Vulnerability Analysis of Aircraft Fuselage Subjected to Internal Detonations

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Abstract

The Air Force, in support of the FAA's (Federal Aviation Administration) Aircraft Hardening Program (AHP), is conducting an extensive test program involving simple cylinders to full scale aircraft such as the B-52s as well as representative commercial airplanes. The purpose of this program is to ascertain the extent of the damage caused by internal explosions and to develop strategies to protect the safety of the passengers. The effects of the internal explosion are very complex, and the tests alone can not provide an adequate understanding to develop protection strategies. The purpose of this paper is to present the analysis results of the B-52 aircraft subjected to internal explosions. In addition analysis results are compared to those obtained from the test program conducted at Davis Monthan Air Force Base.

Two types of analysis will be addressed in this paper:

1. Fluid structure interaction (blast pressures and airframe interaction) using MSC/DYTRAN.
2. Joint and buckling analysis of a B-52 panel using MSC/DYTRAN.

The ultimate goal of the proposed analysis is to develop a vulnerability map of the entire fuselage. This map can be used to make cost effective decisions on hardening of the aircraft against bomb blasts.

Introduction

This investigation is part of the Federal Aviation Administration's (FAA) Aircraft Hardening Program (AHP) being conducted in the Flight Dynamics Directorate (FDD) of Wright Laboratory. The purpose of the AHP program is to assess the vulnerability of commercial aircraft to internal explosions and to investigate various hardening concepts and strategies to protect against catastrophic failure due to internal bomb explosions. An airframe is a complex structure designed for high efficiency (with low margins of safety) and operates at high speeds in a severe dynamic environment. It is impossible to predict the failure scenario of an in-flight explosion because everything about the bomb explosion is uncertain. Its size, location, the time of explosion and the flight condition are all unpredictable. If the bomb is large enough or placed at the right place, it can blow up the airplane instantly. No reasonable amount of hardening can prevent this catastrophe. Even if the initial bomb damage is small, the subsequent flight and the potential crash can completely destroy the airplane and its passengers. Most of the commercial aircraft in service today have evolved into highly optimized systems with respect to structures, aerodynamics, controls, propulsion and avionics under normal operating conditions. However, internal explosion was not a serious design driver in the past. Extensive structures and other subsystems modifications to protect against internal blasts can be prohibitively expensive both in manufacture and operation. Bomb explosion in a commercial aircraft is a rare event, contrary to the public perception created by the mass media. Commercial aircraft routinely log billions of passenger miles without an incident. The weight and cost penalties associated with bomb proofing can make air travel beyond the reach of many passengers. Commercial airlines can ill afford the added cost in the current tight market conditions. Instead, it would be more prudent to understand the vulnerability of the aircraft and to develop strategies to protect it with minimal modifications.

In pursuit of the above objectives, the AHP program at FDD is conducting an extensive test program supported by comprehensive analytical simulation. Since most of these tests are conducted under static conditions on the ground, they provide little or no information on the post explosion flight of the aircraft. Nevertheless, static tests are essential for identifying the potential failure mechanisms and for tuning the analytical models which can be used to predict the behavior of the bomb damaged aircraft in flight.

One of the category of tests involved surplus B-52 aircraft. The internal structure of a B-52 aircraft is quite complex and its fuselage configuration is significantly different from the commercial aircraft but nevertheless it is very much representative of a general aircraft construction. Its semi-monocoque construction consists of transverse (fuselage) frames and longerons covered with skin (Figure 1). The lap joints, butt joints, skin to frame and frame to longeron connections also have similarities to commercial aircraft construction. The major exception is the absence of a floor separating the fuselage into two compartments. The passenger floor in a commercial aircraft separates the cargo hold from the passenger compartment. This separation can make the commercial aircraft fuselage behavior distinctly different from the B-52's single compartment set up. But, nevertheless, the simpler B-52 configuration offers distinct advantages in modeling and understanding before transitioning to more complex commercial aircraft fuselage testing. The purpose of the B-52 tests and analysis can be summarized as follows:

1. Establish a relationship between the size of the explosive and the peak as well as transient pres-

sure levels.
2. Study the effect of the flexible structure on the blast pressure propagation.
3. Identify the failure modes - structural elements and joints.
4. Calibrate the analytical models - static, elastoplastic and transient response models.
5. Develop the basic concepts of a vulnerability map of the fuselage.

Two types of analysis addressed in this paper:

1. Fluid structure interaction (blast pressures and airframe interaction) using MSC/DYTRAN [1]. This analysis involves a global model to predict the overall structural behavior of the aircraft and it is also used for generating a vulnerability map.
2. Joint and buckling analysis of a B-52 panel using MSC/DYTRAN. This represents a local model to simulate the immediate effects of the explosion on a more detailed level.

The ultimate goal of the proposed analysis is to develop the vulnerability map of the entire fuselage. This map can be used to make cost effective decisions on the extent and the type of hardening required against bomb blasts.

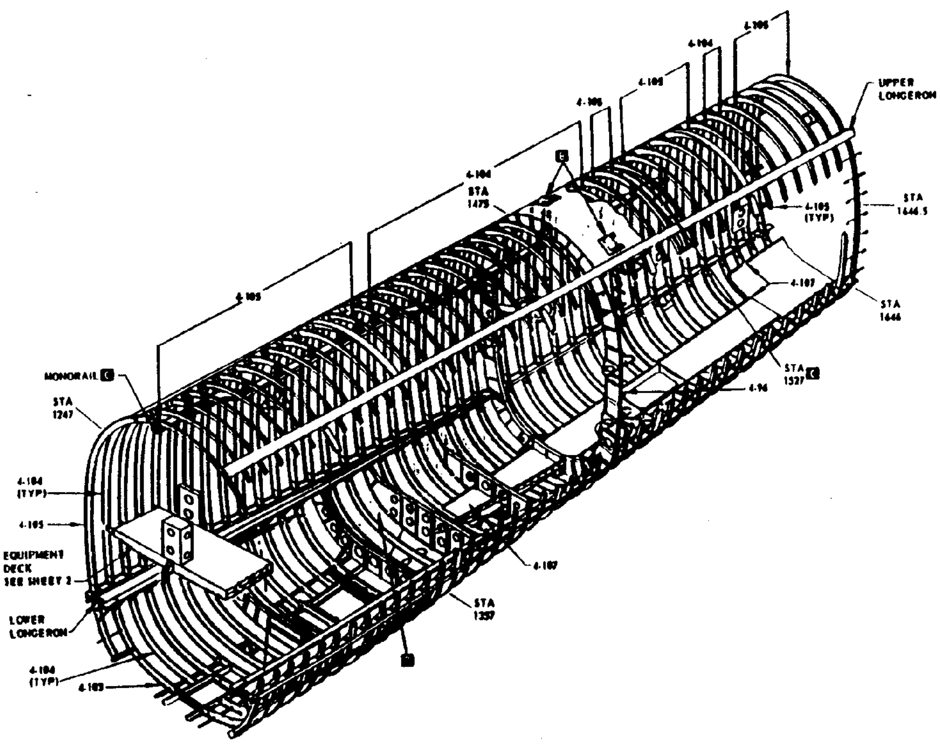

Figure 1. B-52 Fuselage Structure

Concept of Vulnerability Map

The concept of a vulnerability map was proposed in reference [2] in order to make blast analysis objectives more tractable. Aircraft vulnerability raises a number of difficult issues:

1. Size of the bomb.
2. Location of the bomb.
3. Structural arrangement around the explosion.
4. Speed and altitude of the airplane at the time of the explosion.
5. Extent of the initial damage and its effect on the post explosion flight.

The size and location of the bomb are not under our control. It is impossible to design the aircraft for all eventaalities. Having said that it is still necessary to develop a rational strategy for addressing the issue of location and size of the explosion. The proposed vulnerability map concept aids in the development of such a strategy.

There will be significant variation in structural arrangement along the length of the fuselage because of the presence of access doors, etc. The vulnerability of the fuselage varies, both transversely and longitudinally. It is conceivable, but unlikely, that the same bomb placed anywhere in the fuselage will inflict identical damage around the explosion. Even if it did, the consequences may not be the same for the safety of the flight. The vulnerability map concept is based on the premise that the vulnerability of the fuselage varies both longitudinally and transversely. This means all the issues cited above contribute to the seriousness of the explosion. The map in the present context refers to the space (every point) in the fuselage while the vulnerability refers to the size of the explosive at that location that brings down the airplane. The coordinates of each point in the fuselage and a number that refers to the size of the charge, associated with that point, constitute the vulnerability map. If a credible vulnerability map is available for a given plane, then we can ask ourselves two pertinent questions.

1. What is the smallest bomb that can bring down the airplane?
2. What is the largest bomb that can escape the current detection devices?

If there is no gap or overlap between the two limits, then there is no need to expend significant effort in hardening the airplane. However, the critical size of the charge varies with the location in the fuselage. This means that some areas of the fuselage may have gaps between the two limits, while others are satisfactory. Then the hardening concepts can be focussed on those critical areas only. It may not even be necessary to harden the airplane. Instead special containers or assigning more thoroughly inspected baggage to these critical areas can do the job. A credible vulnerability map provides valuable information on the relative vulnerability of various regions of the fuselage.

Having defined the concept of the vulnerability map in generic terms it is necessary to outline a reasonable approach to develop such a map. Basically we need to determine the explosion threshold of each location in the fuselage. This threshold varies not only with the circumstance of the explosion but also with the subsystem contributing to the failure. Obviously it is not possible to conduct an exhaustive, all encompassing, test program to develop such a vulnerability program. Instead a more reasonable approach is to identify any simple failure mode and to construct a vulnerability map analytically with respect to that mode. Now this map can be validated with equally simple test programs. This validation helps to tune the analytical model. Also we have the information on the relative vulnerability of the fuselage with respect to this simple failure mode. For example, the failure criteria is defined as the first yield (according to the Von Mises criteria) of the material due to maximum peak pressure at the location of interest (possible bomb location) and an assumed distribution in the rest of the fuselage. This criteria is neither sophisticated nor represents reality of the bomb explosion but it represents a reasonable estimate of the nature of the peak pressure distribution inside the fuselage. The next simple failure criteria is buckling of the transverse frames in the B-52 due to peak static pressure. Similarly the vulnerability maps can be updated for more sophisticated failure criteria as we progress through the analysis of the test data. Ultimately the vulnerability maps need to be updated not only for the structural criteria on the ground but also in flight where all aerodynamics and control interactions will have significant contributions. The fundamental advantage of this approach is that at each stage (even in case of a simple failure criteria and far reaching approximations) we have some understanding of the relative vulnerability. The vulnerability map proposed here is not meant to be all or nothing, but, instead, its validity depends on the extent of resources assigned to this task. Finally this vulnerability concept is in the spirit of the famous adage, "Philosophy progresses not by answering all the questions but by progressively clarifying them".

Analysis Models

Global B-52 Fuselage Model

The transient dynamic response analysis is performed on the B-52 aft fuselage model using the hydrocode, MSC/DYTRAN. MSC/DYTRAN is a three-dimensional analysis code for analyzing the dynamic, nonlinear behavior of solid components, structures, and fluids. It uses explicit time integration and incorporates features to simulate a wide range of material and geometric nonlinearity. It is particularly suitable for analyzing short, transient dynamic events that involve large deformation, a high degree of nonlinearity, and interactions between fluids and structures. MSC/DYTRAN is a dynamic analysis code coupling a large finite strain, large deflection (Lagrangian) structural finite element idealization with a finite volume fluid flow (Eulerian) simulation. In the simulations performed, the code is operated in the Arbitrary Lagrange Euler (ALE) mode.That is, as the lagrangian structure deforms, the eulerian grid is displaced to match the Lagrangian grid at the points along the interface.

The structure of the B-52 is relatively simple due to the absence of the two compartment arrangement (commercial aircraft have a floor separating the cabin from the cargo hold). Only a part of the aft fuselage (Section 47) was modeled for the analysis. Frames in this section are approximately every 10 *ins* apart. The structure shown in Figure 2 is cantilevered at the forward bulkhead station 1237 and modeled with beam and plate elements. The bulkheads are modeled as thick plates with heavy stiffeners to simulate the actual bulkhead (defined as RIGID surfaces).

The longerons and frames are modeled with bar elements (CBAR), and the skin for the entire section is modeled with plate elements (CQUAD4). The beam element includes extension, torsion, bending in two perpendicular planes and the associated shears. The plate elements are quadrilateral with bending, membrane stiffness, and transverse shear flexibility included in the element. The air inside the fuselage is modeled with eulerian solid elements (Figure 2).

When modeling the detailed interaction of a high explosive with an adjacent material, it is important to represent the correct shape of the explosive charge and to simulate adequately the detonation process. In blast wave modeling, however, the exact shape of the explosive and the details of the detonation process have small effect on the blast wave characteristics at large distances from the explosive. Therefore, to simplify the calculations, the blast wave caused by the explosion is modeled using an ideal gas equation of state. Specific internal energy and density are variables, adjusted to define the state of the gas and to initialize the blast wave. The detonation of C-4 is modeled by assigning an initial density and pressure to the air occupying elements at the location of the charge and corresponding to the energy state expected for a charge of C-4, i.e., $8.72 \times 10^9 in - lbf/slug$. Since the specific internal energy is known for the explosive, and one wants consistency as far as the mass of the explosive is concerned, density and volume for the charge must be defined accurately. The initial high density of the C-4 charge makes the volume of the initial conditions region very small in terms of the number of euler elements that can be filled with the charge. To circumvent this problem, a larger volume is used for defining the initial conditions with a corresponding lower density. This can be achieved by defining the density of the gas as 1/3 to 1/6 the density of the explosive.

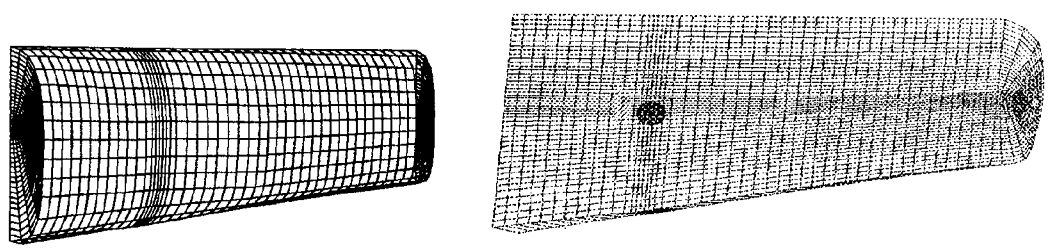

Figure 2. B-52 Lagrangian and Eulerian Model

A sphere with a radius corresponding to the volume of the charge for the given mass and density (for this case 1/5 the density of C-4 is used, $2.858 \times 10^{-5} slug/in^3$) is defined with the energy state for C-4. Therefore, at time $t = 0$, it is assumed the charge has already been detonated.

Also, the charge is assumed to be a hot, high density and high energy ideal gas. The blast wave is formed as the hot, pressurized air expands. This technique was used by MacNeal-Schwendler engineers very effectively [3,4]. The advantage of this method is in modeling blast waves caused by explosives in a single material euler formulation, instead of the more expensive multi-material euler environment with explosives modeled as a separate material model.

Local B-52 Panel Model

The analytical model of the panel consists of shell (CQUAD4) elements for the skin and the frames. Rivets are placed every 1.25" apart. The global model was run using MSC/DYTRAN to generate the transient loads to be applied on the panel, the same code was used to perform a detailed joint analysis on the panel to study the failure of the rivets and frames due to the blast loading.

The local model shown in Figure 3 consists of 6000 elements and nodes. The pressure time histories derived from the global model were transferred as tabular pressure time histories and applied on the mapped elements in the local model. To define the rivet strength, pairs of (CQUAD4) grid points were joined during the analysis with the BJOIN cards. These grid points were given force F_{max} as the failure criteria. When the force in the joint exceeds the specified value, the joint ceases to exist and the grid point act as two separate points from that moment on, simulating the failure of the rivet in carrying the applied load. The constant force failure criterion is met once the following inequality is true,

$$(F_{x1} - F_{x2})^2 + (F_{y1} - F_{y2})^2 + (F_{z1} - F_{z2})^2 < F_{max}^2$$

were, F is the force in the x, y, z directions for grid point on the frame(1) and the skin(2). An elastoplastic material is defined for the model. A material failure model for the shell elements is defined. The failure criteria was defined in terms of equivalent plastic strain of the material. The skin and the frames are made of 7075-T6 aluminum alloy. For this analysis MSC/DYTRAN was operated in the lagrangian mode. The panel model shown in Figure 3 was fixed at the top and bottom. This boundary condition was assumed to simulate the strength and rigidity of the B-52 longerons. At the other two free ends springs (CELAS1) were used to define an appropriate flexibility to the panel model. A spring constant of 100,000 lb/in was used in all the three directions.

Figure 3 shows the five frame stations, 1347, 1357, 1367, 1377 (Butt Joint), and 1387. All the frames in this panel are a standard Z cross-section. The flange of the Z frame is connected to the skin with three grid points. The mid grid point is the actual rivet position which is defined with a F_{max} of 4000 lbs (strength of the rivet) as the failure criterion to be satisfied for the joints to separate, the outer two grids are given a F_{max} of 1000 lbs. This value is assumed to keep the nodes tied together at the beginning of the analysis. For the butt joint, the skin panel was modeled as 0.14 in thick, to account for the splice between the frame and the skin.

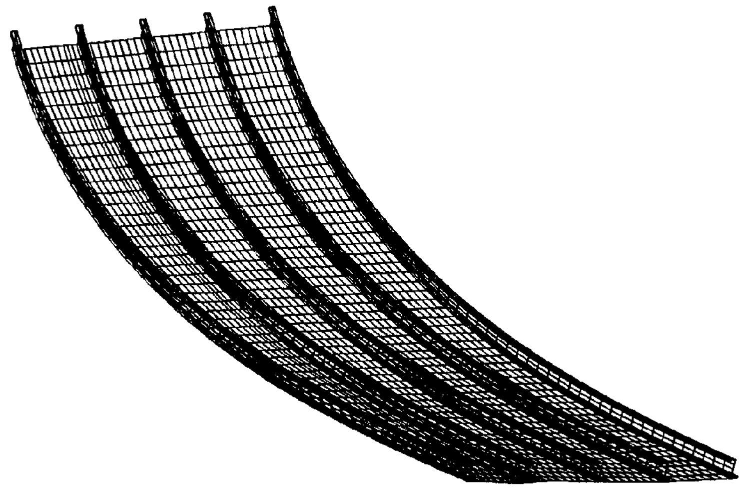

Figure 3. Local B-52 Panel Model

Analysis Results and Comparison with Tests

Global B-52 Fuselage Model

The B-52 blast tests at Davis Monthan AFB in Arizona were conducted using a series of increasing charge weights at three different locations in fuselage section 47. Pressure, velocity and strain data was obtained from gages shown in Figure 4. The data used for comparing with MSC/DYTRAN analysis results were obtained from the test results for a small size charge placed at the centroid of the fuselage cross-section at station 1367 (Figure 4).

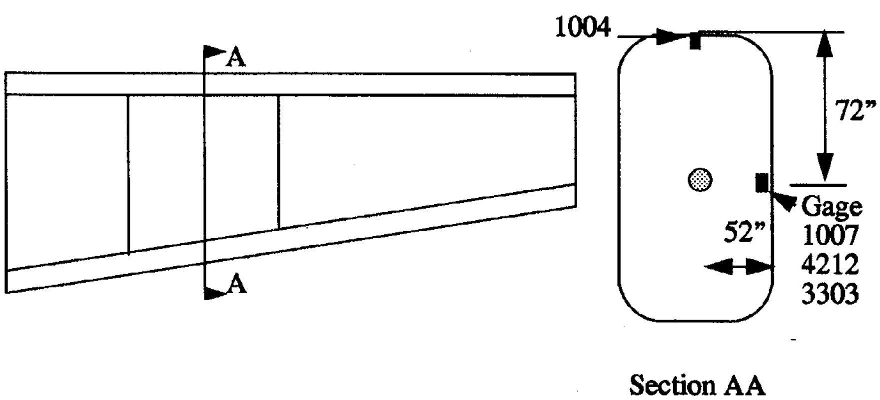

Figure 4. B-52 Pressure Gage Locations

Taking advantage of symmetry, only one half of the structure was modeled. Dynamic analysis was performed with MSC/DYTRAN. In the simulation performed the code was operated in the Arbitrary Lagrange Euler (ALE) mode. A 0.125 *lb* charge was placed at location shown in Figure 4. The detonation of the C-4 charge was modeled as a sphere with the radius corresponding to the appropriate density (1/5) and mass (0.125 *lb*) of the charge, conserving the mass and total energy of the system. The sphere was assigned the energy state corresponding to the C-4 composition. The rest of the fluid inside the fuselage was assigned the density for standard air $1.12 \times 10^{-7} slug/in^3$ and the energy state $3.27 \times 10^8 in - lbf/slug$ to correspond to standard atmospheric pressure (14.69 *psi*). To keep the relative pressure between the outside and the inside of the fuselage zero, a constant pressure of 14.69 *psi* was applied to the lagrange elements (skins) from the outside in the finite element model. The simulation was run for 10 milliseconds.

The gage locations of interest were gage 1004, which is directly above the charge at the crown of the fuselage, 72 *ins* from the charge location and gage 1007 which is at the side of the charge, 50 *ins* away from the charge. Gage 1007 is the shortest distance from the charge. The peak pressure predicted by MSC/DYTRAN for gage location 1004 (Figure 5) is about 8 *psi*, which is lower than the test pressure of 13 *psi*. The pressure spikes at roughly 3, 6.5, and 8 milliseconds correspond to the first two reflections off the bottom of the structure and the bulkheads. Note that the predicted pressure history is much smoother than the actual test data and the first peak arrives earlier than the experimental data. This can be explained in two ways. The first, namely the fact that the element cell near the wall identified as pressure gage for location 1 is 1.5 *ins* in height in the radial direction, and pressure is measured at the center of the cell (0.75 *ins* from the structure). The second effect that can be contributing is the size of the sphere that follows from 1/5 density value of charge. First of all, the pressure wave (blast) will start traveling from the outside of the sphere. Thus, the larger the sphere, the earlier the wave arrives. The second peak in the test data at 5 milliseconds, is not predicted by MSC/DYTRAN. This peak could be the reflection of the frames. The MSC/DYTRAN model has the frames defined as 1-D elements (CBEAM), and, therefore, would not cause a reflection. The same is seen in Figure 7.

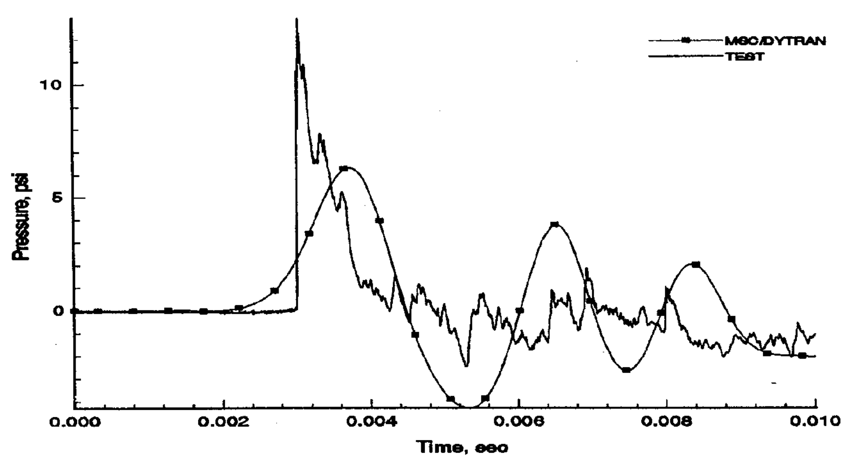

Figure 5. Pressure Data at Gage 1004

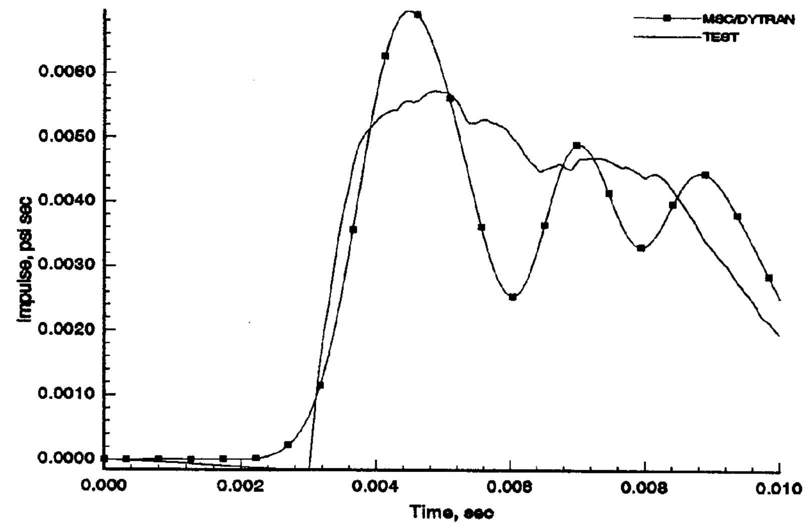

Figure 6. Impulse Data at Gage 1004

Figure 6 shows the predicted impulse for the same gage location. Figures 7 and 8 show the pressure and impulse data predicted by MSC/DYTRAN for gage location 1007. Gage location 1007 is closer to the charge by 20 *ins*, and therefore the time of arrival of the peak pressure is earlier and higher in value (11 *psi*). The comparisons between the pressure/impulse data predicted from MSC/DYTRAN were relatively satisfactory. The predicted pressure for all the locations is acknowledged to be consistently underestimated and typically not very representative of a real explosion. This is due to the fact that the explosive is modeled as an ideal gas, and inherent to this scheme the peaks will appear to be a bit wider and less high. However, the impulse is the physical quantity of importance in modeling structural response to blasts, since the loading of the structure is determined by the impulse that is exerted on the structure, and not by the peaks in the pressure. This is true for very short duration loading, say durations less than 1/5 the fundamental frequency of the structure. From Figure 5, it is clear that loading on the structure is completed by 8 milliseconds. In conclusion, the most important parameter in the analysis as far as the blast wave influence on the structure is concerned is the impulse exerted on the structure. The deviation in the peak pressures is considered as normal but not incorrect, just inherent to the method.

Figure 9 shows the predicted velocity at the same location as gage 1007. The overall magnitude of the velocity data predicted matches with the test data. The velocity peaks to 4.8 m/sec at 3.488 milliseconds in the test to 5.0 m/sec at 3.5 milliseconds in the analysis. Figure 14 shows the strain data plotted at the same location as pressure gage 1007. Due to the small charge size, there is no plastic deformation/strain in the structure. Figure 10 shows the elastic strain in μ *strains*. The test recorded 1204 μ *strains* as the highest strain at 3.5 milliseconds. The analysis predicted 984 μ *strains* at 3 milliseconds. The overall response predicted by the MSC/DYTRAN model closely matches the test data. The MSC/DYTRAN approach makes it possible to take into account complex geometries, blast wave reflection, fluid-structure interaction and highly nonlinear material properties. Hence, MSC/DYTRAN would be a powerful tool in numerical simulation and analysis of built up structures in assessing aircraft vulnerability.

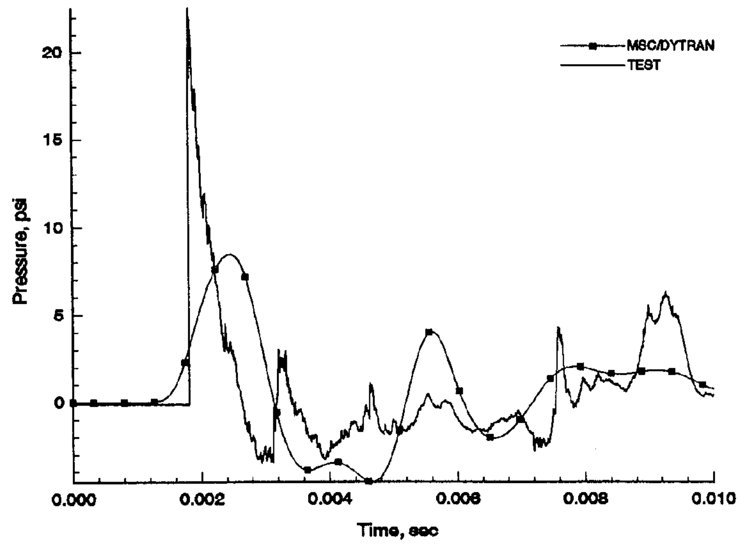

Figure 7. Pressure Data at Gage 1007

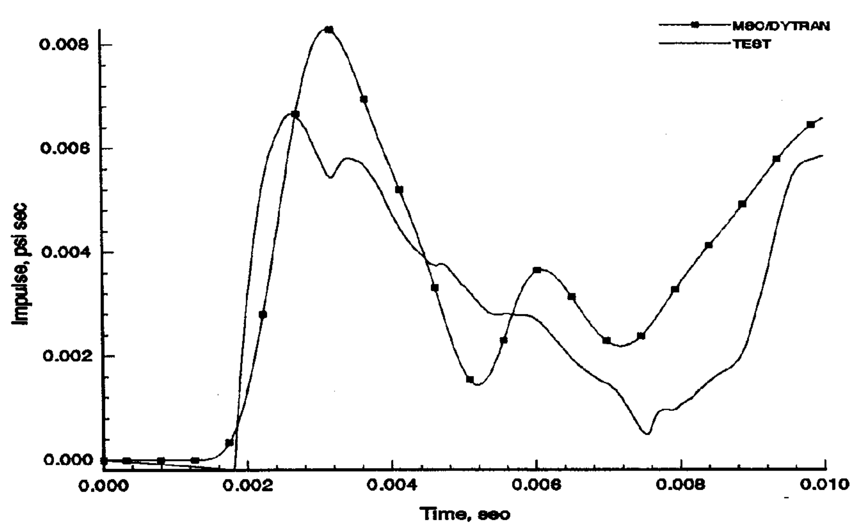

Figure 8. Impulse Data at Gage 1007

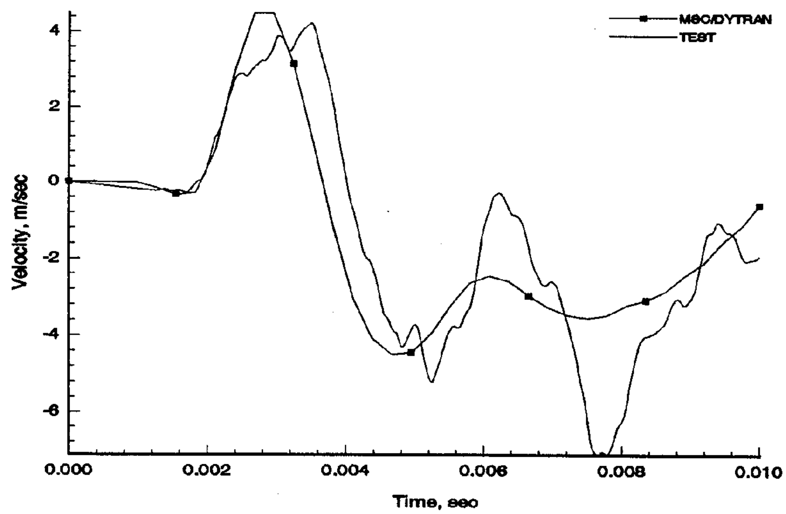

Figure 9. Velocity Data at Gage 4212

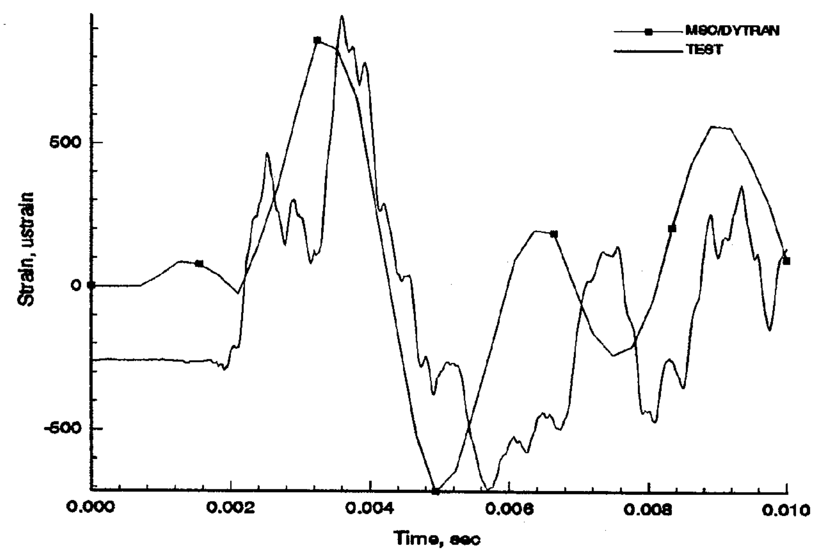

Figure 10. Strain Data at Gage 3303

Local B-52 Panel Model

As a first step, blast analysis described in the previous section was performed on the global model using MSC/DYTRAN. A charge of 1.25 *lb* was detonated at location shown in Figure 4 of station 1367. The fluid/structure interaction analysis was run for 5 milliseconds. Pressure time histories were tapped for the 32 elements between station 1347 to 1387. These pressure time histories were then applied as transient loads to the local model.

The analysis was performed for 5 milliseconds. The results obtained are plotted at different time steps. Failure criteria were established for the joint failure and the material failure of the skin and frames as discussed in the earlier section.

From the observations made during the tests conducted at Davis Monthan, it was noted that for 1.25 *lb* charge, there was no significant tear-out of the skin. Many frames around the charge location area (Stations 1347 through 1387) were damaged in a significant manner. Most of the frames buckled or crippled and a lot of rivets failed causing the separation of the frame from the skin.

Figure 11 plots the panel deformation at 2.5 *ms*. At this time step the peak pressure has subsided and a small negative pressure is being applied to the panel. From the figure buckling of a few frames is apparent. At this time step, there is no significant deformation of the skin. Stress level is around 75,000 *psi*, and the maximum strain about 0.06 *strains* around the joint connections. Indicating the onset of failure, and plastic deformation in the panel. Figure 11 shows the onset of the frame skin separation, indicating rivet failure.

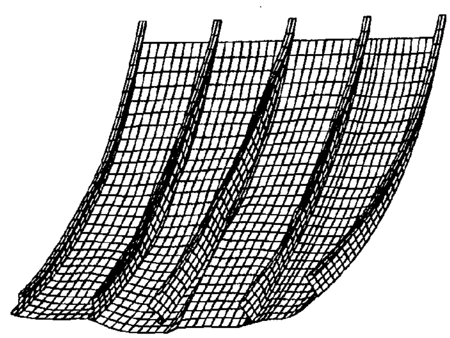

Figure 11. Frame Skin Separation at Time = 2.5 *ms*

At time step 3.5 *ms*, significant damage has occurred to the frames (Figure 12)and many joints seem to have failed separating the frames and the skin. The butt joint also shows significant failure. The buckling of the frames, is caused by the straight edges of the B-52 sides. When the blast wave hits the panel, primarily a large bending moment is created, causing the buckling of the frames. More detailed empirical analysis is provided in reference [5] .

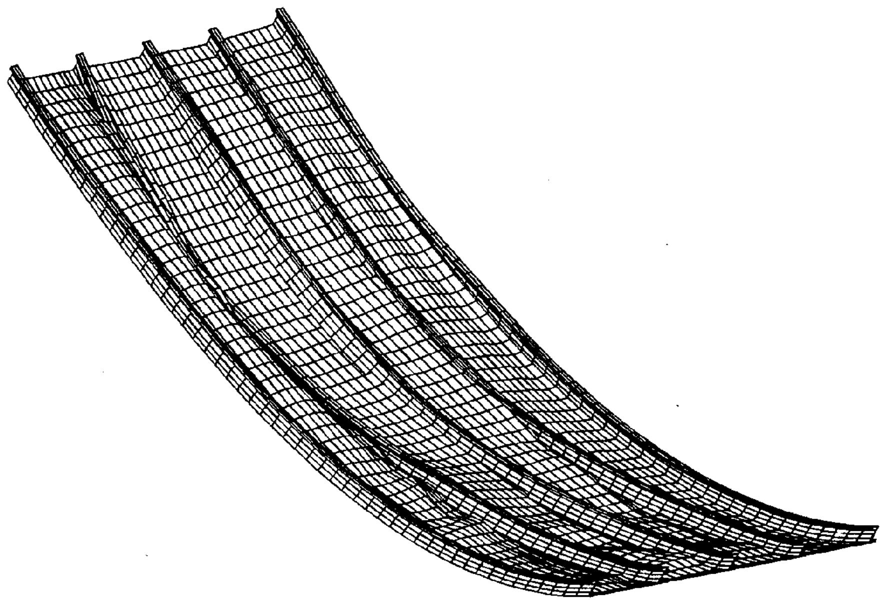

Figure 12. Displacement at Time = 3.5 *ms*

Vulnerability Analysis

The critical locations and the necessary size of the explosives vary along both the length and width of the fuselage. This suggests the idea of mapping the entire fuselage. This map will consist of points (locations) in the fuselage and a number associated with these points. The points will refer to a chart which will describe the location and size of the explosive. In this section an attempt is made to draw such a map, with a static analysis on the B-52 aft section model.

Two distinct types of failure have been identified for the vulnerability analysis with MSC/DYT-RAN.

1. Material or yield failure in the skin (failure criteria - equivalent plastic strain).
2. Compressive (buckling) or tensile failure in the frames (based on maximum and minimum stress in the frames).

The yield stress for 7075-T6 aluminum is 75 *ksi*. The first set of runs was performed for a charge being at the center of a cross section. The charge is moved through stations 1267, 1297, 1327, 1367, 1417, 1466, 1513, 1561.5, 1611. Vulnerable regions are identified by the highest compressive stress that would cause buckling in the frames, and the highest material yield stress in the frames that would cause failure of the bar element. For the skin the vulnerable regions were identified based on the equivalent plastic strain that would cause failure. Figure 13 shows the charge sizes for the center location, at which skin or frame would fail. This analysis presents a qualitative perspective of the vulnerable regions for a given location of charge. Figure 13 shows a significant dip in frame failure from stations 1327 through 1466. Through these stations the charge size dropped to 1.5 *lbs.* Near bulkhead stations 1237 and 1655, skin appears to fail before the frames.

Failure criterion was established for the skins, in terms of effective plastic strain. At present, MSC/DYTRAN does not have any failure criteria established for the bar element. Therefore, this map will be further improved after a failure criteria for the bar elements is established.

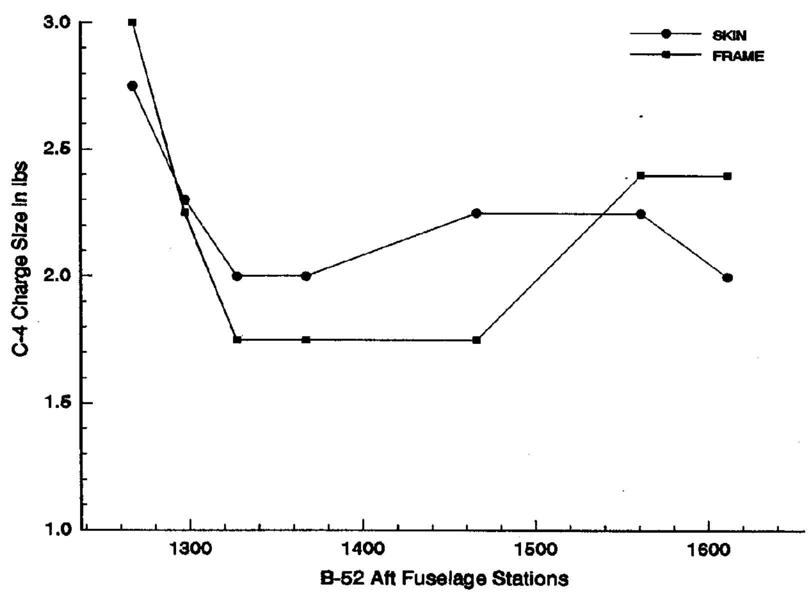

Figure 13. Vulnerability Map of B-52 Aft Fuselage

Summary and Conclusions

As part of the FAA's Aircraft Hardening Program the Air Force conducted numerous blast tests inside B-52 aft fuselages and collected vast amounts of data on the structural response and blast pressure propagation etc. A comprehensive test data reduction takes extensive effort in terms of time and resources. So far only a small fraction of the test data was analyzed. The objective of the present study is to develop comprehensive analytical models and tune them with the help of the data from the static tests. These validated models can then be used to predict the failure scenario and develop vulnerability maps of the fuselage. These maps are expected to be the key elements in evolving cost effective hardening strategies.

A preliminary comparison of the analysis and test data is extremely encouraging particularly in the case of overall structural response (velocity and strain at various points of the structure). The correlation of the measured and predicted blast impulses are also satisfactory. The magnitude of the peak pressure and its exact time of arrival do not compare as well and need further study.

Joint failure and buckling of the fuselage frames were successfully simulated through the analysis of a B-52 panel. A MSC/DYTRAN simulation corroborates well with the observed results during the tests. The concept of the vulnerability map was applied to a B-52 model with two simple structural failure criteria.The first one is based on material failure of the kin and the second one is based on failure of the frames either due to compressive or tensile forces. This map presents a qualitative perspective of the vulnerable regions for a given location of charge.

These analyses have provided a very good insight into the analysis capabilities of MSC/DYTRAN and the methodology that can be implemented while performing analysis on complex built up aircraft structures like commercial planes.

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