Design and explosive testing of a blast resistant luggage container

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Abstract

The development and testing of a blast resistant luggage container is detailed. A design was conceptualized and an analytical feasibility study was performed. Once the results of this analysis proved positive, more detailed models of the container structure were developed, small scale design specimens were constructed and tested to determine strength, and a first prototype was developed. Blast loading predictions were made with a modified wave tracing and combustion code. The first prototype was tested to failure. Based on these results, structural response and blast loading models were modified and a second generation prototype was developed. This container successfully withstood the detonation of a bomb larger than that which caused the loss of Pan American flight 103 over Lockerbie, Scotland in December 1988.

1 Introduction

Acts of terrorism against commercial aviation experienced an upsurge during the 1980’s, culminating with the destruction of Pan American flight 103 over Lockerbie, Scotland in December 1988. In response, the United States government challenged its Federal Aviation Administration (FAA) to undertake a rigorous research and development program aimed at taking a proactive stance against this rising terrorist threat. The FAA responded to this challenge by forming the Aircraft Hardening Program (AHP) in 1990. The primary focus of the AHP is to determine the vulnerability of the commercial aviation fleet to internal bomb detonations, and to identify means of increasing this vulnerability. One such method is to increase the explosive resistance of luggage containers that are normally located within the cargo bays of wide-body transport category aircraft.
Blast resistant luggage containers, if deployed, would protect aircraft and potentially save the lives of passengers and crew. They would offer immediate protection against explosives located in checked luggage, and have a low impact on commercial aircraft operations. However, in order for blast resistant containers to be accepted by the user community, they must not only meet a blast resistant standard, but should exhibit compliance with current design standards for luggage containers, carry reasonable tare weight and unit cost, have high durability (i.e., low frequency of repair), maintainability (i.e., simple inspection and repair procedures), and minimal impact on airline operations. This paper describes the design, development, and testing of an LD-3 type blast resistant luggage container that satisfies many of these criteria. Emphasis is placed on the blast loading models and the results of explosive testing on the container prototypes. Explosive weights are not discussed due to the sensitive nature of the subject matter.

1.1 General Container Design Concept
The design envisioned by Galaxy Scientific engineers is predicated on a blast management philosophy, whereby the explosive products are vented in a controlled fashion to alleviate and distribute overpressures. The concept is based on positioning the container door on the inboard panel, as in Figure 1. In application, two containers would be placed in a door-to-door arrangement, which should not add any operational difficulty for a full airline flight. The spacing between the two containers is approximately 2 inches around the periphery in a typical cargo bay. This arrangement is illustrated in Figure 2.

The container is composed of distinct panels connected by a series of joints. The panels can be chosen from a number of different materials. Primary considerations are high strength, low density, and high impact and fire resistance. Other issues are durability, repairability, and operability. The joints are attached to the panels through a variety of fastening devices. Corners are structurally reinforced.

During an explosive event, the panels have sufficient strength to withstand the preliminary forces and are allowed to expand in a spherical fashion by the joints. Explosive products are vented through the door opening, which can be made out of any frangible material(s). The explosive products are generally focused into the adjacent container, although a small amount of venting occurs between the container gaps. The adjacent container serves to reduce the loads significantly by providing more volume immediately in which the explosive products may expand. Furthermore, luggage in both containers will remove energy from the system through a number of mechanisms, such as crushing, translation and rotation, and heat transfer. The panel strength is sufficient to contain the low velocity (secondary) fragments, as well as any probable high velocity (primary) fragments. Overpressure is then gradually vented throughout the cargo bay of the aircraft.
2 Concept Feasibility

In order to determine if a functional design could be feasibly developed based on the philosophy outlined above, scoping calculations were performed using a single degree of freedom model to represent the container panels. The panel material was selected based on a review of commercially available high-performance materials. Blast loadings were determined for the threat level recommended by the FAA AHP, and the results, in terms of panel thickness, were used to estimate a tare weight for the container. Based on this weight, a go/no-go decision was made regarding more in-depth analysis and design, leading to eventual development of a prototype container.

2.1 Materials Selection

A materials selection process was performed to identify a family of high strength/low weight materials that could be employed in the container design.
Materials investigated included aramid and glass fiber composites, high strength aluminum alloys, and fiber reinforced laminates. Based on comparisons of strength, stiffness, density, and cost, as well as more subjective criteria such as durability, manufacturability, and user acceptance, the fiber reinforced laminate GLARE® was selected for the prototype design.

GLARE® consists of aluminum alloy sheets laminated with layers of fiberglass epoxy prepreg. The material lay-up consists of any combination of \( n \) layers of aluminum sheet and \( n-1 \) interlayers of fiberglass/epoxy prepreg (e.g., 2/1, 3/2, 4/3, etc). It comes in several configurations, but the two configurations chosen for the container application are the GLARES and GLARE5 products. The principal properties for the materials are shown in Table 1.

### Table 1. Typical GLARE® Properties.

<table>
<thead>
<tr>
<th>Mechanical Properties (Typical)</th>
<th>GLARE3</th>
<th>GLARE5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2/1</td>
<td>3/2</td>
</tr>
<tr>
<td>Tensile Ultimate Strength (KSi)</td>
<td>L</td>
<td>96.0</td>
</tr>
<tr>
<td></td>
<td>LT</td>
<td>94.7</td>
</tr>
<tr>
<td>Tensile Yield Strength (KSi)</td>
<td>L</td>
<td>45.7</td>
</tr>
<tr>
<td></td>
<td>LT</td>
<td>41.6</td>
</tr>
<tr>
<td>Tensile Modulus (MSi)</td>
<td>L</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>LT</td>
<td>8.7</td>
</tr>
</tbody>
</table>

While both GLARE3 and GLARE5 have 2024-T3 aluminum alloy sheets, each interlayer of fiberglass prepreg is 0.020 inches in the GLARES versus 0.010 inches in the GLARES. The interlayers have a 50% parallel and 50% perpendicular fiber orientation. A 0.012 inch thick aluminum sheet was selected for this application.

In addition to the properties described above, the material offers a substantial increase in impact resistance over conventional aluminum, and passes the firewall material flame penetration requirements of FAR Part 25, Appendix F, Part III.

### 2.2 Proof-of-Concept Model

The scoping calculation analysis provided a rough estimate on panel thicknesses and overall weight of a blast resistant container based on the design philosophy and materials selected. The model used to perform the scoping calculations consisted of two main parts: loading and dynamic response.

The blast loads were derived from the U.S. Navy INBLAST code, which approximates bare explosive detonations with a wave tracing algorithm. Shock loading includes first order Mach Stem effects. The code also has a combustion algorithm to predict longer duration quasi-static pressures (QSP). The QSP calculations allow for venting of the explosive products into an
adjacent chamber and/or into the ambient air. In order to obtain a pressure time history, a structure must first be geometrically defined and the explosive charge then located within the structure.

For each panel, the pressure-time history was approximated by a bi-linear pressure-time function, as shown in Figure 3. Peak pressures, times of arrival, positive phase durations, and QSPs were available and taken from the INBLAST analysis. This analysis was performed for a bare spherical charge of the given threat level located at the geometric center of the container. The container itself was considered empty of luggage. These data were then entered into the equation of motion for the system.

![Figure 3. Idealized Pressure-Time History for Loading Model.](image)

Based on the ratio of estimated panel length to thickness (260 and above), a 1-dimensional membrane (large displacement) model was assumed for the dynamic response calculations. An elastic, perfectly plastic stress-strain model was adopted to approximate the behavior of the material. Using methodology developed by the AHP [1], which was adopted from both Timoshenko [2] and Biggs [3], equivalent mass, resistance, and load terms were derived in order to solve the equation of motion for the system. This equation was then integrated numerically to determine the minimum thickness of each panel in the container to avoid failure. The largest calculated thickness from the analysis was 0.15 inches. From this, a container weight estimate of 450 pounds was derived. This result was promising enough to continue the development program.

### 3 Prototype Analysis, Design, and Testing

Once the feasibility study proved positive, more detailed analysis and scaled component testing was performed to support the prototype design. From this design, a prototype container was constructed and then tested to failure.
3.1 Analysis and Design

Modified loading models were adopted to reflect the realities of a container filled with luggage. Finite element models of individual panels and a global container model were developed to refine the scoping calculations for panel thicknesses, and to analyze the container response to the blast loads as alternative panel/joint/fastener concepts were evaluated.

The updated blast models considered test data developed by FAA AHP for explosives cased in luggage and for internal blast testing. These data, reported by Gatto and Mayerhofer [4], indicate that luggage attenuates the blast energy considerably. The graphic in Figure 4 shows this trend. The loading models were modified to consider that the explosive charge was cased in a piece of luggage, and surrounded on all sides by at least one additional layer of luggage. This change reduced the peak pressures. The vent area between the two containers was also reduced from 25 to 5 square feet to represent blockage of the door by suitcases. This change affected the duration of the venting process, but did not affect the magnitude of the maximum QSP. The bi-linear model was again used as input to the structural response models.

![Figure 4: Blast Attenuation for Explosives Cased in Hard-Sided Luggage.](image-url)
The minimum panel thicknesses and resultant plastic strains for each panel were determined by a finite element analysis and are based on GLARE5 properties. This analysis indicated that the bottom panel was under the greatest stress. While all other panels satisfied the failure criteria at 0.060 inch thicknesses, the bottom panel required a 0.070 inch thick material.

GLARE5 material in a 3/2 lay-up, with 0.012 inch aluminum sheet for a total thickness of 0.076 inches was selected for the design. Small scale specimens of several different panel/joint concepts were then constructed and tested to failure under static loading conditions to determine strength. An equivalent static load was obtained from the individual panel analysis, and this criteria was used to accept/reject the joint concepts. The strongest joint concept was incorporated into the container design.

3.2 Prototype Testing and Results
The first Galaxy Scientific prototype container was tested under the direction of the FAA in February 1995. The primary test objective was to determine if the design met or exceeded the anticipated standard for blast resistant containers. Secondary test objectives were to measure the container response in the explosive environment, to obtain more precise data on loads encountered, and to determine means of optimizing and/or improving the container design.

3.2.1 Test Set-Up Figure 5 schematically represents the position of the containers immediately prior to the explosive testing. Since the design is predicated on venting the explosive products from one container to an adjacent container of similar design, a steel-reinforced container was used to simulate this arrangement. The prototype container is labeled A in Figure 5, and the "dummy" container is labeled B.
The containers, once loaded to about 75% capacity and with the charge emplaced as closely as possible to the geometric center of the container, were positioned so that they were both laterally and longitudinally aligned, with a spacing of approximately 1 inch between them. Documentation consisted of 11 cameras (video, high speed, and motorized still), 2 pressure transducers (one in each container), and 2 accelerometers (located on the prototype top and side panels, respectively).

3.2.2 Test Results One test was performed at the given threat level. Unfortunately, instrumentation data was not acquired because data acquisition software failed. However, camera coverage provided much useful information. Initial panel responses were localized and were of short duration and magnitude. These responses occurred within 10 milliseconds (ms) of detonation and could be attributed to the shock wave attenuating at different rates as it propagated through surrounding luggage. A more uniform QSP loading followed the localized loading. The panel response to this loading began with a deflection at the center with deformations expanding radially outward from this point.

The prototype container expanded to a maximum deformed shape, and then began to collapse back to its original shape. At approximately 65 ms after detonation, failure initiated midway in the joint connecting the top and side panels, causing the top panel to separate from the joint. Once this occurred, the damage propagated quickly along both directions of the joint-panel line, and complete separation was evident at 80 ms. The corresponding upward momentum of the top panel caused the corner bracket connecting the top and side panels with the door frame to eventually fail at about 120 ms, allowing the top panel to fly up and flip over.

Approximately 25 ms after detonation, the first obvious sign of venting between the two containers appeared in the form of the blast expanding into the dummy container. This venting was continuous and apparent until the eventual container failure. The amount of high pressure gas vented into the dummy container was sufficient to cause the top and side panel structure to deform and respond in a manner similar to the prototype panels, but to a lesser degree.

3.2.3 Test Recommendations Based on the test results described above, a number of design elements were evaluated and their performance was either deemed satisfactory, or recommendations for improvement were made.

The GLARE5 panels performed adequately from a strength perspective as evidenced by a lack of tearing or any bearing failures caused by the loading. The material also displayed an exceptional resistance to fire.

Analysis of the high speed film indicated that the length of time required to relieve the pressure from one container to the other was higher than originally predicted. This was likely due to the presence of blockages (i.e., luggage) within the dummy container. The extended loading times could have contributed to exceeding the design loads of the prototype. The loading models
were modified to account for the extended venting time, as well as the rise time of the QSP and spherical propagation of the loads.

Finally, the chief cause of failure was found to be shear in the attachments between the panel and joint. The attachments were redesigned with higher strength and closer spacing requirements. Staggered placement was also used to reduce the ease with which cracks and failures could propagate.

4 Second Generation Design and Testing

The recommendations from the testing of the first prototype were adopted into the second generation design. This container had the following major design improvements over the first prototype: increased joint thickness to enhance bearing strength; use of larger diameter attachments, reduced center distances, and staggered placement in multiple rows along the panel/joint periphery; and use of thicker panels, specifically GLARE5 in a 4/3 lay-up, with a total thickness of 0.108 inches. This container was tested in September 1995 under the direction of the FAA. The test objectives and test set-up were identical to the previous test.

4.1 Test Results

Two tests were performed, the first at a small charge weight to verify equipment operation and test procedures, and the second at the given threat level to determine if the second generation prototype satisfied the anticipated standard for blast resistant containers.

All equipment functioned properly during the first test. The prototype exhibited no signs of permanent deformations or damage. After removal of destroyed luggage items, the prototype and dummy container were repositioned for the second test. The container successfully withstood the explosive forces from this detonation. A pressure record from this test is presented in Figure 6. Note that the zero time is not time from detonation.

![Figure 6: Pressure-Time History for Test 2.](image)
The container panels deformed spherically. As deformation reached a maximum value, venting was clearly evident between the two containers. The pressure record in Figure 6 indicates that localized shock pressures were followed by a longer duration QSP with a peak of approximately 50 psi. From the pressure record of the dummy container (not shown), a QSP peak of about 10 psi was evident. Only a minimal amount of venting seems to have occurred from gaps in the joints at other surfaces, and via the gap between the two containers. In the seconds following the test, smoldering and smoke was evident, but no fire was present. No perforations or impact impressions from fragments were observed on the container interior surfaces.

After the test event, the container was disassembled for more detailed study of how individual elements performed. Permanent panel deformations ranged from about 7 inches in the top panel, to no permanent deformation in the sloping and bottom panels. No signs of GLARE® delamination were evident. All fasteners were removed and visibly inspected for signs of tensile and shear yielding, but such was not evident on any fastener. This indicates that the panel/joint attachment was over designed.

5 Conclusions and Continuing Work

The second generation prototype successfully withstood the detonation of the established threat level for a blast resistant container. The next steps in the design process will focus on optimizing the container to reduce its weight. Minor design changes will also be made to ensure compliance with current luggage container standards. The FAA is conducting an operational test and evaluation program for blast resistant luggage containers during 1996 and 1997. It is the hope of the Galaxy Scientific design team to be selected to participate in this program.

6 References