Crash Simulation of a Vertical Drop Test of a B737 Fuselage Section With Auxiliary Fuel Tank

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ABSTRACT

A 30-ft/s vertical drop test of a fuselage section of a Boeing 737 aircraft was conducted in October of 1999 at the FAA William J. Hughes Technical Center in Atlantic City, NJ. This test was performed to evaluate the structural integrity of a conformable auxiliary fuel tank mounted beneath the floor and to determine its effect on the impact response of the airframe structure. The test data were used to compare with a finite element simulation of the fuselage structure and to gain a better understanding of the impact physics through analytical/experimental correlation. To perform this simulation, a full-scale 3-dimensional finite element model of the fuselage section was developed using the explicit, nonlinear transient-dynamic finite element code, MSC.Dytran. The emphasis of the simulation was to determine the structural deformation and floor-level acceleration responses obtained from the drop test of the B737 fuselage section with the auxiliary fuel tank.

INTRODUCTION

An important aspect of crashworthiness research is the demonstration and validation of analytical/computational tools for accurate simulation of airframe structural response to crash impacts. Analytical codes have the potential to greatly speed up the crashworthy design process, to help certify seats and aircraft to dynamic crash loads, to predict seat and occupant response to impact with the probability of injury, and to evaluate numerous crash scenarios not economically feasible with full-scale crash testing.

The US Army has been active in supporting crash modeling and simulation codes for many decades. More than 25 years ago, the US Army partially sponsored initial development of the crash analysis code, KRASH [1], by the Lockheed-California Company. KRASH employs a semi-empirical modeling approach using lumped-masses, nonlinear springs, and beam elements, to represent the airframe structure. These codes rely heavily on test data for definition of spring properties to characterize the crushing behavior of the energy absorbing structural components. Good correlation between the model and experimental data is usually obtained for global parameters. However, these codes are ineffective during the design phase where only geometry and material properties are available.

Currently, engineering workstation computational power is sufficient to allow use of a new generation of crash analysis codes to simulate the nonlinear, transient dynamic response of airframe structures in detail. These finite element codes, such as LS-DYNA [2], MSC.Dytran [3], and PAM-CRASH [4], use an explicit solver that eliminates the need to repetitively decompose large global stiffness matrices as is required for implicit codes. Explicit codes require an extremely small time step, whose duration is controlled by the smallest element in the model. A typical time step for a crash analysis would be on the order of a microsecond. Thus, impact simulations of large impact models having an acceleration pulse duration of approximately 0.1 - 0.2 seconds can require many CPU hours to solve on an engineering workstation. These codes are being used extensively to model automobile crashes. To build confidence in the application of these finite element codes to aircraft structures, it is important to demonstrate their capabilities through analytical/experimental validation.

A 30-ft/s vertical drop test of a fuselage section of a Boeing 737 aircraft was conducted in October of 1999 at the Federal Aviation Administration (FAA) Technical Center in Atlantic City, NJ [5]. This test was performed to evaluate the structural integrity of a conformable auxiliary fuel tank located beneath the floor and to determine its effect on the impact response of the airframe structure and the occupants. Such tests present an opportunity to evaluate crash simulations through analytical/experimental correlation. To perform this evaluation, a full-scale 3-dimensional finite element model of the fuselage section was developed using MSC.Dytran [2]. The MSC.Dytran code interface has been written to make the input of the code as compatible as possible with MSC.Nastran [6], a general-purpose finite element code for structural analysis that is widely used in the aerospace industry. The MSC.Patran [7] pre- and post-processing software was used with the MSC.Dytran “Preference” to build the finite element model and to post-process the results. A crash simulation was executed and predictions of the structural deformation and floor-level acceleration responses are correlated with test data obtained from the drop test of the B737 fuselage section with the auxiliary fuel tank. The anticipated outcome of the project will be an evaluation of the accuracy, fidelity, and efficiency of explicit finite element crash modeling for predicting the detailed impact response of transport airframe structures.

EXPERIMENTAL PROGRAM

A vertical drop test of a B737 fuselage section with an auxiliary fuel tank was conducted at the Dynamic Drop Test Facility located at the FAA William J. Hughes Technical Center in Atlantic City, New Jersey. The test article is a 10-foot section of a

Boeing 737-200 airplane from fuselage stations (FS) 400 to 500A (520). A pre-test photograph of the B737 fuselage section with the auxiliary fuel tank is shown in Figure 1. The fuselage was configured with six triple-occupant passenger seats. The middle position of each seat contained an instrumented anthropomorphic dummy, and the remaining seats contained mannequins, each weighing approximately 165-lbs.

A conformable auxiliary fuel tank was filled with 404-gallons of water and mounted beneath the floor of the fuselage section. The fully instrumented fuselage section weighed 8,780-lbs including the 3,740 pound fuel tank. The outer floor beams at each end of the test section were reinforced to minimize open-end effects. Several features of the fuselage configuration are important to note for the model development due to the fact that they affect model symmetry and overall stiffness. The section contained a cargo door and associated stiffened structure located on the lower right side of the fuselage, as shown in Figure 2. Also, the fuel tank was not centered beneath the floor, but was located closer to the rear of the fuselage section.

The fuselage section was instrumented with accelerometers placed on the seat rails and side-walls of the fuselage section. In total, approximately 120-channels of data were collected at 10,000 samples/second during the impact test.

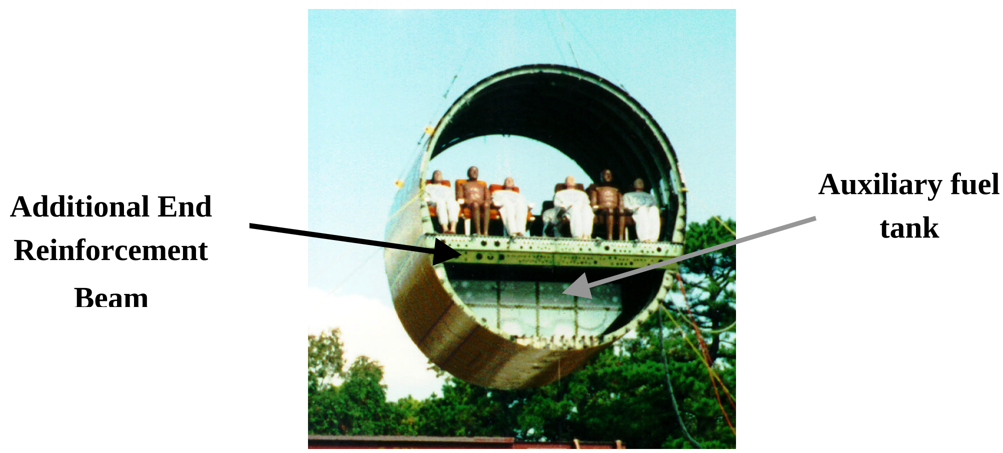


Figure 1. Pre-test photograph of the B737 fuselage section with auxiliary fuel tank.

The fuselage section was raised to a height of 14-ft. and dropped vertically to achieve a 30-ft/s velocity at impact. Floor-level acceleration data in the vertical direction were integrated to obtain the vertical velocity change. Any channel in which the integrated velocity change was not comparable with the impact velocity plus rebound was not used for correlation with the analysis. In general, the floor-level acceleration traces contained high amplitude, high frequency oscillations. Consequently, prior to correlation with the analytical data, selected acceleration responses were filtered using a 60-Hz 2-

pole low-pass digital filter to remove the high frequency ringing from the underlying crash pulse. It is also noted that accelerometers located on the floor directly above the fuel tank were not used for analytical correlation.

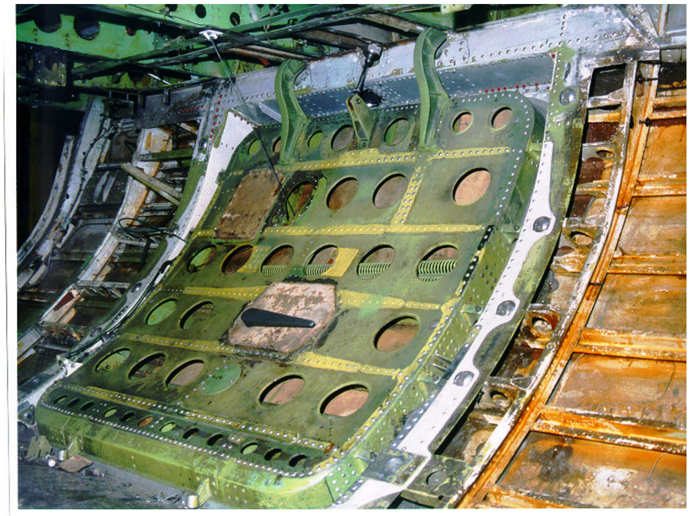


Figure 2. Photograph of the cargo door located on the lower right side of the fuselage section (FS 440 to 490, approximately).

A post-test photograph of the fuselage section is shown in Figure 3. Damage to the fuselage section consisted of severe yielding and fracture of the lower fuselage frames and wrinkling of the skin on the lower left side of the fuselage section. The deformation of the lower fuselage was asymmetric about the centerline due to the presence of the door and associated stiffeners located on the lower right-hand side of the fuselage. On the left-hand side, a second damage site developed with fracture of fuselage frames. Similar damage is not seen on the right-hand side of the fuselage. The auxiliary fuel tank was punctured, which allowed post-test leakage.

B737 FUSELAGE SECTION MODEL DEVELOPMENT

Geometric measurements were obtained from a pre-test B737 fuselage section at the FAA Technical Center. The model geometry was developed from these detailed measurements, since engineering drawings of the fuselage section and fuel tank were not available. Many simplifying assumptions were made to keep the geometry as simple as possible. For example, many cut-outs, joints, fasteners, and doublers were ignored. Development of the model was performed using the pre-processing software package, MSC.Patran. The geometric model was discretized, element and material properties were assigned, contact was defined between the tank and the surrounding structure, and initial conditions were input. Two views of the finite element model of the fuselage section are shown in Figure 4.

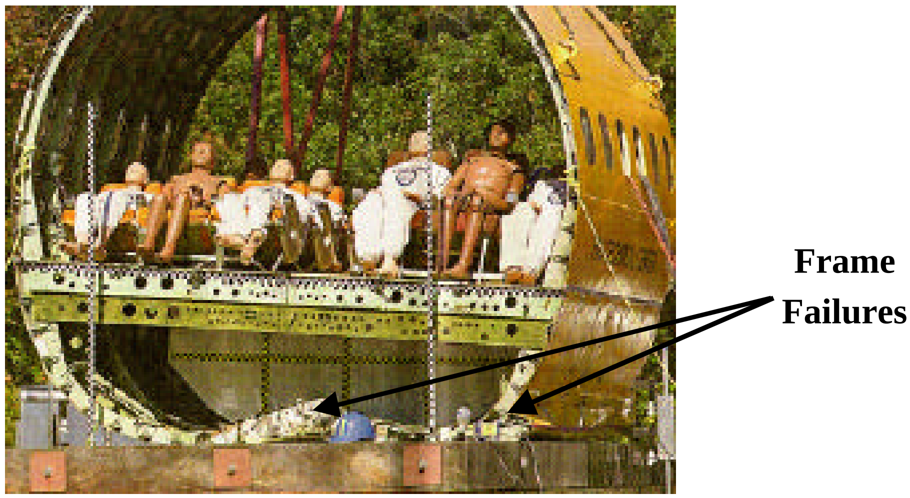


Figure 3. Post-test photograph of B737 fuselage section.

The MSC.Dytran model consists of approximately 9,600 nodes and 13,000 elements, including 9,000 shell and 4,000 beam elements. In addition to the outer skin, fuselage frames, and floor; the model contains the longitudinal stringers, the fore and aft floor reinforcements, and the auxiliary fuel tank with attachments. In addition, the lower right-side door was modeled, including its associated stiffened structure. Cutouts in the fuselage skin were used to represent the windows on both sides of section and the stiffened structure surrounding the windows was modeled using beam elements. The outer surface of the fuel tank was modeled using shell elements and the thickness of these elements was adjusted such that the total weight of the tank was 370-lbs, matching the experimental weight.

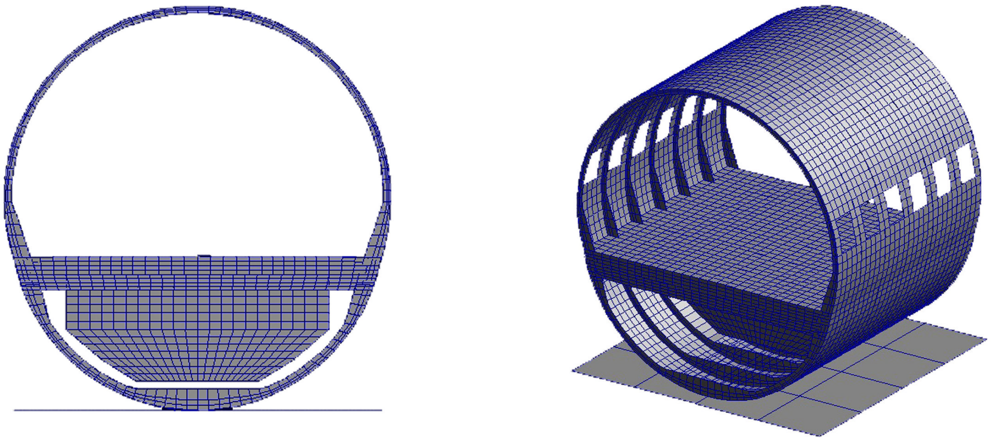
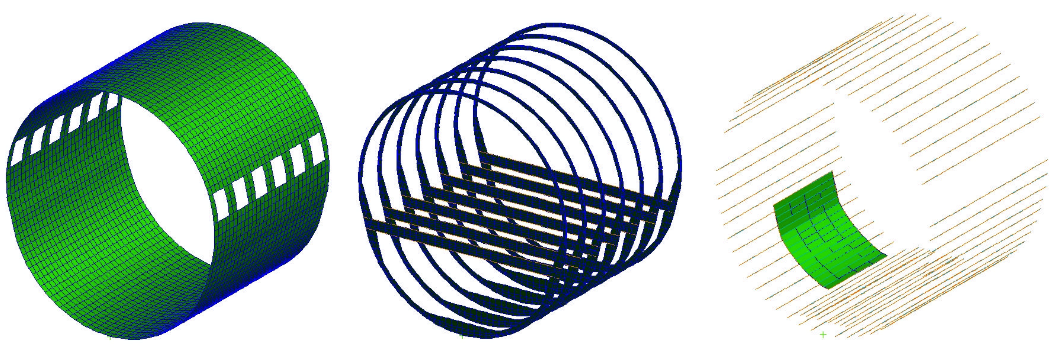
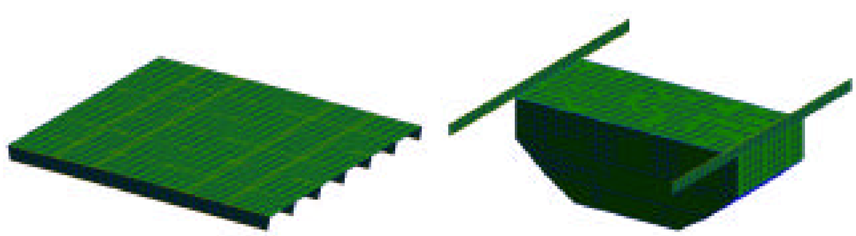


Figure 4. Model of the B737 fuselage section with an auxiliary fuel tank.

Concentrated masses were placed inside the fuel tank to represent the 404-gallons of water. A flat impact surface was added to the model. Some of the individual components of the model are shown in Figure 5, including the outer skin, fuselage frames, and auxiliary fuel tank. Beam elements are difficult to distinguish from the shell elements as they are represented as straight lines in Figure 5.



(a) Outer skin. (b) Frames and floor beams. (c) Door and stringer beams



(d) Floor and floor beams. (e) Auxiliary fuel tank and support beams.

Figure 5. Components of the MSC.Dytran model of the B737 fuselage section.

A master-surface to slave-node contact was defined between the impact surface and the nodes forming the lower portion of the fuselage section. Two other contacts were defined, one between the fuel tank and the lower cargo floor and the other between the top of the fuel tank and the passenger floor.

Most of the primary structure was assumed to be either 2024-T3 or 7075-T6 aluminum. The material formulation chosen for the model, DMATEP, is a general-purpose isotropic bilinear elastic-plastic material property with yielding and ultimate failure strain. The yield of 2024-T3 was assumed to be 47,000 psi, while the yield of 7075-T6 was assumed to be 60,000 psi. The yield on the 7075-T6 was lowered from handbook values (73,000 psi) to partially account for stress risers, fatigue, size effects, and corrosion. A failure strain of 5 percent was assigned to the 7075-T6 aluminum based on experience obtained from earlier modeling of a Boeing 720 section [8]. The entire fuselage model weighed 8800 lbs., which is close to the 8,870 lbs. weight of the fully-instrumented test article. Seats and dummies were not modeled; but the mass of the seats and dummies were accounted for as concentrated masses located at each seat leg-seat track location on the floor.

All nodes in the model, except those forming the impact surface, were assigned an initial velocity of 360 in/s. The model was executed for 0.1 seconds (100 milliseconds) which required about 24 hours on a Sun Ultra 450 workstation computer. The time step for the solution was approximately two microseconds. The requested output included deformed geometry and acceleration, velocity, and displacement time histories for several nodes whose positions correspond to the locations of selected accelerometers.

ANALYTICAL AND EXPERIMENTAL CORRELATION

An analysis of the data led the FAA Technical Center personnel [5] to conclude that the auxiliary fuel tank came loose from the mounting track shortly after impact. Consequently, the model was changed to allow the tank to move freely within the cargo hold, and additional contact surfaces were defined to prevent penetration of the tank through the surrounding structure. A portion of the predicted contact force between the tank and the surrounding fuselage structure is plotted in Figure 6. The plot indicates that the tank initially contacted the lower cargo floor at approximately 10 ms after impact and contacted the upper floor beams slightly before 50 ms. These time values closely correspond with the values measured experimentally as reported in Reference [5]. The accurate simulation of the tank behavior is critical to achieving good prediction of the fuselage response. The fact that the tank was not constrained by the support beams adds even more complexity to the simulation. The tank is shown in Figure 7 intruding into the two floor beams located at fuselage stations FS460 and 480 at time 70 ms. This intrusion caused failure of the beams and damaged the integrity of the floor.

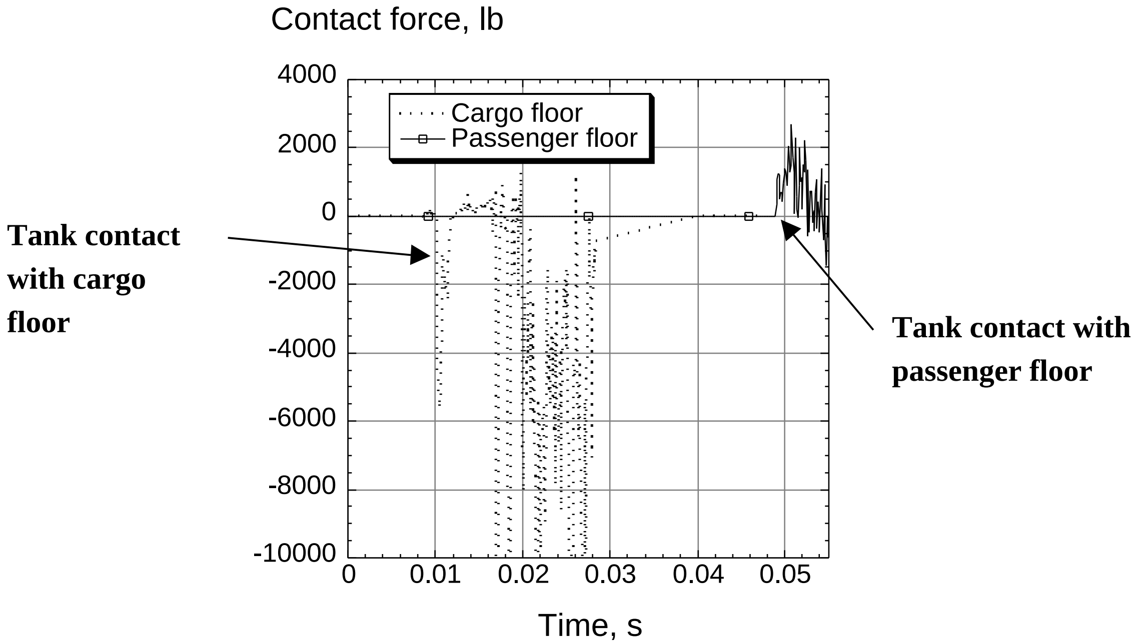


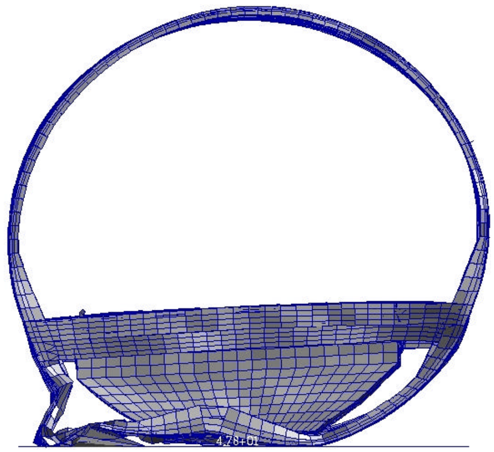
Figure 6. Contact for tank into cargo floor (10ms) and passenger floor (50ms).

Figure 7. Tank intrusion into the floor beams (FS460 and 480) at time 70 ms.

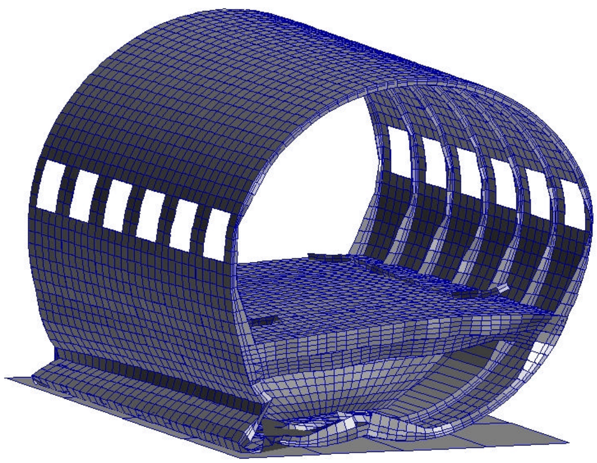
Deformed plots of the front and rear of the fuselage section are compared with pictures and high-speed video in Figures 8 and 9, respectively. The plots show that the observed deformation pattern of the fuselage is closely captured by the simulation results.

Comparisons of the predicted and experimental velocity response for the left and right edges of the fuselage floor are illustrated in Figure 10. The experimental velocity was obtained from integration of the corresponding acceleration traces. The comparison between data and analysis is good and shows the correct trends. Though noisy, the analytical velocity was not filtered since filtering would shift the initial and final velocity values. The results shown in Figure 10 verify that the right side floor velocity goes to zero sooner than the left side, due to the stiff cargo door and frame.

a. Rear view picture post–test.



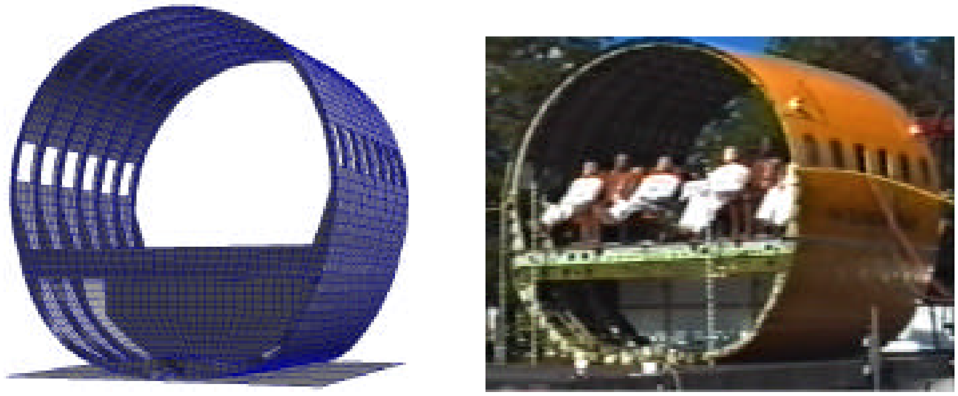
b. Analysis rear view at time 70 ms.



c. Analysis rear view at time 100 ms.

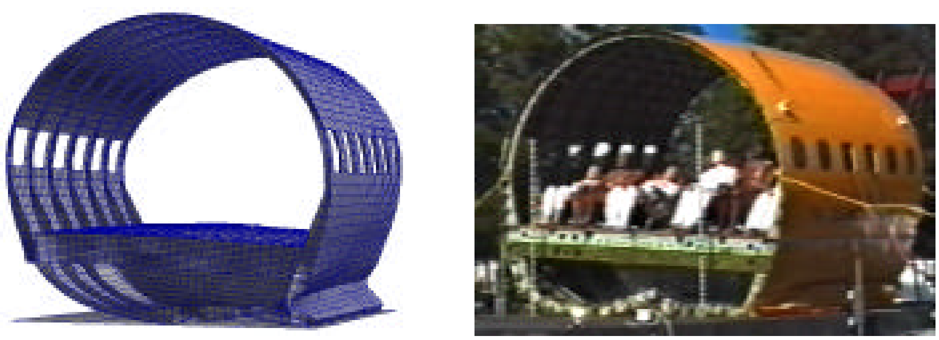
Figure 8. Post-test rear view of test article compared with the analysis.

The deformation measured at the floor level is asymmetric from left-to-right, due to the stiff door structure on the right side, and asymmetric front-to-rear due to the placement of the tank. The maximum predicted deformation for the left side was 24 inches on the front and 21 inches on the aft, compared to 21.7 and 20.7 inches measured experimentally post-test. The maximum right side deformation was predicted to be 18 inches on the front and 16 inches on the aft, compared with the post-test measured values



a. Font view at time = .02 seconds.

b. Front view at time = .06 seconds.



c. Front view at time = .10 seconds.

Figure 9. Front views of the drop test compared with analysis.

of 10.7 and 10.5 inches, respectively. Note that the post-test measurements were taken at rest, while the predicted values are the maximum dynamic values that occur near 100 ms. The maximum predicted deformations should be larger than the equilibrium post-test deformations. As the stored elastic energy at maximum deformation is released, the deformed fuselage "springs back", especially the subfloor region on the right side of the fuselage (with the strong cargo door) where less failures of the frames occurred.

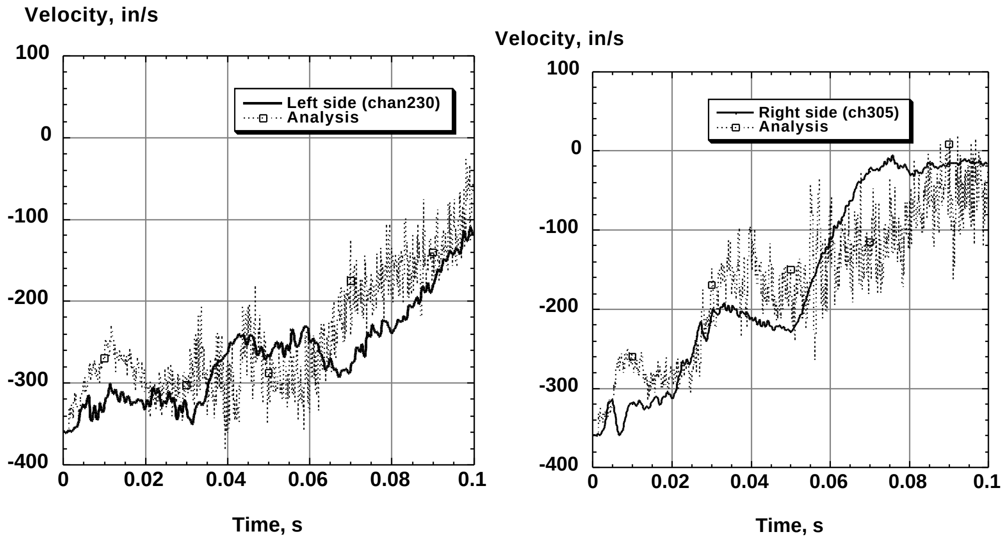


Figure 10. Left and right side measured floor velocity compared with analysis.

The acceleration responses on the left and right side of the fuselage floor are shown in Figure 11. All acceleration data were filtered with a 60 Hz 2-pole low-pass digital filter. The filtering was performed forward in time, then backward in time to eliminate phase shifts. As a result, the actual cut-off frequency of the filter is 48-Hz. The predicted peak acceleration of 33 g's on the right side of the floor is comparable to the peak experimental acceleration of 36 g's. The right side acceleration follows the experimental trend reasonably well; whereas, the left side acceleration is not as well simulated due to the complex failure of the frames in that region. The maximum acceleration predicted for the left side floor is 30 g's, which is slightly higher than the measured peak value of 26 g's. Acceleration comparisons for other locations on the floor are shown in Figures 12 through 14 for the right rear seat track, the right front seat track, and the left front seat track. Typically, peak accelerations compare within 10 to 20 percent; however, some time shift is seen in most of the traces.

Several factors may have influenced the accuracy of the simulation. As mentioned previously, many approximations were made in defining the geometry of the fuselage section, and in estimating the material properties for the fuselage structure and the fuel tank. Because the seats and dummies were represented in the model using concentrated masses applied to nodes on the floor, the failure of the seats on the right-hand side of the fuselage floor could not be simulated. Consequently, the change in floor loading due to the seat failure was not captured in the model. The accurate simulation of the fuel tank proved to be one of the most difficult challenges. In the test, the auxiliary fuel tank broke loose from the mounting brackets shortly after impact. Also, even though MSC.Dytran has the capability to model fluid-structure interaction problems, a simpler approach was taken to represent the water in the fuel tank by using concentrated masses. The more complicated fluid-structure interaction model (coupled Eulerian-Lagrangian) would be necessary to accurately model the dynamics and failure of the fuel tank. Considering the complexity of the problem due to the dynamics of the fuel tank and the number of approximations made in the model development, the crash simulation performed well in predicting the outcome of the test.

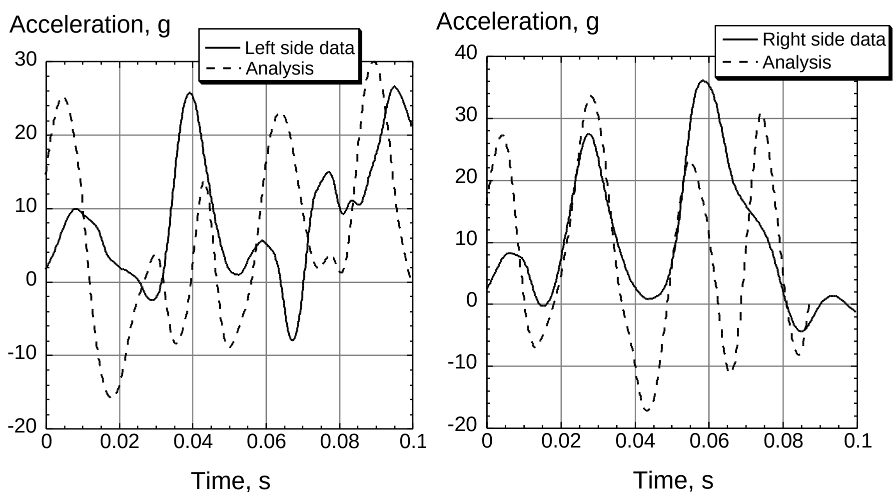


Figure 11. Left and right side floor accelerations compared with analysis.

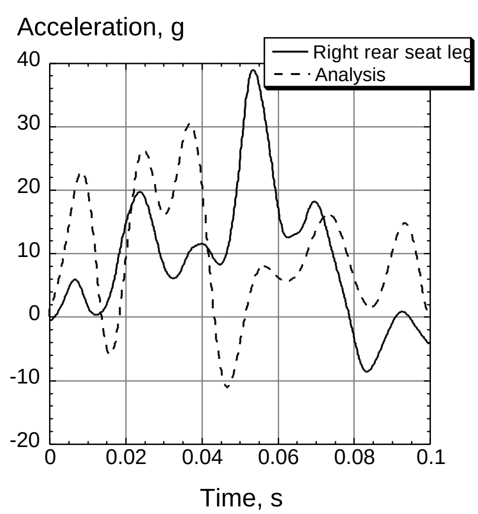


Figure 12. Comparison of measured floor acceleration at right rear seat (right rear leg) with analysis.

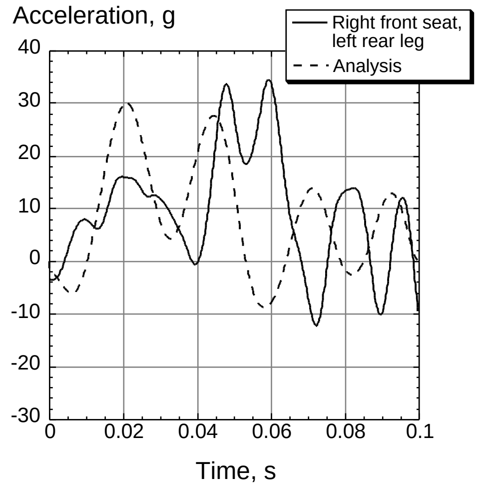


Figure 13. Comparison of measured floor acceleration at right front seat (left rear leg) with analysis.

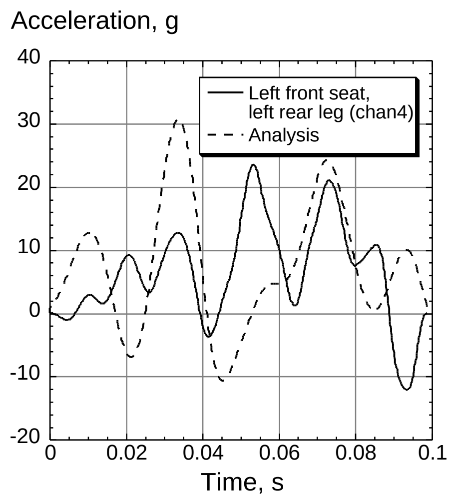


Figure 14. Comparison of measured floor acceleration at left front seat (left rear leg) with analysis.

CONCLUDING REMARKS

The correlation between the analytical predictions from the MSC.Dytran crash simulation and the experimental results from the vertical drop test of a B737 fuselage section shows that the simulation accurately predicted the sequence of events including the time of contact between the tank and the cargo and passenger floors. The predicted velocities for the left and right sides of the floor closely matched the experimental data. The predicted buckling of the left side of the fuselage and the failures of the bulkhead frames in the center and on the right side were nearly identical to the observed deformations and failures. Also, the predicted peak values of floor accelerations were typically within 10 to 20 percent of the experimentally measured values. Considering the complexity of this problem due to the presence of the fuel tank and the number of approximations made in the model development, including the fuselage geometry and material properties, the model performed well in predicting the outcome of the test. The degree of analytical and experimental correlation obtained for this simulation illustrates the potential of transient dynamic finite element modeling as a predictive tool for aircraft crashworthiness.

ACKNOWLEDGEMENTS

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