Crash Simulation of a Vertical Drop Test of a B737 Fuselage Section with Overhead Bins and Luggage

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ABSTRACT

This paper describes a transient dynamic crash simulation of a 30-ft/s vertical drop test of a Boeing 737 (B737) fuselage section. The drop test of the 10-ft. long fuselage section of a B737 aircraft was conducted in November of 2000 at the FAA Technical Center in Atlantic City, NJ. The fuselage section was outfitted with two different commercial overhead stowage bins and six triple-occupant passenger seats with mannequins and anthropomorphic test dummies. In addition, 3,229-lbs. of luggage were packed in the cargo hold to represent a maximum take-off weight condition. The main objective of the test was to evaluate the dynamic response of the overhead stowage bins in a narrow-body transport fuselage section when subjected to a severe, but survivable, impact. A secondary objective of the test was to generate experimental data for correlation with the crash simulation. A full-scale 3-dimensional finite element model of the fuselage section was developed and a crash simulation was conducted using the explicit, nonlinear transient dynamic code, MSC.Dytran. Pre-test predictions of the fuselage and overhead bin responses were generated for correlation with the drop test data. A description of the finite element model and an assessment of the analytical/experimental correlation are presented. In addition, suggestions for modifications to the model to improve correlation are proposed.

INTRODUCTION

An important aspect of crashworthiness research is the demonstration and validation of computational tools for accurate simulation of airframe structural response to crash impacts. In fact, the "validation of numerical simulations" was identified as one of five key technology shortfalls during the Workshop on Computational Methods for Crashworthiness [1] that was held at NASA Langley Research Center in 1992. 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.

Currently, engineering workstation computation 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 MSC.Dytran [2], 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, typically less than a microsecond, whose duration is controlled by the smallest element in the model. Thus, impact simulations of large models having a pulse duration on the order of 30-40 milliseconds can require several CPU hours to solve on an engineering workstation. Presently, 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 computational capabilities through analytical/experimental validation.

The Crashworthiness Program at the FAA William J. Hughes Technical Center obtained two fuselage sections of a narrow body transport category B737 airplane. This airplane is subject to Part 25 of the Federal Aviation Regulations. The interior paneling was removed from both fuselage sections, exposing the internal skeletal structure. In October of 1999, the FAA conducted a vertical drop test of a 10-ft. long B737 fuselage section with a conformable auxiliary fuel tank mounted beneath the floor. The purpose of the test was to evaluate the structural integrity of the auxiliary fuel tank, its fuel containment characteristics, and its effect on the structural response of the fuselage section [3]. A 30-ft/s vertical drop test of the second fuselage section was conducted in November of 2000. For this test, the fuselage section was outfitted with two different overhead stowage bins. Instead of the auxiliary fuel tank, luggage was placed beneath the floor in the cargo hold. This test was conducted to evaluate the structural response of the overhead bins during a severe, but potentially survivable, impact.

These tests provide an invaluable opportunity to evaluate the capabilities of computational tools for crash simulation 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. For the initial simulation, the model was configured to represent the B737 fuselage section with the auxiliary fuel tank. The results of this simulation are provided in Reference 4. For the second crash simulation, the model was reconfigured to represent the B737 fuselage section with overhead bins and luggage and pre-test predictions were generated for correlation with the test data. The importance of correlating pre-test simulation results with test data is to build confidence in the use of explicit nonlinear transient dynamic codes as a design evaluation and aircraft certification tool. It is hoped that, in the future, crash simulations such as the one presented in this paper will reduce the need for expensive full-scale drop testing to verify airframe crashworthiness.

MSC.Dytran is a general-purpose finite element code for simulating highly nonlinear transient response of solids, structures, and fluids. The code has the capability of simulating fluid-structure interactions using an Eulerian-Lagrangian coupling technique. The MSC.Dytran code interface has been written to make the input of the code as compatible as possible with MSC.Nastran [5], a general-purpose finite element code that is commonly used in the aerospace industry for structural analysis. The MSC.Patran [6] pre- and post-processing software was used with the MSC.Dytran “Preference” to build the finite element model and to post-process the results. The compatibility between MSC.Dytran, MSC.Patran, and MSC.Nastran is an added benefit that may eliminate the need for developing a separate airframe model specifically for performing a crash analysis.

This report describes the development of the finite element model, the correlation between the pre-test predictions and test data from the November 2000 vertical drop test of the B737 fuselage section with overhead bins and luggage, and an assessment of model accuracy including suggestions for modifications to the model to improve correlation.

EXPERIMENTAL PROGRAM

The test article is a 10-foot section of a Boeing 737-100 airplane from fuselage stations (FS) 380 to 500. In addition to the overhead stowage bins, 3,229-lbs. of luggage were packed in the cargo hold to represent a maximum take-off weight condition. The passenger cabin was outfitted with 6 triple-occupant passenger seats. An instrumented Hybrid II anthropomorphic dummy was placed in the center position of each seat, while the remaining seats contained non-instrumented mannequins. An additional floor beam was mounted to each end of the fuselage section to minimize the open-end effects. Two large camera mounts, each weighing 70 lbs., were attached to the upper fuselage frames; and two cameras, each weighing 22-lbs., were secured to each mount to record the response of the overhead bins. The total weight of the fully instrumented B737 fuselage section was 8,870 lbs. A pre-test photograph of the fuselage section is shown in Figure 1.

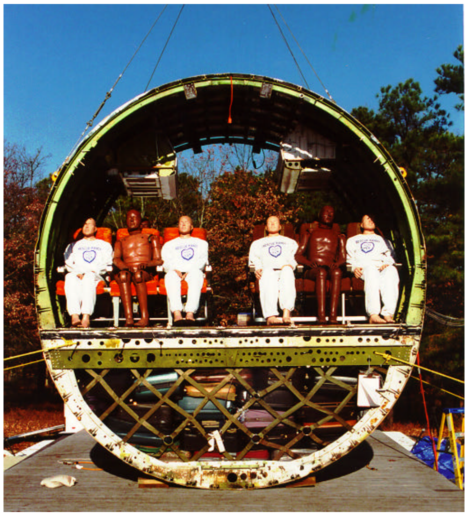


Figure 1. Pre-test photograph of the B727 fuselage section with overhead bins and luggage.

The test article was outfitted with two commercial overhead stowage bins mounted in the passenger cabin. A 60-inch Hitco bin was mounted on the left side of the cabin between FS 429 and FS 489. A 60-inch Heath Tecna bin was mounted on the right side of the cabin between FS 426 and FS 486. The overhead bins were loaded by installing 200-lbs. of plywood in the Hitco bin and 120-lbs. of plywood in the Heath Tecna bin, corresponding to the maximum weights specified for each bin. The plywood was installed in the bins to achieve a uniformly distributed mass loading. Each bin was instrumented with five accelerometers. Tri-axial accelerometers were mounted to the bottom of each bin and two vertical accelerometers were mounted to the center of the ends of each bin. In addition, the support linkages and brackets were heavily instrumented with strain gages that were calibrated to provide axial loads.

The fuselage section was instrumented with vertical and tri-axial accelerometers placed on the left and right seat rails and vertical accelerometers mounted to the upper and lower sidewalls. The six anthropomorphic dummies were instrumented with lumbar accelerometers and load cells. In addition, the impact platform at the FAA's Dynamic Drop Test Facility was instrumented with 12 accelerometers, 12 load cells, and 13 string pots located beneath the platform. The fuselage section was raised through its center of gravity to a height of 14-ft., and was dropped vertically to achieve a 30-ft/s velocity at impact. Approximately 140-channels of data were collected at 10,000 samples/second during the impact test using a digital data acquisition system.

A post-test photograph of the fuselage section is shown in Figure 2. Damage consisted of 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 cargo door and its associated stiffened structure located on the lower right-hand side of the fuselage. On the left-hand side, a second damage site developed with fracture of the fuselage frames. All seats on the right side of the fuselage floor failed during the test. However, no failure of the overhead bin support brackets or linkages occurred. It is apparent that the luggage prevented the formation of the large plastic hinge that is typically observed upon impact of transport fuselage sections, and resulted in the deformation pattern of the lower fuselage shown in Figure 2.

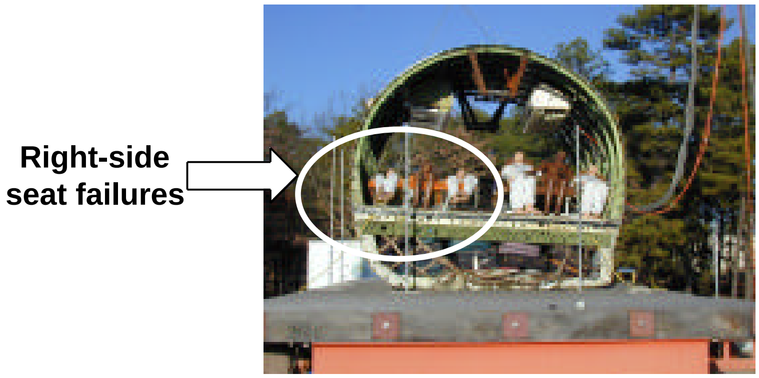
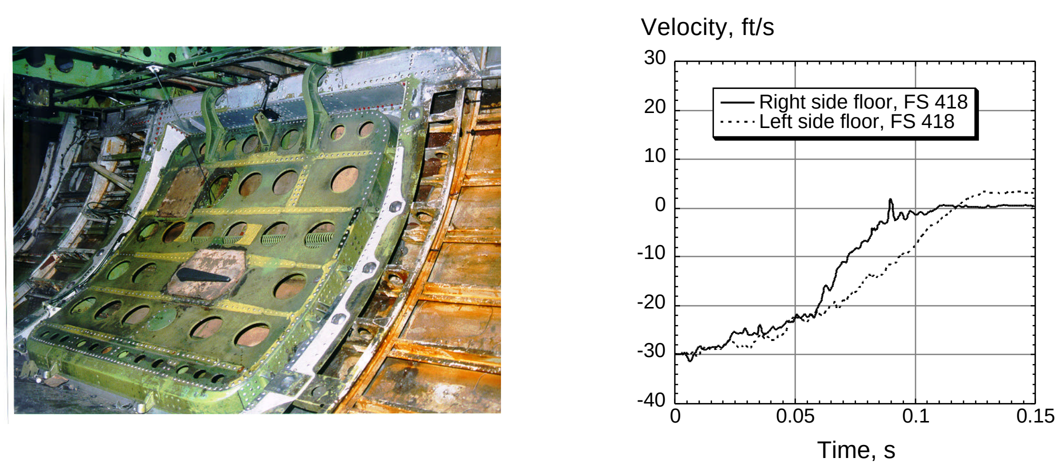


Figure 2. Post-test photograph of the B737 fuselage section with overhead bins and luggage.

An important factor in the fuselage configuration is the asymmetry due to the door located on the lower right side of the fuselage section, shown in Figure 3(a). To determine the effect of the door for this drop test, the acceleration traces obtained from two accelerometers located on the right outer and left outer seat tracks at FS 418 were integrated to obtain the velocity change versus time, as shown in Figure 3(b). This plot indicates that until about 0.06 seconds, the two responses are nearly the same. After that time, the velocity on the right side is being removed somewhat more quickly than on the left side. The right- and left-side velocity responses have stopped (crossed zero velocity) by 0.11 and 0.12 seconds, respectively. These results indicate that the influence of the door on the fuselage response has been mitigated somewhat by the presence of the luggage in the cargo hold.



(a) Photograph of the door. (b) Floor-level velocity versus time responses.

Figure 3. Asymmetry due to the door and its effect on floor-level velocity response.

B737 FUSELAGE SECTION MODEL DEVELOPMENT

Model of the Fuselage Section

The model geometry was developed from detailed geometric measurements made of the test article, since engineering or technical drawings of the fuselage section were not available. Several assumptions were made to keep the geometry as simple as possible. For example, many of the cutouts, joints, fasteners, and doublers were ignored. Development of the model was performed using the pre-processing software package, MSC.Patran [6]. A geometric model of the fuselage section was developed containing the important structural features of the airframe. The geometric model was discretized, and element and material properties were assigned. The complete finite element model of the B737 fuselage section with overhead bins is shown in Figure 4. Components of the model including the outer skin, fuselage frames, floor, longitudinal stringers, and the fore and aft floor reinforcements are shown in Figure 5. 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 the section, and the stiffened structure surrounding the windows was modeled using beam elements.

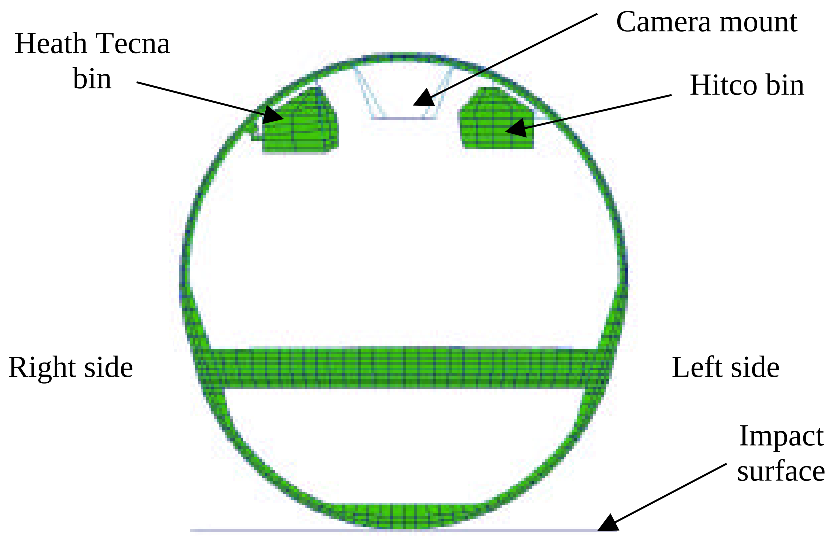
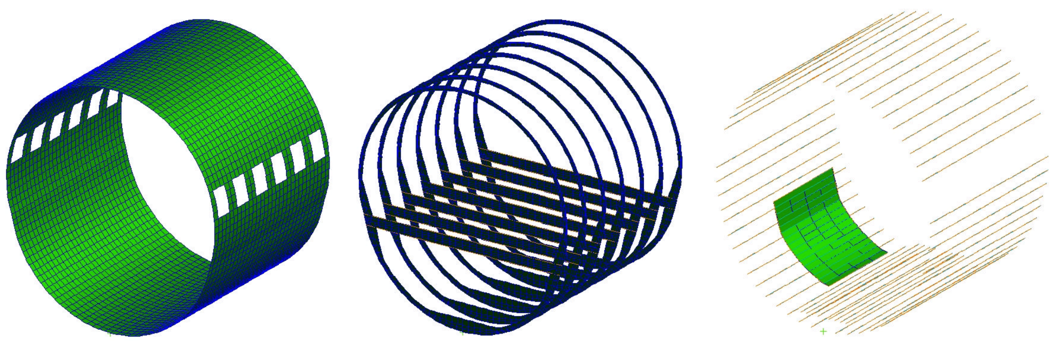


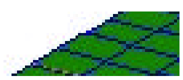
Figure 4. Front view of the model of the B737 fuselage section with overhead bins.

The B737 fuselage section model contains 9,759 nodes and 13,638 elements, including 9,322 shell and 4,316 beam elements, and 250 concentrated masses. 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 additional contact surfaces were defined between the fuselage structure and the Heath Tecna and Hitco bins. These contact surfaces were defined to prevent the bins from passing through the fuselage during impact. As shown in Figure 4, the camera mounts were included in the model and the inertial properties of the cameras were represented using concentrated masses. The seats and dummies were not modeled; however, their combined mass was accounted for as 24 concentrated masses that were assigned to nodes located at each seat leg-seat track position on the floor. All nodes in the model, except those forming the impact surface, were assigned an initial vertical velocity of 30 ft/s.

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 stress of 2024-T3 was assumed to be approximately 47,000 psi, while the yield stress of 7075-T6 was assumed to be 60,000 psi. The yield stress of the 7075-T6 aluminum was lowered from handbook values (73,000 psi) to partially account for stress risers, fatigue damage, size effects, and corrosion. A failure strain of 5 percent was assigned to the 7075-T6 aluminum based on experience gained during an earlier project involving simulation of a Boeing 720 fuselage section drop test [7]. A list of material properties used in the model is provided in Table 1.



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



(d) Floor and floor beams.

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

Table 1. Material properties used in the MSC.Dytran model of the B737 fuselage section with overhead bins and luggage.

Material name	Material type	Young's modulus, psi	Density, lb-s^2/in^4	Poisson's ratio	Yield stress, psi
Aluminum 2024-T3	DMATEP	1.06e07	.0002525	.33	47,000
Aluminum 7075-T6	DMATEP	1.04e07	.0002525	.33	60,000
Heath Tecna struts	DMATEP	1.04e07	.0002525	.33	N/A
Heath Tecna outer shell	DMATEP	2.75e06	.0000638	.35	N/A
Heath Tecna floor	DMATEP	5.0e06	.0001146	.35	N/A
Hitco outer shell	DMATEP	2.75e06	.00012	.33	N/A
Hitco bin floor	DMATEP	2.75e06	.0001137	.33	N/A
Hitco linkages	DMATEP	1.04e07	.0002525	.33	N/A
Impact surface	DMATEP	9.0e08	0.00075	0.3	N/A

As described previously, 3,229-lbs. of luggage was placed in the cargo hold beneath the floor of the fuselage section prior to the impact test. The luggage was tightly packed and secured using straps and netting. Several techniques were used to represent the inertial properties of the luggage in the finite element model. The final approach was to use a "percentage area method." A line was drawn horizontally at the expected height of the luggage, which was approximately 1-ft. below the floor. The total area encompassed below the horizontal line and the inner fuselage frames was calculated. Next, lines were drawn vertically from each node in the region to intersect the horizontal line. The percentage area of each "rectangle" formed was determined by dividing the small area in each rectangle by the total area. These ratios were then used to determine the percentage of the 3,229-lbs. of luggage to be assigned to the nodes at that location. Using this approach, 60% of the weight of the luggage, or 1,937.4 lbs., was attached to the nodes forming the cargo floor. The remaining weight of 1,291.6-lbs. was applied in decreasing amounts to the nodes along both sides of the fuselage frames. It was assumed that the fuselage section was loaded uniformly from front to back by the luggage.

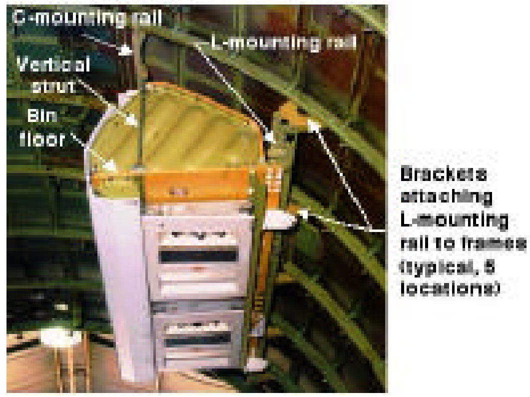
This method of representing the inertial properties of the luggage was selected because it is efficient and it represents a fairly accurate distribution of the loading provided by the luggage to the fuselage frames at initial impact. However, several important properties of the actual luggage are not modeled using this approach. For example, the inertia of the luggage is approximated and is distributed to the nodes on the fuselage frames. During the impact, the weight of the luggage can shift and provide a different loading path to the fuselage structure, which cannot be modeled using the current approach. The frictional loading between the fuselage section and the luggage is not modeled. Since the individual pieces of luggage are not modeled, no material properties are assigned to represent the "compressibility" of the luggage. During the actual impact, the luggage will react the loads applied by the fuselage floor and the lower fuselage frames and skin. However, since the luggage was not physically modeled, there is no mechanism to develop and apply these reactive forces. One obvious way to correct these deficiencies in the model is to represent the luggage using solid elements and to assign a material property that accurately represents the compressive properties of the luggage. However, this approach was not taken due to the fact that no data on the material properties of luggage were available.

Model of the Heath Tecna Overhead Bin

A photograph of the Heath Tecna bin installed in the fuselage section is shown in Figure 6(a). The bin is located on the right, or door, side of the fuselage section. The empty bin weighs 56 lbs. and consists of a fiberglass shell and a composite sandwich floor. The bin is secured to the aircraft by instrumented support brackets and struts, including C- and L-cross-section mounting rails attached to the fuselage frames. Two vertically-mounted struts and matching brackets, designated HT-1, HT-2, HT-3, and HT-4 in Figure 6(b), are used to attach the bin to the ceiling of the test section and to provide support for vertical loading. The vertical struts are 0.5-inch diameter solid cylindrical rods, approximately 14-inches in length. For the drop test, the bin was loaded with 120-lbs. of plywood.

The finite element model of the Heath Tecna bin is shown in Figure 7. The outer surfaces and floor of the bin are modeled using shell elements. The vertical support struts that attach the bin floor to the C-mounting rails are modeled using one-dimensional beam elements. Beam elements can carry axial load, as well as bending, torsional, and shear loads. As shown in Figures 6 and 7, the support struts are inclined at an angle of approximately 5° from true vertical. The elements representing these struts are inclined at the same angle in the model.

The C-mounting rails are modeled using shell elements. In the test article, the C-rails are attached to the fuselage frames using brackets. In the model, the C-rails are attached using beam elements. The bin floor is also secured to the fuselage section through an L-mounting rail that is attached to the fuselage frames at five locations, as shown in Figures 6 and 7. The bin is attached to the L-mounting rail at two locations by brackets. In the model, the L-mounting rail and brackets are modeled using shell elements. The plywood that was placed in the Heath Tecna bin is modeled as 15 concentrated masses, each weighing 8 lbs. These masses are attached to nodes on the bin floor and are uniformly spaced along the length and width of the platform.



(a) Photograph of the Heath Tecna bin installed in the B737 fuselage section.

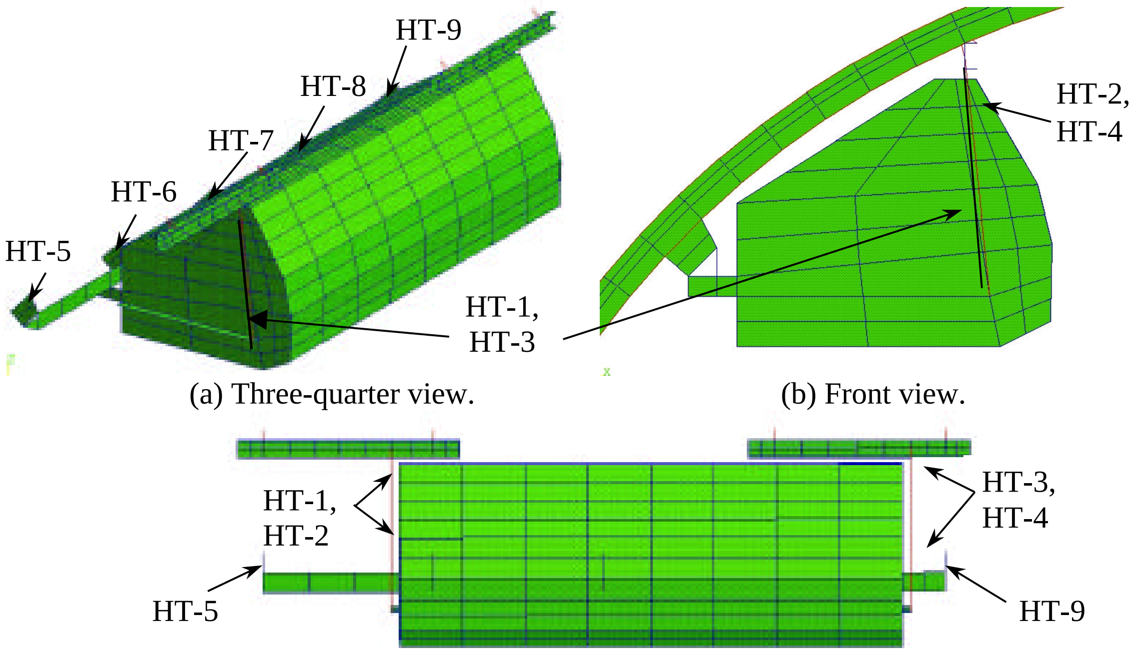
(b) Component designations for the Heath Tecna overhead bin.

Figure 6. Heath Tecna bin photograph and component designations.

Three unique material properties were assigned to the elements forming the outer surface of the bin, the bin floor, and the vertical support struts. The densities of the materials assigned to the outer shell and bin floor were adjusted such that the total empty weight of the Heath Tecna bin was 56 lbs. A third material property was assigned to the elements representing the vertical support struts. The specific material properties used in the model are listed in Table 1.

Following inspection of the Heath Tecna bin, it was determined that the components most critical for maintaining structural integrity during impact were the vertical support struts and mounting brackets. The FAA supplied one of the 0.5-in. diameter struts and it's mounting bracket for testing. The strut is notched on one end and is attached to the bracket by a through bolt, while the other end is threaded. A 0.25-in. diameter eyebolt is screwed into the support strut and it is attached to a triangular bracket on the bin floor with a single 0.25-in. diameter bolt and lock nut.

A tensile test was performed on the Heath Tecna support strut and bracket assembly. The notched end of the strut was loaded through the bracket and the threaded end was loaded through the eyebolt. To ensure that only tensile loads were applied, a test fixture was fabricated to align the bracket with the eyebolt. The strut was loaded quasi-statically using a bench-top load test machine. The measured load-deflection curve is shown in Figure 8. The assembly failed at the hole where the bolt connects the notched end of the strut to the bracket. The measured ultimate failure load was 1,656 lbs. This test result provides a single data point that can be used as a guideline for estimating failure of the strut and bracket during the dynamic test. However, it must be noted that the actual support struts may experience a much more complex loading scenario during the impact test, including shear, torsion, and bending. In the model, the vertical support struts were assigned material properties typical of 7075-T6 aluminum with no yielding or failure. The axial force response of the elements forming the support struts was output during the simulation.



(a) Three-quarter view. (b) Front view.

(c) Side view.

Figure 7. Finite element model of the Heath Tecna bin.

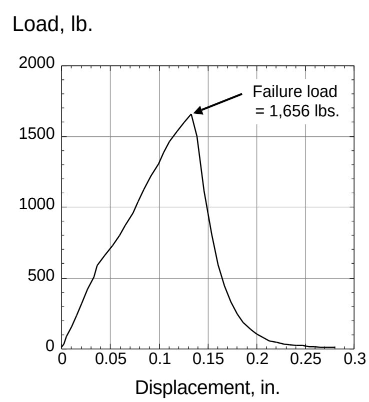
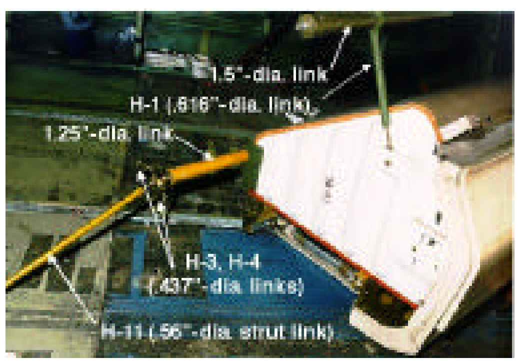


Figure 8. Load versus displacement response of Heath Tecna support strut assembly.

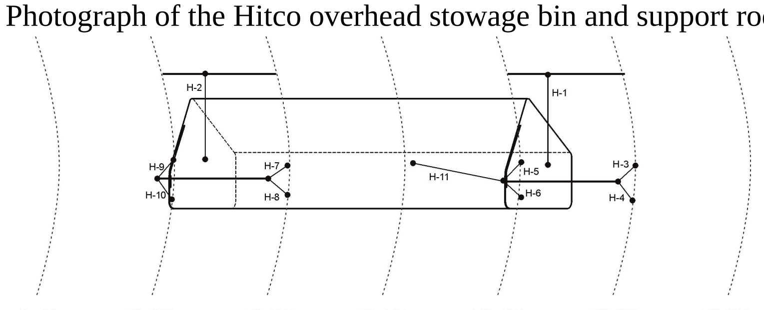
Model of the Hitco Overhead Bin

A photograph of the Hitco overhead bin is shown in Figure 9(a) prior to installation on the fuselage section. This bin is located on the left side of the fuselage section and consists of an outer shell, floor, and several support linkages. The empty bin weighs 57 lbs. For the test, the bin was loaded with 200-lbs. of plywood and instrumented with five accelerometers. In addition, the bin is secured to the airframe by 11 support linkages, as shown in Figure 9(b), which were instrumented with strain gages. Vertical support is provided by two 0.616-in. diameter tie-rod links that are attached to both ends of the bin. These tie-rod links connect the bin to two 1.5-in. diameter horizontal links that are attached to the fuselage frames at FS 400 and FS 420 and at FS 460 and FS 480. The two 0.616-in. diameter tie-rod links are approximately 10 inches in length and are threaded on one end to receive a 0.25-in. diameter eye-screw. The eye-screws are attached to brackets located on both ends of the bin with a bolt and lock nut. When the bin is mounted to the fuselage section, the 0.616-in. diameter links are oriented vertically. Prior to the drop test, the FAA performed a tensile test on the 0.616-in. diameter linkage in which an ultimate failure loads of 5,350-lbs. was obtained. This load can be used as a guideline for estimating failure of the support link during the impact test.

The finite element model of the Hitco bin is shown in Figure 10. The outer surfaces and floor of the bin are modeled using shell elements and the support linkages are modeled using beam elements. A wall thickness of 0.125-inches was specified for each of the support links. The mass and inertial properties of the 200-lbs of plywood added to the Hitco bin are represented as 24 concentrated masses, each weighing 8.33-lbs. These masses are attached to nodes on the bin floor and are uniformly spaced along the length and width of the floor. Three different material properties were defined for the elements forming the Hitco bin. The densities of the materials assigned to the outer shell and floor were adjusted such that the total weight of the empty bin is 57 lbs. The support links were assigned material properties typical of 7075-T6 aluminum with no yielding or failure, and the axial force response was requested as output for correlation with the test data.

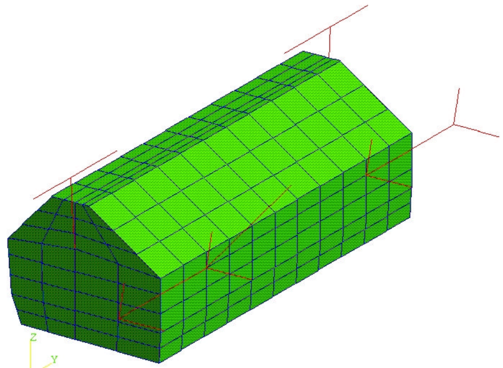


(a) Photograph of the Hitco overhead stowage bin and support rods.

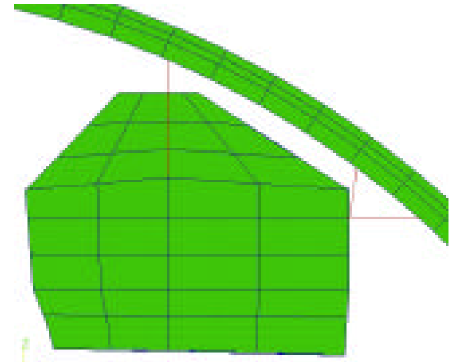


(b) Component designations for the Hitco bin.

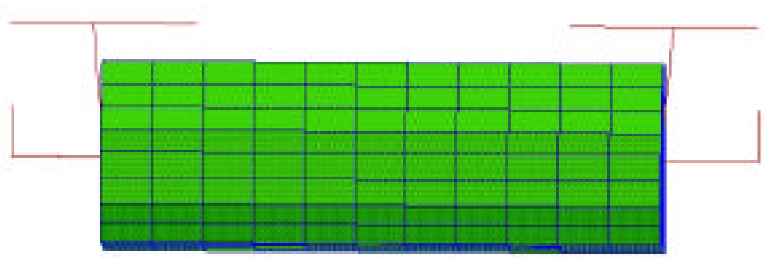
Figure 9. Photograph and component designations for the Hitco bin.



(a) Three-quarter view.



(b) Front view.



(c) Side view.

Figure 10. Finite element model of the Hitco bin.

The specific material properties are listed in Table 1. It should be noted that the material properties of the outer shell and floor of both the Heath Tecna and Hitco bins are unknown and the values assigned to them are "best guess" estimates. Until these properties are known and input into the model, it is not possible to determine accurately the effective stress or strain in the bins as a function of time. Also, it is important to note that the door hinges and latches of the bins are not modeled. It is assumed that the doors of the bins cannot open during the impact test.

B737 Fuselage Section Model Execution

One check of the integrity of the finite element model is to compare the mass of the individual components with the corresponding weights of the test article. A weight comparison of the test article and model is shown in Table 2. The total weight of the model is 4.5% heavier than the actual B737 fuselage section. The differences in mass appear in the empty weight of the fuselage section and in the combined seat, occupant, and other weights that are accounted for in the model using concentrated masses. The empty weight of the model is expected to be somewhat heavier that the actual fuselage section due to the fact that most of the cutouts were not included. Also, the variations in the geometry of the actual fuselage section were accounted for by using average values in the model. For example, measured skin thicknesses varied from 0.045- to 0.07-in., so a weighted-average value of 0.05-in. was used in the model. The total weight of all concentrated masses is somewhat higher than the experimental value due to the fact that many small masses (2-3 lbs. each) were assigned to nodes where output was requested as a means of lowering the high-frequency response.

The model was executed in MSC.Dytran, Version 2000, for 0.2 seconds of simulation time on a Sun Ultra Enterprise 450 workstation computer. The simulation required 36 hours of

CPU with a final time step of 2.67 microseconds. Requested output included the deformed geometry and acceleration, velocity, and displacement time histories for several nodes whose positions correspond to the locations of selected transducers. Post-processing of the model was performed using MSC.Patran [4].

Table 2. Weight comparison of the model and test article.

Component	Test weight, lbs.	Model weight, lbs.
Fuselage section, empty	1,360	1,526
Combined seats, occupants, and misc.	3,620	3,845
Hitco bin and plywood	257	257
Heath Tecna bin and plywood	176	176
Cameras and mount	228	240
Luggage	3,229	3,230
Total	8,870	9,274

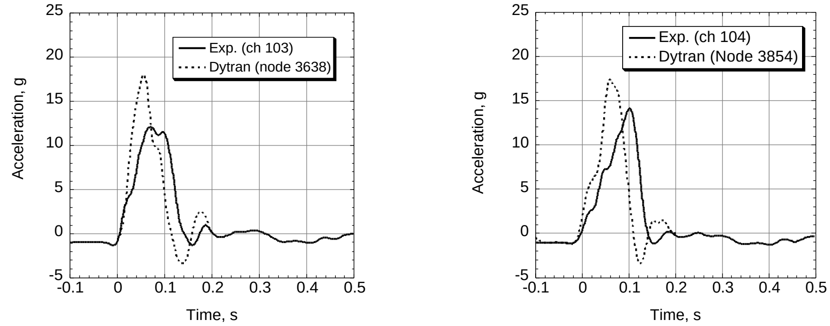
ANALYTICAL AND EXPERIMENTAL CORRELATION

In this section, the correlation between the pre-test predictions and test data from the November 2000 vertical drop test of the B737 fuselage section with overhead bins and luggage are presented including seat track, fuselage sidewall, and overhead bin acceleration time histories. In addition, the report includes the analytical and experimental force time histories of the Heath Tecna and Hitco bin support linkages. Due to the large amount of data, only selected channels are provided in this report. Finally, an assessment of model accuracy is provided with suggestions for improvements to achieve better agreement.

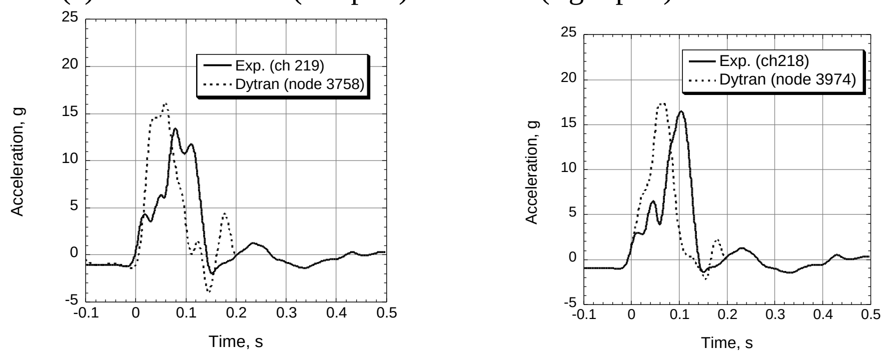
For the acceleration time histories, both the analytical and experimental data are filtered using a 20-Hz 2-pole Butterworth low-pass digital filter to remove the high frequency ringing from the underlying crash pulse. The filtering was performed forward in time, then backward in time to eliminate the phase shift. As a result, the actual cut-off frequency of the filter is 16-Hz. The reason for using such a low cut-off frequency was to ensure that the fundamental crash pulse was extracted. This filter is based on the equations specified in the SAE J211-1 [8]. For the axial force time histories, the analytical predictions contained high frequency oscillations. As a result, a smoothed curve fit of the analytical data is plotted versus the raw experimental data.

Seat Track Acceleration Responses

The predicted acceleration time histories are correlated with the experimental data obtained from accelerometers located on the left and right seat tracks at FS 418 and FS 484 in Figures 11 and 12, respectively.

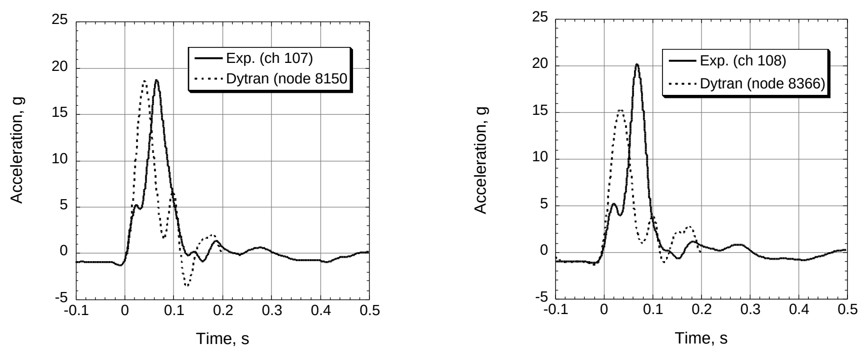


(a) Left-side inner (left plot) and outer (right plot) at FS 418.

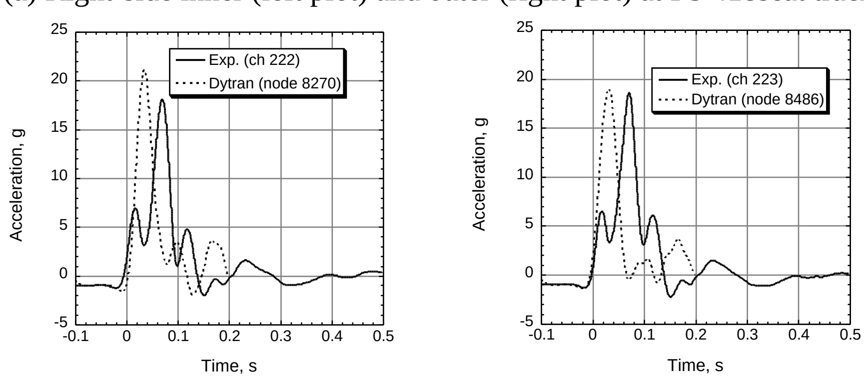


(b) Left-side inner (left plot) and outer (right plot) at FS 484.

Figure 11. Predicted and experimental left seat track acceleration responses.



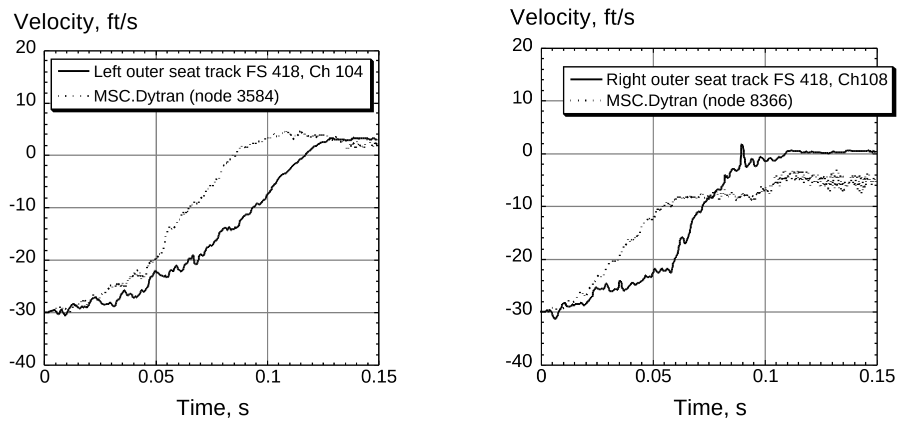
(a) Right-side inner (left plot) and outer (right plot) at FS 418seat track.



(b) Right-side inner (left plot) and outer (right plot) at FS 484.

Figure 12. Predicted and experimental right seat track acceleration responses at FS 418.

Comparisons of the predicted and experimental velocity responses of the left and right outer seat track locations at FS 418 are plotted in Figure 13. The experimental velocity was obtained from integration of the corresponding acceleration traces. The analytical velocity responses were obtained directly from output of the simulation, i.e., they were not obtained by integration of the analytical acceleration traces. It should be noted that the accelerometer located on the right side seat track at FS 418 is directly above the front edge of the door. These plots indicate that the model is removing velocity more quickly than the test article. For example, on the left outer seat track, the predicted response has reached zero velocity at .085 seconds, while the experimental response reaches zero velocity at 0.115 seconds. For the right outer seat track, the experimental velocity response reaches zero velocity at 0.11 seconds with no rebound velocity shown. However, the predicted response levels at a velocity of -5 ft/s at 0.11 seconds and never crosses zero velocity. One explanation for this behavior is that, in the model, the floor is rotating, as well translating. The counter clockwise rotational velocity subtracts from the translational velocity on the left side causing it to be removed more quickly, and adds to the velocity on the right side.

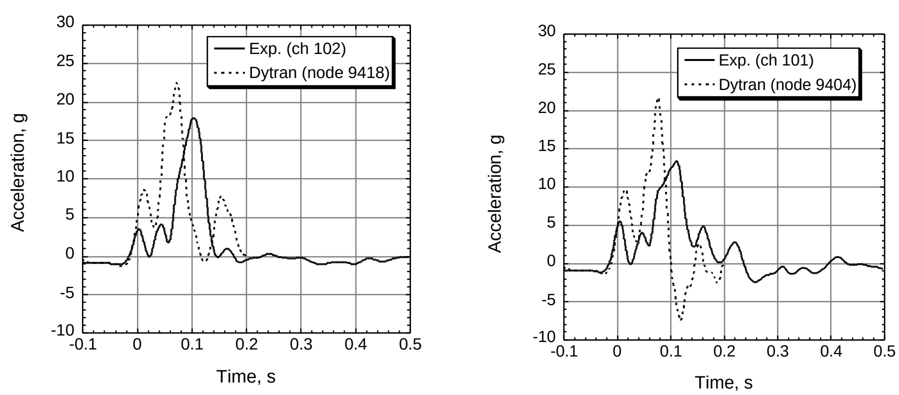


(a) Left outer seat track. (b) Right outer seat track.

Figure 13. Predicted and experimental velocity time histories of the outer seat tracks at FS 418.

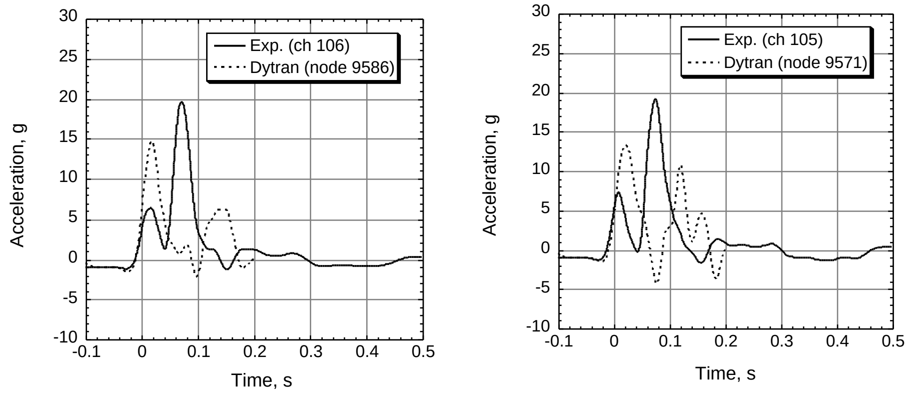
Fuselage Sidewall Acceleration Responses

The predicted and experimental acceleration responses for locations on the upper and lower fuselage sidewalls at FS 400 are presented for the left- and right-side of the fuselage in Figures 14 and 15, respectively.



(a) Left lower sidewall. (b) Left upper sidewall.

Figure 14. Predicted and experimental left sidewall acceleration responses at FS 400.

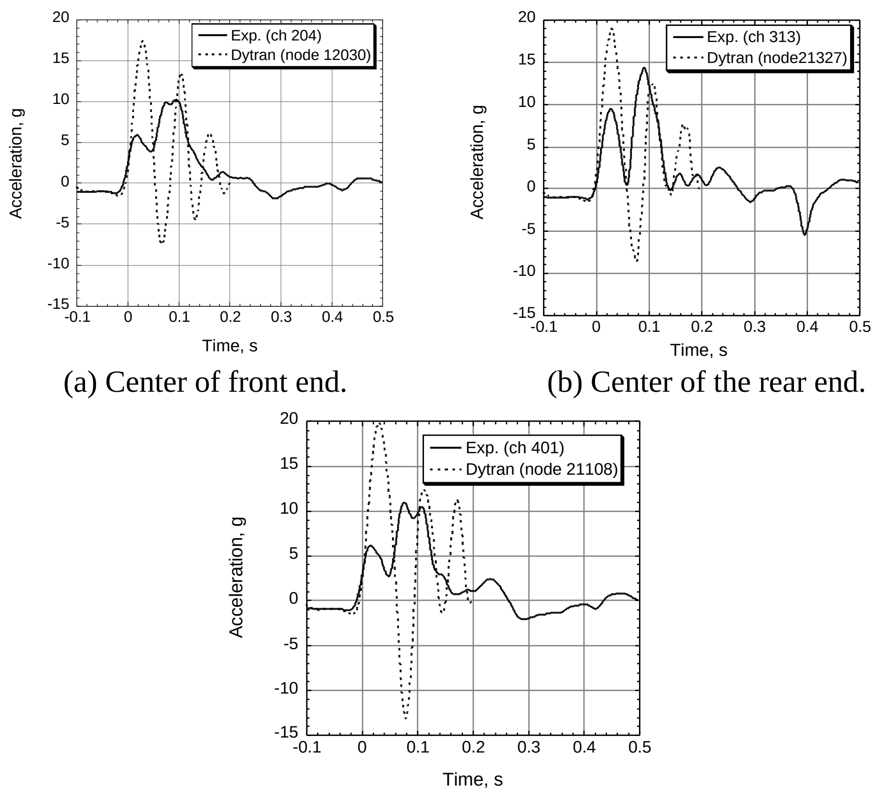


(a) Right lower sidewall. (b) Right upper sidewall.

Figure 15. Predicted and experimental right sidewall acceleration responses at FS 400.

Heath Tecna Bin Responses

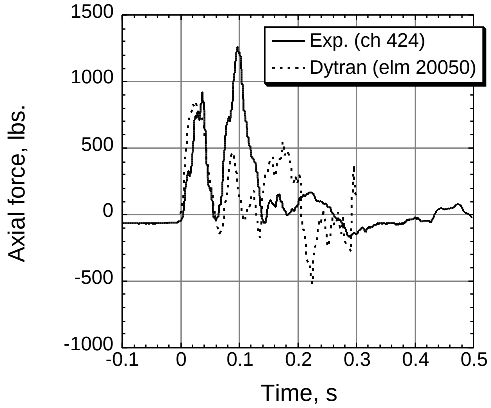
The predicted and experimental vertical acceleration responses for locations on the center of the front and rear ends of the Heath Tecna bin and at the bottom center of the bin are shown in Figure 16. The predicted and experimental axial force time histories of the vertical struts HT-1 and HT-3 are shown in Figure 17.



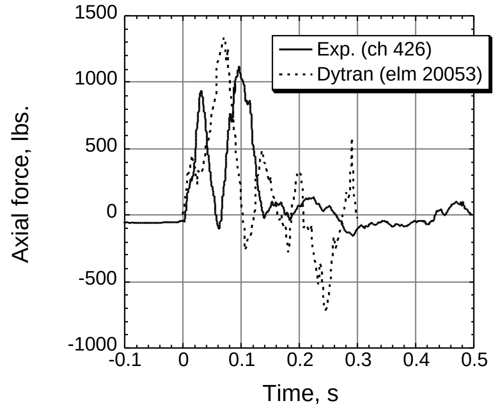
(a) Center of front end. (b) Center of the rear end.

(c) Bottom center.

Figure 16. Predicted and experimental vertical acceleration responses of the Heath Tecna bin.



(a) Heath Tecna bin forward strut HT-1.

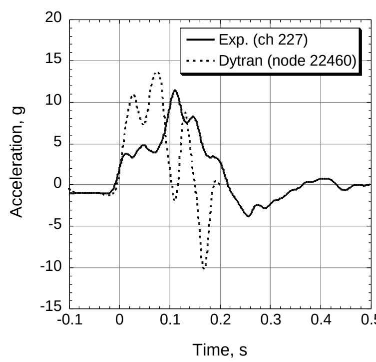


(b) Heath Tecna bin aft strut HT-3.

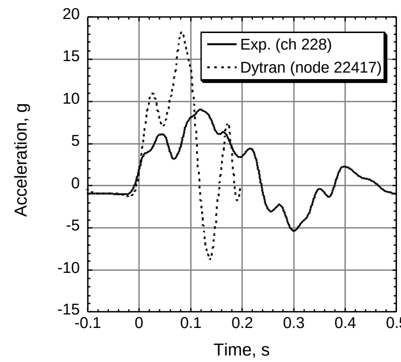
Figure 17. Predicted and experimental force responses of the Heath Tecna vertical support struts.

Hitco Bin Responses

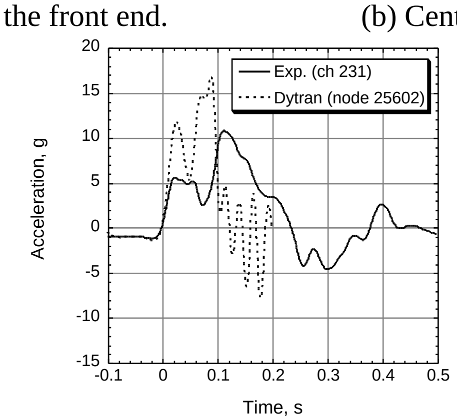
The predicted and experimental vertical acceleration responses for the center of the front and rear ends of the Hitco bin and at the bottom center of the bin are shown in Figure 18. The predicted axial force time histories of the two primary vertical support linkages H-1 and H-2 are shown in Figure 19.



(a) Center of the front end.

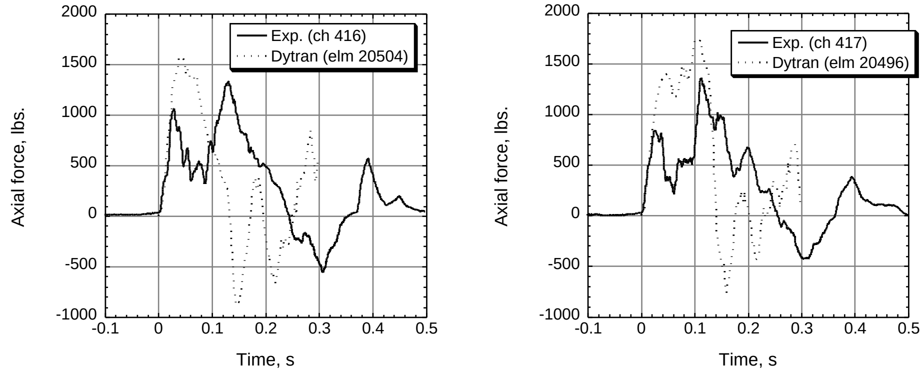


(b) Center of the rear end.



(c) Center of the bottom of the bin.

Figure 18. Predicted and experimental vertical acceleration responses of the Hitco bin.



(a) Hitco link H-1. (b) Hitco link H-2.

Figure 19. Predicted and experimental axial force time histories of Hitco bin links H-1 and H-2.

Assessment of Simulation Accuracy

Based on the test and analysis correlation presented in the previous section of this report, several general statements can be made regarding model accuracy. The predicted seat rail acceleration responses matched the overall shape and duration of the experimental acceleration pulses fairly well. Also, the peak acceleration values were well predicted i.e., within 25% except for the left inner seat rail at FS 418. However, a phase shift in the time of occurrence of the peak acceleration was typically seen. In general, the high level of correlation was surprising given the large number of approximations used in the model development. One suggestion that would result in a more accurate representation of the test article is to model the luggage using solid elements. These elements would be assigned material properties typical of the average compressive response of luggage.

Another issue that might affect the floor-level acceleration response is the fact that all of the triple-occupant aircraft seats located on the right side of the fuselage failed during the test, as shown in Figure 2. This factor is important since a large portion of the occupant weight is transmitted to the fuselage structure through the seats. In the model, the inertial properties of the seats and occupants are represented using concentrated masses attached to nodes on the floor. The use of concentrated masses is a good approach as long as the load transfer path remains constant. In this case, the load transfer path was altered by the failure of the seats. For a more accurate simulation, the seats and dummies would have to be added to the model. However, this approach is not practical at this time. A possible alternative would be to incorporate the seats into the fuselage model, and then represent the inertial properties of the dummies by attaching concentrated masses to the seat nodes.

For the fuselage sidewall locations, the correlation with test data varied according to position. For the accelerometers located on the left side of the fuselage, the simulation predicted the overall shape, duration, and peak g's of the acceleration pulses quite well. However, the correlation for channels located on the right side of the fuselage section was not as good. The experimental acceleration responses on the right side of the fuselage section, shown in Figure 15, typically exhibit a two-peak pulse with a 7-g peak occurring first and a 17- to 20-g peak occurring next. In general, the predicted acceleration responses exhibited the opposite shape, a large initial peak with a smaller second peak. It is possible that the seat failures on the right side of the fuselage floor influenced the fuselage sidewall acceleration responses, as well.

The predicted axial force responses of the Heath Tecna bin vertical support struts, shown in Figure 17, compare favorably with the experimental data. These linkages were represented using beam elements and the axial force was correlated with the calibrated load response measured during the test. It is useful to note that the predicted axial force response for both rods did not exceed the 1,656-lb. failure load determined previously from the tensile test. The predicted axial force responses of the Hitco bin support linkages correlated fairly well with the experimental data, see Figure 19. As with the Heath Tecna bin, it is useful to note that the predicted axial force responses for the 0.616-in. diameter links (H-1 and H-2), shown in Figure 19, did not exceed their ultimate failure load of 5,350 lbs. Neither the Heath Tecna nor the Hitco bin support linkages failed during the test.

The predicted force responses are given in the local coordinate system in which the x-axis is defined as the axial direction of the individual beam element. The beam elements shared common nodes with the bin on one end and the fuselage frame on the other end. This modeling approach did not allow the beam elements to rotate in response to bending loads. A suggested improvement would be to add rotational springs to represent the various joints or connections between the individual linkages and between the linkages and the bin and fuselage structure. One difficulty in implementing this approach will be determining the appropriate stiffness to input for the joints.

Finally, the assessment of model accuracy provided in this report has been described qualitatively. However, to assess fully the model accuracy, the correlation results must be defined in quantitative terms. These measures may include comparisons of pulse duration, magnitude and phasing of peak acceleration, average or mean acceleration values, onset rate, and frequency content. In addition, comparisons of integrated responses, such as the velocity and displacement time histories could be used, especially for the accelerometers located on the fuselage floor.

Ongoing Research

Currently, several of the modifications discussed in the previous section are being implemented. For example, a compressive load test on luggage was performed by placing several pieces of packed luggage between the platens of a load test machine, and applying a compressive load to failure. A mix of soft- and hard-sided luggage was tested to characterize the "average" compressive response. The B737 fuselage section model has been modified to represent the luggage using solid elements and the material properties determined from the compression test were assigned to these elements.

In addition, work is underway to include the impact platform in the B737 fuselage section model. All previous models have represented the platform as a rigid surface. By adding the impact platform, it will be possible to correlate analytical data with test data obtained from the platform to validate the model. Also, it may be possible to determine what influence, if any, the loading platform has on the test results. Other changes to the model will be evaluated including: (1) rediscretizing the model in certain locations where known failures occur, (2) adjusting the material properties, especially for those elements forming critical structure, (3) changing the element formulation from beam to shell elements in some locations, (4) adjusting the contact force penalty factor from the default value and adding friction. It is important to note that each of the modifications or changes to the model will be performed independently of one another, thus allowing an understanding of the influence of the change on the results.

CONCLUDING REMARKS

The FAA conducted a 30-ft/s vertical drop test of a 10-ft. long B737 fuselage section with two different overhead bins and luggage in November of 2000. This test provided an invaluable opportunity to evaluate the capabilities of computational tools for crash simulation through analytical/experimental correlation. To perform this evaluation, a full-scale 3-dimensional finite element model of the fuselage section was developed using the nonlinear explicit transient dynamic finite element code, MSC.Dytran. Crash simulations were performed to generate pre-test analytical predictions of fuselage and overhead bin dynamic responses.

The MSC.Dytran model of the B737 fuselage section contained 9,759 nodes and 13,638 elements, including 9,322 shell and 4,316 beam elements, and 250 concentrated masses. The model was executed for 0.2 seconds of simulation time on a Sun Ultra Enterprise 450 workstation computer that required 36 hours of CPU with a final time step of 2.67 microseconds. The predicted seat rail acceleration responses matched the overall shape and duration of the experimental acceleration pulses quite well. Also, the peak acceleration values were well predicted, i.e., within 25% with one exception. However, a phase shift in the time of occurrence of the peak acceleration was typically seen. For the fuselage sidewall locations, the correlation with test data varied according to position. For the accelerometers located on the left side of the fuselage, the simulation predicted the overall shape, duration, and peak g's of the acceleration pulses quite well. However, the correlation for channels located on the right side of the fuselage section was not as good. The peak accelerations of the Heath Tecna bin are predicted to be between 15- and 20-g, with no failure of the vertical support struts. For the Hitco bin, the peak accelerations were predicted to be between 15- and 40-g depending upon location. Also, even though the axial loads in the support linkages of the Hitco bin were significantly higher than those of the Heath Tecna bin, the analysis indicates no failure of any of the support linkages. No failures of the Heath Tecna or Hitco bin support linkages were observed during the test.

ACKNOWLEDGEMENTS

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