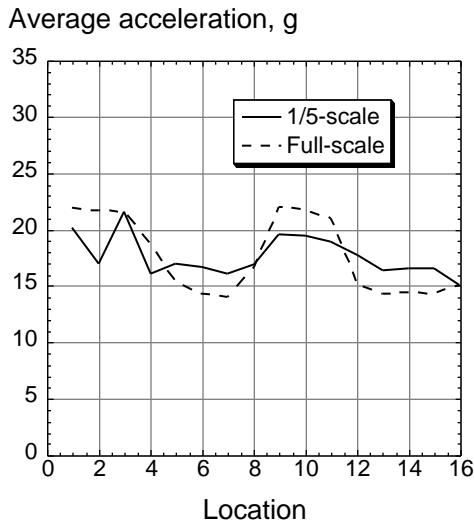
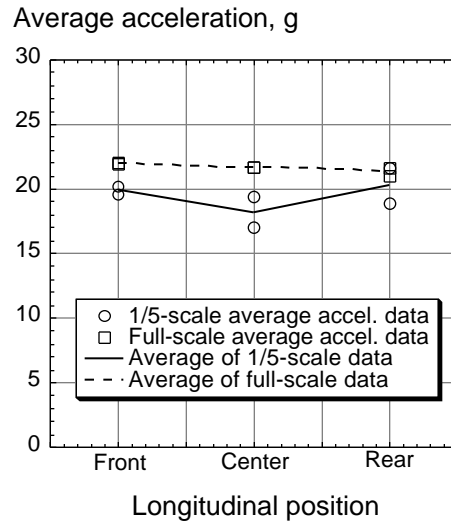


Figure 9. Comparison of average acceleration versus floor location.

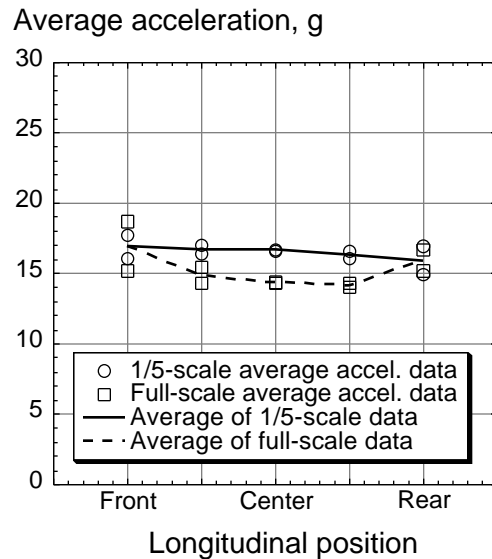
Next, the 1/5- and full-scale average acceleration data are plotted as a function of longitudinal position in Figure 10. The data are plotted separately for inboard and outboard floor locations, since the acceleration and velocity responses for these locations are quite different. The 1/5- and full-scale average acceleration data are plotted as points at each of the five longitudinal positions. Also, an average value is calculated for the 1/5- and full-scale data at each longitudinal position, which is then plotted as a line in Figure 10. The plots show the scatter in the average acceleration data as a function of longitudinal position for the 1/5- and full-scale test data.

For the outboard data shown in Figure 10 (a), the line representing the averages of the full-scale data is relatively flat, indicating that there is little variation with longitudinal position on the floor, and it is approximately 3-g higher in magnitude than the corresponding 1/5-scale data. The line representing the averages of the 1/5-scale data indicates a reduction in average acceleration in the

center of the section compared with the front and rear edges. Interestingly, for the inboard data shown in Figure 10 (b), the opposite results are found. The line representing the averages of the 1/5-scale data is relatively flat, indicating that there is little variation in average acceleration with longitudinal position on the floor. The corresponding full-scale line matches the 1/5-scale line at the front and rear longitudinal positions, but is approximately 3-g less than the 1/5-scale data in the center region of the floor. For both sets of data, the outboard average acceleration responses are higher in magnitude than the inboard responses. The differences observed in the 1/5- and full-scale average acceleration data indicate that some minor scaling anomalies are present.



(a) Outboard data.



(b) Inboard data.

Figure 10. Comparison of average acceleration data versus longitudinal position.

To further quantify the correlation between the 1/5- and full-scale test data, the change in velocity for each data channel was

calculated by integrating the acceleration response over the pulse duration to obtain a value equal to the area under the acceleration curve, which is the velocity change. Then, the velocity change is squared to obtain a number that is proportional to kinetic energy. The percentage differences between the full-scale and 1/5-scale velocity change and velocity change squared were determined for each floor location, numbered 1 through 16, and the results are plotted in Figure 11 as a function of floor location. The differences in velocity change are within $\pm 10\%$, except for one location (position 12). The differences in velocity change squared are within $\pm 20\%$, except for two locations (positions 3 and 12).

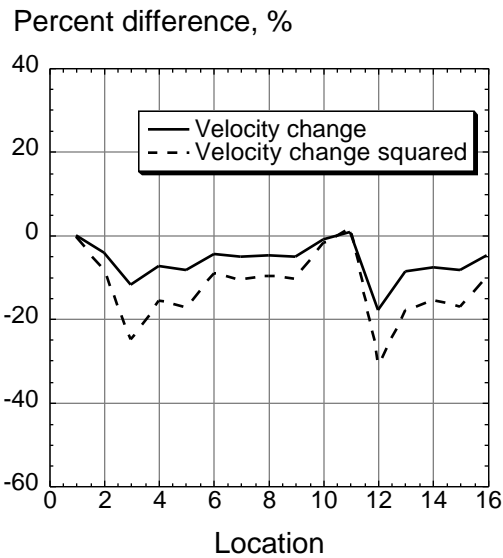


Figure 11. Percentage difference in velocity change and velocity change squared versus floor location.

A final technique used to quantify the agreement between the 1/5- and full-scale test data is to determine the correlation coefficient [12]. The correlation coefficient, R , for two acceleration responses is given by Equation 1,

$$R[f(t), g(t)] = \frac{\int_0^T f(t)g(t)dt}{\sqrt{\left\{ \int_0^T [f(t)]^2 dt \right\} \left\{ \int_0^T [g(t)]^2 dt \right\}}} \quad (1)$$

where $f(t)$ is the 1/5-scale acceleration curve, $g(t)$ is the corresponding full-scale acceleration curve, and T is the pulse duration. For perfect agreement between the two curves, the correlation coefficient would be equal to 1. The correlation coefficients calculated between the 1/5- and full-scale test data are plotted as a function of floor location in Figure 12. All of the coefficients fall in the range between 0.8 and 0.95. Thus, for this measure of correlation, the agreement between the two sets of test data is within 20%.

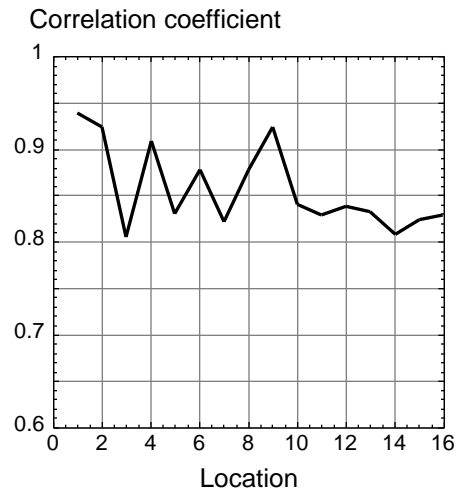


Figure 12. Correlation coefficients between the 1/5- and full-scale test data versus floor location.

To determine if the correlation coefficients calculated for the 1/5- and full-scale data are truly significant, another calculation was performed on the two sets of test data to determine the correlation coefficients for symmetric locations within the data set. Fourteen pairs of data were identified as having either lateral (side-to-side) or longitudinal (front-to-rear) symmetry. For example, considering the channel locations numbered in Figures 3 and 4, positions 1 and 3 are symmetric longitudinally and positions 1 and 9 are symmetric laterally. Correlation coefficients were determined for each of the fourteen symmetric locations in the 1/5-scale and full-scale test data. For the 1/5-scale data, the coefficients ranged from a low of 0.782 that was calculated between positions 12 and 16 and a high of 0.982 that was calculated between positions 2 and 10. For the full-scale test data, the coefficients ranged from a low of 0.803 that was calculated between positions 1 and 3 and a high of 0.984 that was calculated between positions 8 and 16. Thus, the correlation coefficients, shown in Figure 12, fall within the channel-to-channel variation for symmetric locations for both the 1/5- or full-scale drop tests.

Discussion of Results

The data comparisons and correlation studies show that the differences between the two tests are relatively small from a scaling perspective, thus indicating that the appropriate scaling procedures were used in fabricating the test specimens and in conducting the experiments. If perfect agreement had been obtained between the 1/5- and full-scale test data, then it could be said that true replica scaling was achieved and no scaling effects were present. However, the small differences in the test data indicate that some minor scaling anomalies may be present. Consequently, it is useful to examine some of the differences between the test articles and the impact conditions.

Mass Scaling

One difference between the two tests is that the empty weight of the 1/5-scale model fuselage section was 0.8-lbs. heavier than desired for ideal mass scaling. The extra weight may be attributed to excess resin in the 1/5-scale model fuselage sec-

tion that was not removed during the fabrication process. Instead of reducing the weight of the lead masses to compensate for the difference, the total amount of weight on the floor of the 1/5-scale model composite fuselage section was scaled appropriately to match the full-scale floor weight. It was considered more important to accurately scale the amount of weight on the floor, since this weight is reacted directly by the subfloor during the impact. However, one consequence of this decision was an anomaly in the mass scaling causing the 1/5-scale model fuselage section to be effectively 8% heavier than the full-scale fuselage section, i.e. the scaled weight of the fuselage section is 10.74 lb. times 125, or 1,342.5 lbs. which is 8% higher than the 1,243-lb. weight of the full-scale test article. The anomaly in mass scaling causes errors in the scaling of the potential and kinetic energy, since both are proportional to mass.

Energy scaling

Typically in a drop test, the total potential energy is equal to the drop height plus the crush distance multiplied by the weight (mass times gravity). The potential energy is converted to kinetic energy minus the total work, including dissipative work performed in crushing of the subfloor and elastic work performed in deforming the fuselage. According to the scaling procedure used for this test, the scale factor for potential energy is $1/3$, where $1/5$ is 1/5. Thus, the ratio of total potential energy for the 1/5- and full-scale fuselage drop tests should equal 125. However, since the 1/5- and full-scale fuselage sections exhibited different amounts of total crush, the scale factor for potential energy is altered. For these drop tests, the full-scale fuselage section experienced a 2.5% increase in the total potential energy relative to the 1/5-scale fuselage section. The relative increase in potential energy translates into increased kinetic energy and total work performed by the full-scale fuselage section.

Pre-Existing Damage

As mentioned previously, the full-scale fuselage section was dropped from a height of 1.75 inches prior to the 10-ft. vertical drop test. As a result of this test, a permanent subfloor crush of 0.25 inches was recorded and no other structural damage was documented. It might be supposed that this relatively minor drop test resulted in some additional damage such as micro cracks in the composite face sheets or some partial debonding of the face sheets from the foam core, which contributed to the differences seen in the relative amount of damage experienced by the 1/5- and full-scale subfloor sections during the 10-ft. drop tests. However, a second 25-ft/s vertical drop test of a newly fabricated, pristine full-scale fuselage section was performed in August of 2002 with the same loading configuration. The acceleration responses from this test were nearly identical to the ones obtained during the November 2000 drop test and the total amount of subfloor crushing was approximately the same. Consequently, the previous 1.75-in. drop had little or no influence on the 10-ft. drop test results for the full-scale fuselage section.

Impact Attitude

Another difference between the 1/5- and full-scale drop tests was the test technique. The full-scale fuselage section was supported from an A-frame on the 70-ft. drop tower. Upon impact, the fuselage section was essentially in free fall. Based on timing differences between the front and rear acceleration data, it was determined that the full-scale fuselage section actually impacted the concrete with a 1.0-degree pitch, front-end down. Conversely, the guide wires used in the drop test of the 1/5-scale model fuselage section prevented any pitching motion and the section hit perfectly flat. The 1.0-degree pitch attitude may explain why the full-scale average acceleration data, shown in Figure 10, slope slightly downward from the front to the rear.

Foam Crushing

One final difference between the 1/5- and full-scale test articles relates to the closed-cell Rohacell foam used in the construction of the energy absorbing subfloor. The Rohacell foam has a uniform density with a constant number of cells per linear inch of length. As mentioned previously, the geometric dimensions of the full-scale fuselage section were scaled by a factor of 1/5 in sizing the scale model fuselage section. However, the cell size in the Rohacell foam was not scaled. Consequently, the full-scale subfloor section contains roughly 125 times more cells than does the 1/5-scale subfloor section. Given a statistical variation in flaws, one would expect there to be more defects in the greater volume of material. Thus, the full-scale subfloor should appear weaker than the 1/5-scale model subfloor section. In fact, the full-scale subfloor crushed 21% more than the 1/5-scale subfloor, when the "scaled up" crush distance from the 1/5-scale drop test was compared with the full-scale data. The only effective means of eliminating this source of scaling anomalies would be to scale the cell size within the Rohacell foam, which is not a feasible approach at this time.

Concluding Remarks

This paper presents a comparison of test data obtained from 25-fps vertical drop tests of a 1/5- and full-scale composite fuselage section. The data comparisons are performed to assess the scaling procedure and to determine if scaling effects are present. For the full-scale drop test, the 5-ft. diameter fuselage section was configured with ten 100-lb. lead blocks attached to seat rails on the floor, five per side. For the 1/5-scale drop test, the 1-ft. diameter fuselage section was configured in a similar manner as the full-scale section, with ten 0.8-lb. lead masses attached to simulated seat rails on the floor.

Comparisons of the test data are presented including floor-level acceleration and velocity responses and an assessment of structural damage. In general, the 1/5-scale acceleration responses exhibited higher peak values and shorter pulse durations than the full-scale responses. Also, both subfloor sections exhibited the same damage modes including debonding of the face sheets away from the foam core and fracturing or brittle failure of the foam material. The central region of the subfloor showed crushing and compaction. However, the relative amount of damage was greater for the full-scale subfloor.

To further assess the test data correlation, comparisons of the average acceleration data are made as a function of floor location and longitudinal position. The average accelerations range in magnitude from 14- to 22-g. Generally, the full-scale data show greater variation in average acceleration than do the 1/5-scale data, i.e. the full-scale average acceleration data are higher for the outboard locations and lower for the inboard locations than the corresponding 1/5-scale data. Next, the percentage differences in the change in velocity and the velocity change squared are compared as a function of floor location. The differences in velocity change are within $\pm 10\%$ and the differences in velocity change squared are within $\pm 20\%$. Finally, correlation coefficients were calculated for corresponding 1/5- and full-scale data channels. These coefficients were then plotted versus floor location. The correlation coefficient for perfect agreement between two acceleration curves is 1. The correlation coefficients for the 1/5- and full-scale test data fall in the range between 0.8 and 0.95. Thus, for this measure of correlation, the agreement between the two sets of test data is within 20%.

From a scaling perspective, the differences between the 1/5- and full-scale tests are relatively small, indicating that appropriate scaling procedures were used in fabricating the test specimens and in conducting the experiments. The small differences in the scaled test data are attributed to minor scaling anomalies in mass, potential energy, and impact attitude.

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