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Design and test of a blast shield for boeing 737 overhead compartment

Xinglai Dang and Philemon C. Chan*
L3 Communications, 3394 Carmel Mountain Road, San Diego, CA 92121-1002, USA

Abstract. This work demonstrates the feasibility of using a composite blast shield for hardening an overhead bin compartment of a commercial aircraft. If a small amount of explosive escapes detection and is brought onboard and stowed in an overhead bin compartment of a passenger aircraft, the current bins provide no protection against a blast inside the compartment. A blast from the overhead bin will certainly damage the fuselage and likely lead to catastrophic inflight structural failure. The feasibility of using an inner blast shield to harden the overhead bin compartment of a Boeing 737 aircraft to protect the fuselage skin in such a threat scenario has been demonstrated using field tests. The blast shield was constructed with composite material based on the unibody concept. The design was carried out using LS-DYNA finite element model simulations. Material panels were first designed to pass the FAA shock holing and fire tests. The finite element model included the full coupling of the overhead bin with the fuselage structure accounting for all the different structural connections. A large number of iterative simulations were carried out to optimize the fiber stacking sequence and shield thickness to minimize weight and achieve the design criterion. Three designs, the basic, thick, and thin shields, were field-tested using a frontal fuselage section of the Boeing 737–100 aircraft. The basic and thick shields protected the integrity of the fuselage skin with no skin crack. This work provides very encouraging results and useful data for optimization implementation of the blast shield design for hardening overhead compartments against the threat of small explosives.

1. Introduction

Commercial aircraft is a vulnerable target for terrorist bombing, and the optimal solution to ensure aircraft safety against bomb threats should involve a combination of structural hardening and detection. While detection is still the primary countermeasure, detection of explosives in carried and checked baggage is time consuming, and small, but potentially lethal levels of explosives can still escape detection. A complete dependence on detection for blast defense will be prohibitively costly, if not impossible.

Previous studies have demonstrated the feasibility of adding blast hardening to protect the aircraft in flight. The feasibility of using a Hardened Unit Load Device (HULD) in place of the current unhardened devices for transporting checked luggage in the cargo compartment on wide-body aircraft was studied and proven by work sponsored by FAA [3]. The HULDs were designed to contain a quantity of explosive greater than the lower limits of present detection equipment [3]. This provides an onboard countermeasure against bomb threats from the checked luggage.

While the HULD will protect aircraft against bombs placed in checked baggage, the aircraft is still vulnerable to threats from small explosives smuggled on board. Even small quantities that fall below the established lower limits of present detection equipment can be stowed in an incendiary device on-board an aircraft in carry-on overhead luggage compartments. Setting off such devices in an unhardened overhead bin can result in extensive and serious damage to aircraft fuselage structures that will lead to in-flight catastrophic failure. Hardening of aircraft overhead bins can provide crucial additional protection against terrorist bombing attempts.

Previous work indicates that the use of composite materials can provide an effective, lightweight method for blast hardening of an overhead luggage bin. High-strength, man-made fibers were utilized in the design of HULD using a

*Corresponding author. Tel.: +1 858 720 4114; E-mail: Philemon.Chan@L-3com.com.

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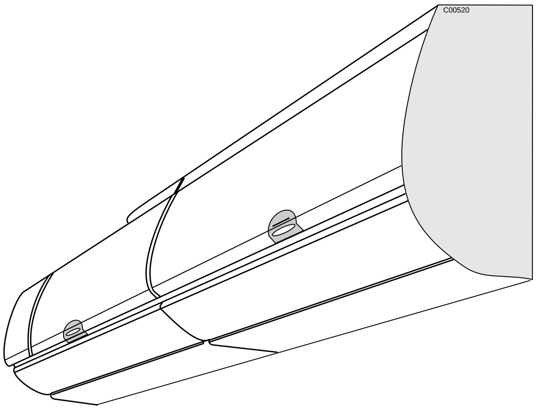


Fig. 1. Schematic of overhead compartment on the Boeing 737 aircraft.

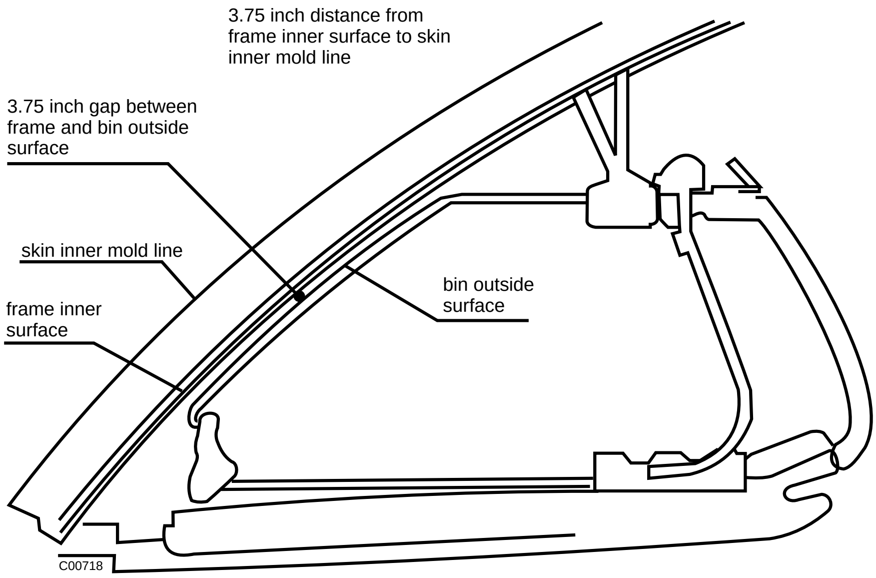


Fig. 2. Boeing 737 overhead bin cross-section.

unibody concept. In work sponsored by the National Institute of Justice (NIJ), the same methodology was also used for the development of a relatively low cost, lightweight, easily transportable container for police departments to use as temporary storage containers for potentially explosive devices. The present work adopts the similar unibody composite technology with finite element model simulations playing a central role in the design.

The objective is to demonstrate the feasibility of using a blast shield to harden the current Boeing 737 overhead bin compartments without requiring any modification of bins already in use [2]. Figure 1 shows the general shape of an overhead bin in a Boeing 737-type aircraft. Figure 2 shows the cross-sectional view of the bin attachment to the fuselage. The 737 aircraft compartment unit is 80 in. long by about 20 in. high and 32 in. deep. It has two doors, each 40 in. long, which swing out of the compartment. A compartment unit is supported on the aircraft frames, which, like circular rings, are arranged one by one along the aircraft axial direction and about 20 in. apart. A blast shield design should fit into the compartment itself without the need of aircraft structural modification. This study includes material selection, flame tests, shock holing tests, material model validation, shield design and construction, and field testing.

2. Method

2.1. Design considerations

The purpose of the blast shield is to protect the fuselage structural integrity, especially the outer skin, against a certain charge level detonated inside the bin. The inner shield design is adopted because of its easy installation into existing bin compartments (Figs 1 and 2). Thin shell structure is the best choice because of the minimum material required for maximum area coverage. To provide strong protection to the fuselage structure with minimum weight penalty, the shield should be made of composite materials with high strength-to-weight ratio, high stiffness, and high fracture toughness. Ballistic armor protection material is needed to laminate the shell structure against fragments. Composite material is sensitive to machining, which can easily cause local damage to the composite material in the form of delamination, fiber breakage and matrix crack. To avoid these failures, a unibody blast shield design is adopted. To increase bending stiffness, the critical portion of the shield uses a wavy shell shape to help reduce deformation during the blast event.

According to TSA/FAA regulations [1,3] the blast shield must satisfy the Code of Federal Regulation (CFR) requirements for flame resistance [1], which affects the selection of materials. For composite materials, however, a proper fire retardant chemical component can be integrated into the matrix to serve the purpose.

The design must account for the structural coupling with the fuselage and frame responses. A retired top half frontal fuselage section of a Boeing 737 aircraft was purchased for design and field testing. A complete fuselage section was modeled using finite element method. The finite element analysis (FEA) software, LS-DYNA [4,5] was used as the design computational tool. Shock holing tests provided guidance for the selection of material failure models in LS-DYNA.

2.2. Blast load

If a blast is inside an enclosure, the blast loading applied on the walls is dependent on the charge type and weight, standoff, the surrounding materials and ventilation [1,6–13]. The multiple reflections of the blast wave in an enclosure play an important role, resulting in a long duration and complex pressure loading on the enclosure walls. The significance of the multiple reflections depends on many other conditions.

For an overhead compartment, the blast loading depends mostly on the first shock, since the compartment will be easily destroyed by it. The first shock is also the primary blast loading in a well-vented container. Therefore, in our design simulation and finite element analysis, the design loading is based on the first shock reflection loading on the inner surface of the bin. Experiments for blast loading in a container [6] show that the shock waves are strongly dissipated when the charge is surrounded by luggage. But so far the effects of the dissipation from the luggage are not completely understood. It is conservative to consider a bare charge inside the overhead compartment for design.

The Conwep Code was used to predict the blast loading from a bare charge in air. Conwep is already integrated with LS-DYNA3D for structural analysis simulation. Conwep is a collection of conventional weapons effects calculations from the correlations found in TM-5-855-1, "Fundamentals of Protective Design for Conventional Weapons [21]." However, multiple reflections of shock wave are ignored by Conwep.

2.3. Survey of materials

Materials were surveyed to screen candidates for the blast shield while maintaining minimum weight and cost. Because of their extreme stiffness and high strength with low density, fiber-reinforced polymer matrix composite laminates have been widely used for high-performance structures [14–17]. When compared with conventional metals, composite laminates have a higher stiffness-to-weight ratio and strength-to-weight ratio as well. The material cost is usually higher than that of conventional metals, with the cost of the molding tool, lay-up and curing factored into the manufacturing price. The resulting mold is then used for the lay-up of laminates in a specific shape. Once the mold is made, however, it can be used repeatedly for manufacturing hundreds of parts. As a result, even though the cost of composite laminates is relatively high for construction of the research testing samples, it will actually be much cheaper in mass production.

Fig. 3. Shock holing test set-up for test panel.

Since concern for the weight of the blast shield is a dominant factor for commercial aircraft, a wide variety of composite materials was included in the survey. Low-density metal such as aluminum was used for comparison. Metal materials ordinarily have much larger plastic deformations before breakage than composite laminates, and may be more vulnerable to shock holing. An explosion in the overhead compartment may generate metal or nonmetal fragments that can be a serious threat to aircraft structure, the perforation of the outer skin of the fuselage in particular. Kevlar can be laminated into the blast shield as one or more layers for protection against fragments.

2.4. Fire test

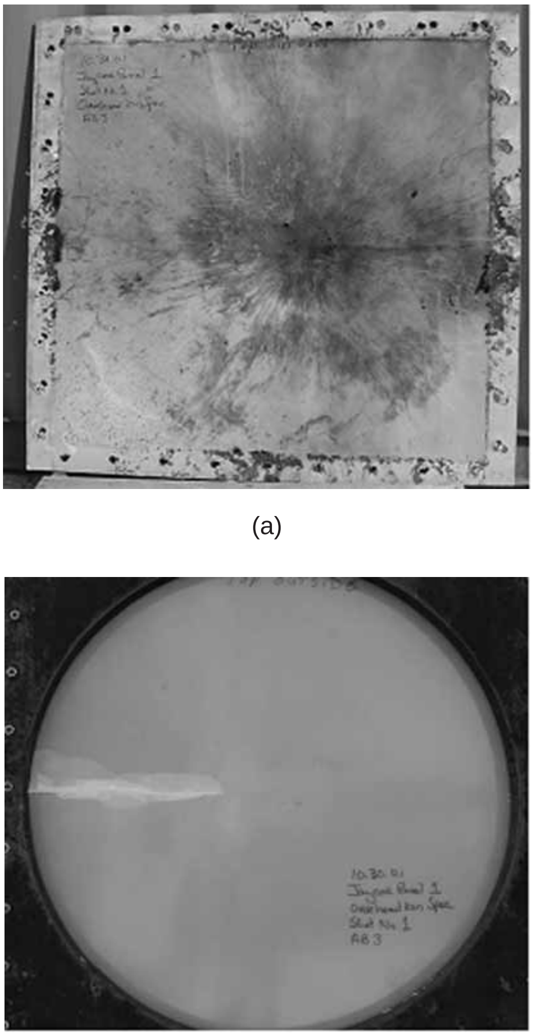
Once materials were selected, they were subjected to fire testing according to CFR Part 25.853a, b [1], which regulates fire testing for aircraft passenger compartment materials. In order to comply with CFR Part 25.853a, b [1], the selected materials were laminated to the thickness of the blast shield as a flat plate and then they were cured. Test specimens cut from the plate were subjected to pass four distinct tests:

- Vertical Bunsen test (25.853a);
- Vertical Bunsen test (25.853b);
- Heat-release rate test;
- Smoke test

By passing these tests, the selected materials were qualified for use in the blast shield.

2.5. Shock holing test

When the charge is placed at a short distance from the blast shield, the shock can perforate the shield, a phenomenon called shock holing. Shock holing tests were used to assess the resistance of blast shield materials to shock perforation. For our blast shield design, the shock holing test data were also used to evaluate the material models in the FEA software LS-DYNA. Failure in the composite laminates includes fiber breakage, delamination, and matrix



(a)

(b)

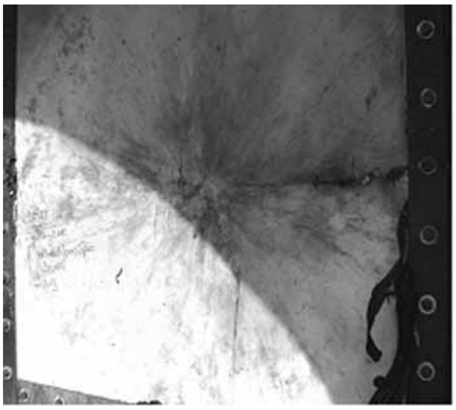
Fig. 4. Panel 1 after shock holing test. (a) Inside view; (b) Outside view.

crack. Any combination of these failure modes will significantly affect the performance of the laminates. During the blast event, the blast shield may experience some of these failure modes. The choice of failure models directly affects the design results of the blast shield in the simulation.

In general, three failure models in LS-DYNA (material models 22, 54 and 55) are used for composite laminates. Material model 22 is the Chang-Chang failure model for an orthotropic material, with an optional brittle failure for composites. Material models 54–55 are enhanced models where unidirectional layers in an arbitrary orthotropic composite shell can be defined. Material model 54 is an enhanced material model 22, and model 55 is the Tsai and Wu failure model. Material models 54–55 usually give similar results and compare well with test data, while model 22 usually results in a more conservative design [18]. In order to select a proper material model, specimens were designed using the different material models for shock holing tests to validate the material models.

2.6. Coupled fuselage finite element model

A fuselage finite element model was constructed to simulate the response of the aircraft structure coupled with the bin with the blast shield installed when subjected to a blast in an unpressurized condition. The simulation results



(a)

(b)

Fig. 5. Panel 2 after shock holing test. (a) Inside view; (b) Outside view.

were used to analyze the effectiveness of the blast shield. A simulated design was considered acceptable when the blast shield was not perforated and the fuselage did not show structural failure. The dimensions of the fuselage structure were obtained from field measurements. The material data were estimated based on standard handbook values and "best guess" [19]. Most of the primary structure was made of either 2024-T3 or 7075-T6 aluminum. The bin structure included some composite and foam materials, besides aluminum. For a used aircraft, material strengths such as yield stress, ultimate stress and elongation strain should be lowered from the regular values to account for stress risers, fatigue damage, size effects and corrosion [19].

When a unibody blast shield is selected as the design approach, the weight penalty becomes a concern. To withstand a certain shock load, a flat blast shield would require a certain thickness to obtain adequate stiffness and strength. A thinner wavy blast shield can possibly provide the same strength with less weight, but the wave amplitude has to be limited to a small range to minimize intrusion of the overhead compartment space. To optimize the wavy shape design, extensive finite element model simulations for different shield shape candidates and material variations were carried out.

Using a large number of model simulations, three inner blast shields were designed for the field tests. Two of them, the basic shield and thick shield, were based on different composite material models, and the third, the thin shield, was a thin design to explore the possibility of substantial weight reduction.

Fig. 6. A Boeing 737–100 fuselage section used for pre-prototype field tests.

Fig. 7. Bin location and attachment in Boeing 737–100 fuselage section.

2.7. Field test

Field tests in an unpressurized condition were carried out for the three shield designs at Aircraft Restoration, Tucson, Arizona. The tests were conducted using a top front half fuselage section of a Boeing 737–100 retired aircraft with all original bins intact. Each shield was installed in a bin and tested separately using the same charge level and placement inside the bin. Only video and photographic data were taken. Grids were drawn on the fuselage outer skin to indicate deformation after each blast. High-speed video data were taken to evaluate the deformation of the fuselage outer skin. Each shield was examined for failure after the test.

3. Results

3.1. Material survey

The survey of composite materials is shown in Table 1. For optimization of cost and weight, E-glass/epoxy and Kevlar were selected to fabricate the blast shield. E-glass fiber is widely used in industry and is very low cost. Its

Table 1
Survey of composite materials

Items/Materials	Sp/Ep	Ar/Po	Gr/Ep	S-gl/Ep	E-gl/Ep	Alum.
Material type	YLA RS-1(w)	Ke281/F141(w)	IM7/Ep	Sp-250/Ep	Scochply 1002	2024-T3
Fiber volume frac. (%)	66.10	56.00	62.00	60.00	45.00	
Longitude modulus (msi)	1.93	4.80	22.10	6.70	5.50	10.00
Transverse modulus (msi)	1.80	4.80	1.30	1.90	1.20	10.00
Poisson's ratio	0.062	0.05	0.33	0.29	0.26	0.30
Shear modulus (msi)	0.26	0.21	0.71	0.74	0.60	3.80
Tensile strength l(ksi)	61.67	73.00	362.00	200.00	154.00	50.00
Tensile strength t(ksi)	61.05	73.00	12.20	8.60	4.50	50.00
Shear strength (ksi)	15.39	7.90	23.30	13.80	10.40	28.90
Fracture toughness	High	High	Low	Low	Low	Low
Cost	V. high	High	High	Low	V. low	V. low

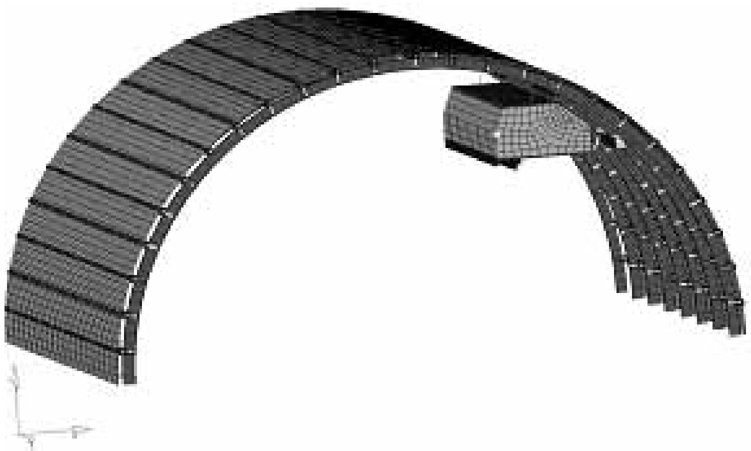


Fig. 8. Full fuselage coupled with a bin finite element model.

tensile strength is superior to aluminum and comparable to ballistic armor materials Spectra and Kevlar. Its density is about half that of aluminum, but is 50 and 30 percent higher than that of Spectra and Kevlar, repectively. Spectra, however, is very expensive. Compared to Graphite, E-glass is much cheaper, while Graphite is stiff but brittle. S-glass has mechanical properties that are slightly more superior to those of E-glass, but it is much more costly. Kevlar was selected because it is much cheaper than Spectra and widely used as a ballistic material for fragment containment. The Kevlar material was laminated in the blast shield to reinforce the resistance to shock perforation and contain fragments.

3.2. Shock holing tests

Two designs were fabricated for shock holing tests using panels consisting of the selected materials. The designs were based on two separate material damage models (Mat 22 and Mat 54–55). That is, when E-glass/Epoxy and Kevlar laminate was designed as a test panel, it was modeled with Mat 22 or Mat 54–55 in LS-DYNA to simulate the shock holing test. After surviving the shock loading without perforation based on the adjustment of its stacking sequence and thickness using a large number of simulations, a test panel design candidate was obtained. Based on minimum weight and thickness, the best case of all the design candidates was then selected. The finite element simulations of shock holing tests using LS-DYNA resulted in the following two panel designs:

Panel 1 (based on Mat 22):
44.5” $\times$ 44.5” $\times$ 0.35,” cross ply laminate
0.30” thick of E-glass $+$ 0.05” thick of Kevlar

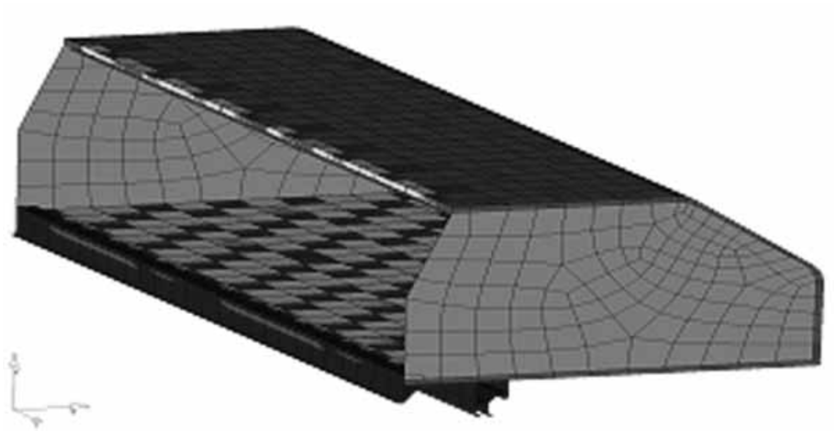


Fig. 9. Bin finite element model.

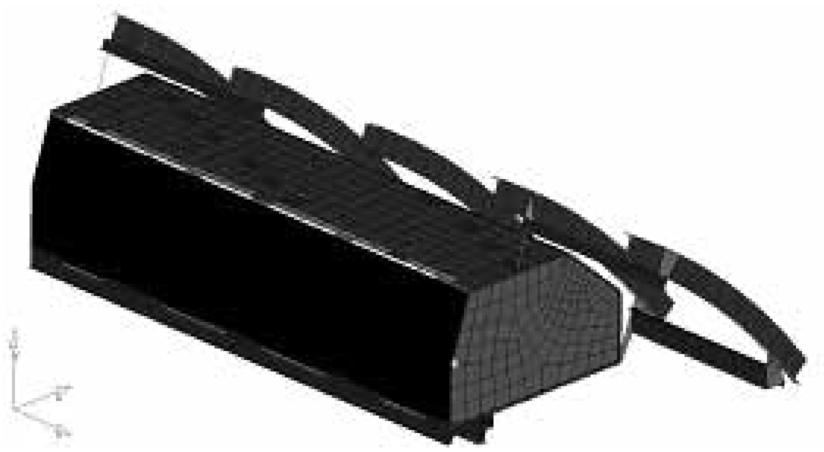


Fig. 10. Front view of the bin attachments to frames.

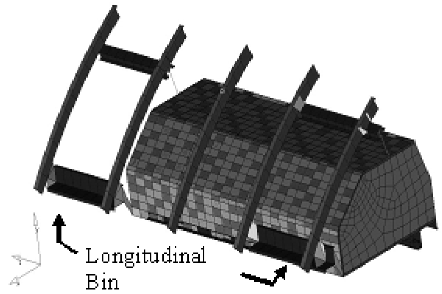


Fig. 11. Back view of the bin attachments to frames.

Panel 2 (based on Mat 54–55):
44.5” × 44.5” × 0.27,” cross ply laminate, all E-glass

Manufactured by our fabricator, Composiflex, the panels were sent to TSA for shock holing tests. As shown in Fig. 3, the test panel was mounted on a test frame using bolts. The test frame had a circular opening (Fig. 4). A certain charge was placed in a bag located close to the center of the panel, and the bag was held on the back side of

Fig. 12. Basic shield.

Fig. 13. Thick shield.

the test frame by strings.

As seen in Figs 4 and 5, after explosion both panels survived the shock without perforation, although some fiber breakage and delamination were induced. Both panels passed the shock holing tests, indicating that the E-glass/Epoxy laminate with thickness no less than 0.27 in. can withstand the shock without perforation for the specified charge and distance. By comparing the damage in both test panels, it was concluded that Mat 22 was conservative, and Mat 54–55 was adequate and could be used for blast shield design. Therefore, the tests validated the finite element material and failure models.

3.3. Fire test

For the five tests conducted by FAA, specimens were made of E-glass/epoxy and Kevlar. Four distinct tests were carried out:

- Vertical Bunsen Burner test (per FAR Part 25.853a: 60 second burn).
- Vertical Bunsen Burner test (per FAR Part 25.853b: 12 second burn).
- Heat-release rate test.
- Smoke test.

All specimens passed the above tests in compliance with CFR Part 25.853a, b [1].

Fig. 14. Thin shield.

Fig. 15. Inside view of basic shield test set-up.

3.4. Fuselage-bin coupled model

A top frontal section of Boeing 737 fuselage was purchased for design and field tests. Detailed geometric and structural data of bins, frames and fuselage components were obtained from field measurements. Some fuselage material properties could only be estimated. The inner shield was designed with full consideration of fuselage coupling using detailed finite element simulations. Figure 6 shows the fuselage section purchased. Figure 7 shows a bin location relative to the fuselage and the attachments holding the bin to the fuselage.

Based on the data measured from the fuselage section, a finite element model of the fuselage coupled with the bin was developed (Fig. 8). The model included a 10-ft top half fuselage section with a left bin hardened by a shield inside. Auxiliary components with minimal structural significance were ignored (i.e., insulation, pipes, hoses, electrical equipment, etc.). The fuselage section model included the outer skin, frames, longitudinal stringers and brackets. All these components were modeled as shell elements. The connections between the frames and longitudinal stringers through brackets were implemented in the model with tied contact interfaces [5], as were the riveting connections between the skin and longitudinal stringers. The overhead bin model was composed of bin support frames, two end plates, and the top and bottom panels with sandwich structure (Fig. 9). Almost all of those components were modeled as shell elements, with the exception of the sandwich structure, which used shell elements for the top and bottom sheets, and solid elements for the sandwiched foam. The door panel was modeled with shell elements, as was the inner blast shield, where Mat 22 or Mat 54–55 was used to define the through-thickness integrations for the laminate structure.

Fig. 16. Outside view of basic shield test set-up.

Fig. 17. Inside view of fuselage after basic shield test.

The fuselage model included the upper and lower bin attachments (Figs 10 and 11). The upper attachment consisted of two C-cross-section mounting rails attached to the frames through brackets and two cylindrical rods suspending the bin from the C-mounting rails through pin connections. The lower attachment consisted of two L-cross-section mounting rails attached to the frames through brackets, with two brackets attached to the L-mounting rails through three pins on each side of bin. One bin spans four frames, but the major load bearing is on two frames in the middle section. A general contact option [5] was used in the model to simulate all possible contact interactions among all model components.

Either the 2024-T3 or 7075-T6 aluminum was used to define most of the primary fuselage structure. Mat 24, a piecewise linear plasticity material model, was chosen for the aluminum materials. Using handbook values for the preliminary analysis, the yielding stress and failure plastic strain were defined for each aluminum material.

3.5. Shield design

Figures 12–14 show the three designed and manufactured inner shields obtained after many FEA simulations and trade-off optimization. The shield has a flat top and a wavy panel facing the outside of the aircraft. Three test samples were manufactured, each with a different stacking sequence, thickness (t), and lamination. They are called the basic, thick and thin designs. Mat 22 is conservative and was used for the thick shield design. Mat 54–55 is

Fig. 18. Outer skin view after basic shield test.

Fig. 19. Fuselage sectional view after basic shield test.

less conservative and was used for the basic and thin shield designs. Zero degree indicates the fiber direction in the aircraft longitudinal direction. The three designs are summarized as follows (Figs 12–14):

1. **Basic design** (**bilaminate,** $t = $ **0.25”**)
   Top layer: Kevlar, 0.05” thick, [$0°/90°/0°/90°/0°$];
   Bottom layer: E-glass, 0.20” thick, [$0°/45°/90°/-45°/0°$]
2. **Thick design** (**single laminate**)**,** $t = $ **0.43”**
   E-glass, [$0°/45°/90°/-45°/0°$]
3. **Thin design** (**bilaminate,** $t = $ **0.20”**)
   Top layer: Kevlar, 0.05” thick, [$0°/90°/0°/90°/0°$];
   Bottom layer: E-glass, 0.15” thick, [$0°/45°/90°/-45°/0°$]

3.6. Field tests

To evaluate the three designs, field tests were conducted on February 19–20, 2003 at Aircraft Restoration, Tucson, Arizona. Three overhead bins of the Boeing 737 fuselage section were hardened with the test samples and tested separately. The inner shields were only tight-fitted into the bins with no hardware mounting. The test sequence was basic, thick, and thin shields. The charge was placed at the bin center. The charge was set off by Tucson Bomb

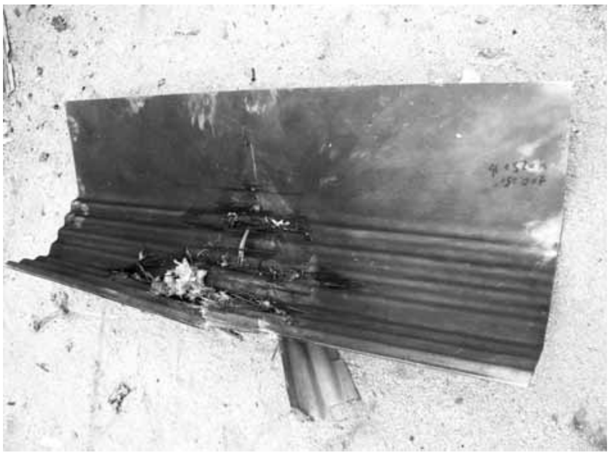


Fig. 20. Inside view of basic shield after test.

Fig. 21. Outside view of basic shield after test.

Squad. Grids were laid on the outer fuselage skin for visual evaluation of deformation. High-speed and VHS video data were taken, and digital camera pictures were also taken.

The field test results are summarized as follows:

Basic Shield Test

Figures 15 and 16 show the set-up of the basic shield test. The black ball (Fig. 15) is the charge located inside the bin.

Figure 17 shows the inside view of the fuselage after the blast. The fuselage outer skin was all intact, with no change in the exterior grid pattern (Fig. 18). There was about 0.2-in deformation in the area closest to the explosive. There were no cracks or breakage of the outer skin. Behind the bin, two middle frames were twisted with one cracked. The longitudinal stringers were deformed, with two brackets deformed. The bin was completely demolished by the blast (Fig. 19).

Figure 20 shows the inside view of the basic shield after the blast. Post-blast examination of the basic shield indicated some local damage in the bottom center region closest to the charge (Fig. 20). There was some fiber breakage, matrix crack and delamination in the center of the bottom area next to the charge. Some delamination was present in the middle region at the two ends (Fig. 20). Figure 21 shows the outside view of the blast shield after the blast. Some cracking occurred in the center of the bottom area. The Kevlar layer delaminated from the E-glass layer

Fig. 22. Outside view of fuselage section before thick shield test.

Fig. 23. Outside view of fuselage section after thick shield test.

in the center area closest to the charge.

Thick Shield Test

The thick shield protected the fuselage and the frames, leaving them intact. There was no change in the grid pattern on the outer skin (Figs 22 and 23). There was minimal deformation of the skin, but with no cracks or breakage. No significant deformation of the frames behind the bin was noted, and there were no frame cracks or breakage. No deformation or damage of the longitudinal stringers was evident, and no brackets were damaged. The bin was completely demolished, with the neighboring bin end-plates also blown away.

Figure 24 shows the inside view of the thick shield after the blast. Post-blast examination indicated only minimal damage in the center bottom region closest to the charge. The inside area had minor local fiber breakage, cracked matrix and delamination. There was a minor delamination in the middle region at the two ends. Figure 25 shows the outside view of the thick shield after the blast. A small amount of local delamination in the center of the bottom area was evident. There was no change in the shape of the shield.

Thin Shield Test

Using the thin shield, there was about 0.3-in deformation in one grid where some paint peeled off (Figs 26 and 27). There was a 2-in crack along a rivet line in the area close to the top of the shield (Fig. 28). However, for the frames behind the bin, there was no significant deformation, cracking or breakage. One of the longitudinal stringers

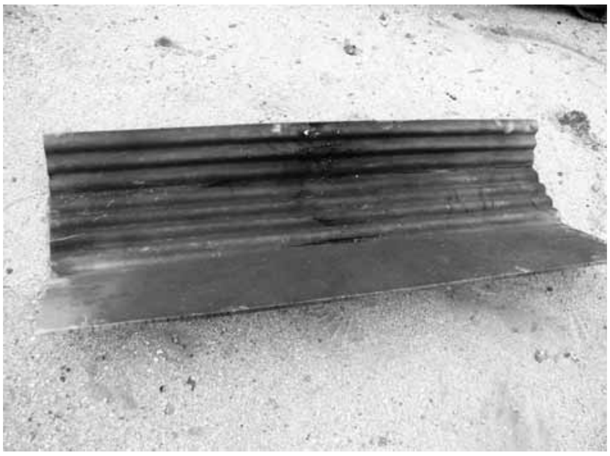


Fig. 24. Inside view of thick shield after test.

Fig. 25. Outside view of thick shield after test.

Fig. 26. Outside view of aircraft section before thin shield test.

showed slight deformation close to the top of the shield, but there was no bracket damage. The bin was completely demolished.

Figure 29 shows the inside view of the thin shield after the blast. In the bottom center area close to the charge, there was fiber breakage, cracked matrix and delamination. Minor delamination was found in the middle region

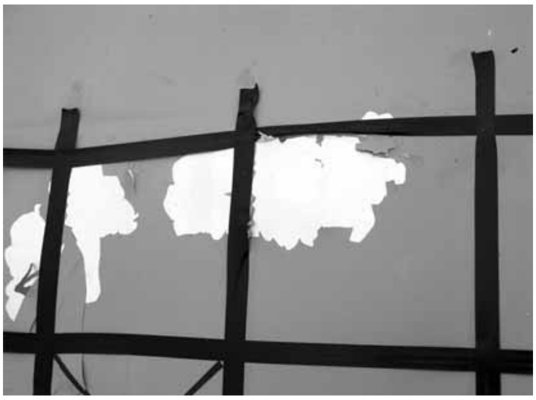


Fig. 27. Outside view of fuselage section after thin shield test.

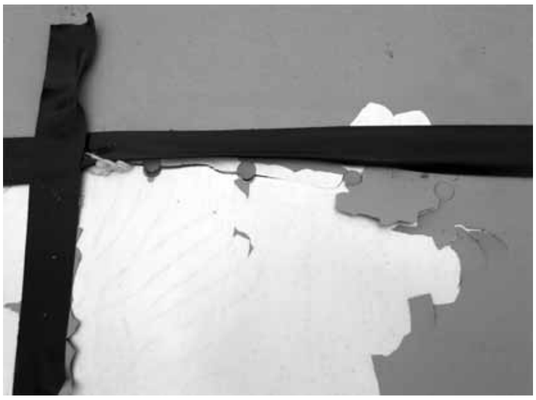


Fig. 28. Close-up view of skin crack after thin shield test.

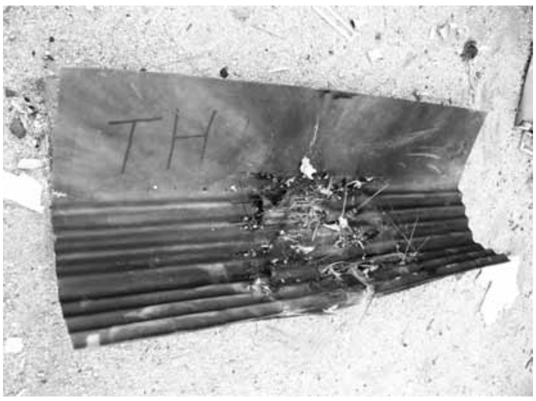


Fig. 29. Inside view of thin shield after test.

at the two ends (Fig. 29). Figure 30 shows the outside view of the thin shield after the blast. There was some crack-through at the center bottom area closest to the blast. The Kevlar layer delaminated from the E-glass layer in the center area at the bottom (Fig. 29).

In summary, the thick shield provided very strong protection. The basic shield protected the fuselage with a crack in one frame. The basic shield was considered acceptable based on the fact that there was no outer skin damage. The thin shield protected the frame and stringer structure, but with outer skin cracking from the stringers along a

Fig. 30. Outside view of thin shield after test.

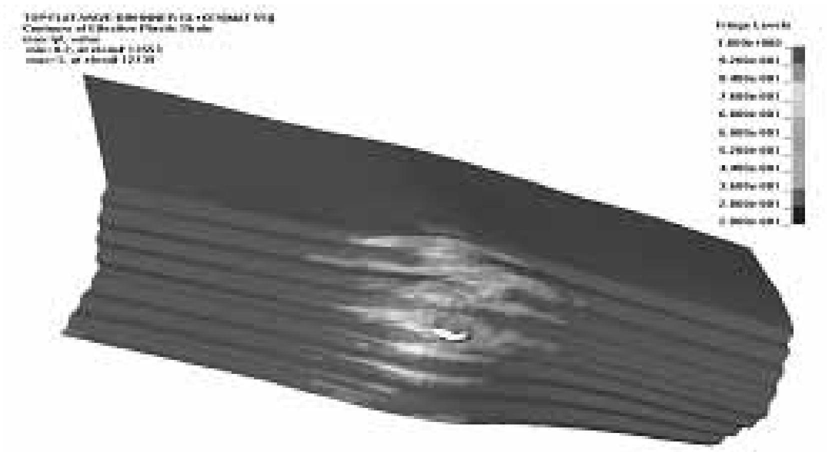


Fig. 31. Basic shield damage by blast simulated by the revised model (inside view).

rivet line. The thin shield was considered unacceptable due to outer skin cracks. Test results suggested that the bin material and connector properties used in the FEA model were too strong and should be weakened in the model. Revised model simulations were performed to calibrate the model and gain more insight.

3.7. Use of field test data to calibrate the LS-DYNA model

The test results indicated that the deformation pattern and damage area were logical and generally agreed with the predictions of LS-DYNA simulations, but the severity of damage was worse than the predictions. This was true not only for the fuselage structures and overhead bins, but also for the blast shields. In all three tests, the bins were completely demolished, which suggested that the bin strength was over-estimated. Simulations showed that foam properties in the bin sandwich structure could strongly affect the damage of the bin, and a weaker foam material was expected to reflect the fact the bin was demolished in the blast. Moreover, the damage in the fuselage structure occurred mostly near the rivet line, which was a stress concentration region for both connected components.

After accounting for the additional material property degradation due to stress concentration, fatigue damage, size effects and corrosion, and weakened foam material in the bin sandwich structure [19], the revised finite element model resulted in much better agreement with the test data. Figures 31 and 33 show the inside and outside views of the basic shield damage calculated using the revised model. They agree well with the corresponding test results

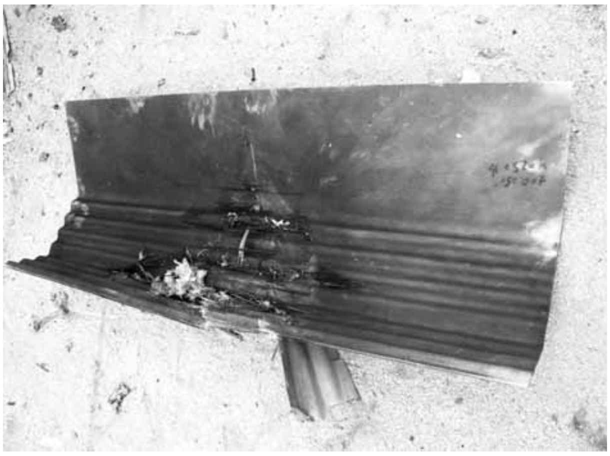


Fig. 32. Basic shield after test (inside view).

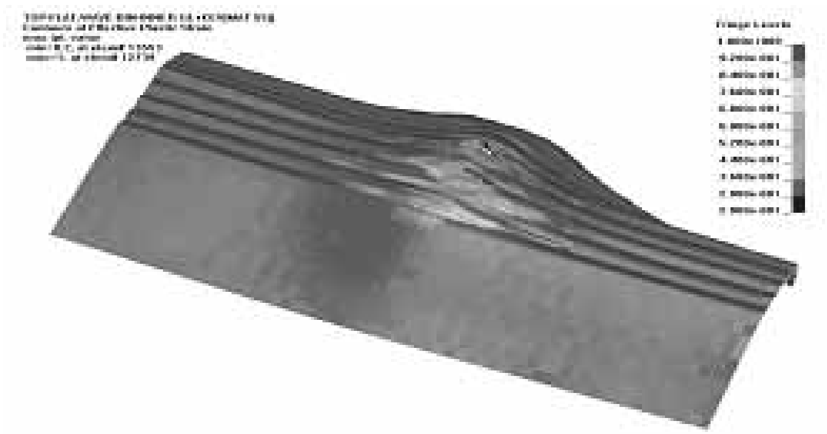


Fig. 33. Basic shield damage by blast simulated by the revised model (outside view).

shown in Figs 32 and 34, respectively. Comparing Figs 35 to 36, it is evident that the revised simulation shows a slight plastic deformation of the aircraft skin with no crack or failure in agreement with the basic shield test results. Therefore, the revised model should be used for future designs.

4. Discussion

The field tests have demonstrated the feasibility of using a blast shield to harden the overhead bin of a Boeing 737 aircraft. The basic and thick blast shields protected the integrity of the Boeing 737–100 aircraft skin during the blast. Since only three design samples were tested on one aircraft fuselage, no statistical quantification of the data can be drawn.

The present work shows that the response of the blast shield to the blast is strongly coupled with the fuselage structure. The design requires detailed knowledge of the fuselage structural data. However, such information is very difficult to obtain accurately. In particular, material property data, which are crucial for the design, are difficult to validate, and material properties for old structures can also degrade significantly. The structural variability between aircraft versions will make the design even more challenging. Another uncertainty is that the spanning of the overhead bin by the frames behind is not uniform for all bins. Not only a bin can be spanned by either three or four frames, the exact contacts between the frames and the bins are not the same for all bins. This means that extensive

Fig. 34. Basic shield after test (outside view).

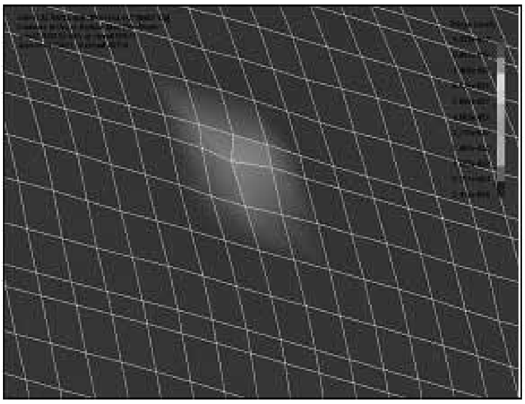


Fig. 35. Plastic strain in fuselage outer skin simulated by the revised model.

sensitivity studies are required to identify the weakest bin/frame configuration, and that is beyond the scope of the present work.

A few design improvements are identified. The current design has a full flat top portion the same size as that of the overhead bin. It seems that at least half of this top portion is not needed since the protection is mainly for the aircraft skin on the side. Therefore, it seems that a portion of the flat top can be removed, and this extra material can be added to the wavy panel to increase strength and stiffness. Furthermore, practically, the lowest cost material, E-glass, was used for the present design. To further save weight and also increase strength, better materials can be considered that can provide even better fragment protection. In the current design, a Kevlar layer is integrated into the blast shield to protect against fragments, but its performance against the fragments has not been investigated in detail in this study.

5. Conclusions

The feasibility of using an inner blast shield to harden the overhead bin compartment of a Boeing 737 aircraft has been demonstrated. The unibody concept using composite materials was used. The blast shield was designed using finite element modeling. The material was selected based on a material survey to identify the lowest cost material, E-glass, that would be adequate to achieve the objective with a tolerable weight penalty. A wavy shield concept was adopted to increase strength and stiffness with less weight. The material panel first passed the shock holing and the

Fig. 36. Outer skin plastic deformation after basic shield test.

FAA fire tests. The shock holing tests also validated the material models used for the design. Three designs were field-tested using a top frontal fuselage section of the Boeing 737–100 aircraft. The basic and thick shields protected the integrity of the fuselage skin. The test data were used to improve the finite element model. This work provides encouraging results and data for future improvement and optimization of the blast shield design.

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