

# High-Speed Imaging of Shock-Wave Motion in Aviation Security Research

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## Abstract

Accident investigations such as Pan Am 103 and TWA 800 reveal the key role of shock-wave propagation in destroying the aircraft when an on-board explosion occurs. This paper surveys the role of shock wave propagation inside an aircraft fuselage, caused either by a terrorist device or by accidental circumstances. While aircraft-hardening research has been under way for more than a decade, no aircraft-hardening experiments to date have used the crucial tool of high-speed shock-wave imaging to visualize shock motion. Here, Penn State's Full-Scale Schlieren flow visualization facility provides the first real shock-motion images in aviation security scenarios: 1) Explosions beneath full-size aircraft seats occupied by mannequins, 2) Explosions inside partially-filled standard luggage containers, and 3) Luggage-container explosions resulting in hull-holing.

## 1. Introduction

### 1.1 Aviation Security

The rise in worldwide terrorism, especially directed at commercial air transportation, has required that measures be taken to harden aircraft against catastrophic in-flight failure due to concealed explosives. The Pan Am 103 disaster [1] and several other incidents in the 1980's and 90's costing many hundreds of lives [2] showed that the modern terrorist is sophisticated enough to obtain and conceal modest amounts of explosive capable of destroying an entire aircraft. Most recently, the September 11, 2001 terrorist attacks in the United States involved at least one case (United Flight 93) where terrorists claimed to have smuggled a bomb on board. Accordingly, research to make commercial airframes less vulnerable to internal explosions has been conducted for several years under the FAA's Aircraft Hardening Program.

The Pan Am 103 investigation revealed the key role of blast overpressure and shock wave propagation in the disintegration of the aircraft within seconds of the explosion. The detailed accident report [1] suggests that the fuselage skin was shattered near the blast due to shock overpressure, followed by extensive fuselage cracking driven by the hull pressurization. The report also describes the possible formation of Mach-stem shock waves, which appear to have propagated through internal cavities and channels within the aircraft, causing damage at locations remote from the explosion. However, the shock wave patterns and gas dynamics described in this report were based mostly on conjecture. No attempt was made at the time to predict such shock motion numerically or to reproduce it experimentally. Since this disaster, several experiments have examined the damaging effects of blast waves due to explosions onboard aircraft. Unfortunately, despite these experiments, the actual gas-dynamic phenomena of such an onboard explosion remain poorly understood.

### 1.2 Literature Review

#### 1.2.1 Full-Scale Airframe and Luggage-Container Tests

A primary goal of full-scale airframe experiments has been to realistically simulate scenarios of terrorist bombings. To this end, several explosive tests have been performed on actual aircraft structures to analyze damage and to acquire data on blast loading in such large explosions. In May 1997, a retired Boeing 747 was sacrificed at Bruntingthorpe, UK, for the purpose of validating the most recent aircraft hardening techniques employed by the FAA and DERA [3,4]. Aging military aircraft were also used to study blast damage in terms of shock holing of the hull, quasi-static pressure loading, and cabin pressurization [2,5,6].

High-speed video observations, post-blast inspection, and pressure transducers were used in these tests, but no optical imaging of shock wave motion was attempted. Pointwise pressure data are sometimes lost due to the harsh test environment, and are often not very revealing of the key flowfield phenomena. Furthermore, such full-scale tests are very expensive and difficult to repeat.

Further full-scale research has examined the hardening of aircraft luggage containers. Pan Am 103 and similar aviation terrorism incidents show the need for a luggage container able to withstand a significant internal explosion. Thus, subsequent research focused on methods to vent explosive energy from these containers and to contain explosive overpressure using blast-mitigating materials [4]. Experiments also examined the effects of luggage and charge location on the pressure loading inside luggage containers, as well as damage due to luggage fragmentation [7,8]. Under the FAA Aircraft Hardening Program, Jaycor Inc. and Galaxy Scientific Inc. developed prototype HULDs (Hardened Unit Load Devices) capable of containing the blast of a bomb having a certain size and configuration [9]. Initial test results were promising and some airlines agreed to conduct operational trials using these units [9,10]. However, these HULDs are heavier and more costly than standard luggage containers, and the FAA has not yet developed a deployment plan for them in airline service. Further effort appears necessary before hardened luggage containers are accepted by the aviation industry.

### **1.2.2 Blast Mitigation and Shock Propagation in Porous Media**

In efforts to develop HULDs, researchers have studied the blast-mitigating effects of luggage and of liner materials to protect luggage containers against explosive damage. Experiments show that luggage plays a key role in absorbing blast energy [8]. However, the degree to which luggage mitigates the blast wave depends on the material and contents of the luggage. Moreover, it is unknown whether the explosive shock overpressure or the hurling of luggage fragments at high speed is the primary damage-inducing mechanism in the case of a luggage-container explosion. In this complicated scenario, the presence of luggage may even have a detrimental effect on airframe integrity.

Related basic studies have considered shock wave propagation in porous media. Experiments show that most porous materials attenuate shock waves and thus reduce the potential for damage [8,11]. However, some tests reveal an adverse effect: certain foams and textiles may act to reflect shock waves or store blast energy, thus amplifying pressure levels and increasing the risk of damage to surrounding structures [12,13]. Several materials and liners have been tested for use in HULDs, the most successful of which tend to be composite materials with high strength-to-weight ratios. Despite some success, research on blast-mitigating materials continues due to the excessive weight and cost of existing HULDs.

### **1.2.3 Numerical Simulations**

Numerical modeling of aircraft explosions plays an important role in aircraft hardening research. While some simulations have concentrated only on flowfield modeling [14] or structural damage [15], several others have attempted to simultaneously predict interior blast wave behavior and related structural damage [5,16,17]. These computations typically involve the use of codes that link together the fluid and structural mechanics. Some numerical simulations also attempted to model blast wave patterns in an aircraft interior [18]. However, it is very challenging to model 3-D fluid and structural response simultaneously, and to provide sufficient resolution to see shock wave reflection patterns. Furthermore, such numerical simulations may involve simplifying assumptions that detract from the accuracy of the model. Thus, in order to predict explosive damage and to understand blast wave behavior thoroughly, experimental validation of such computations is absolutely necessary.

### **1.2.4 Scale-Model Tests and Interior Blasts**

Following the international ban on above-ground nuclear testing, numerous scale-model studies have used ordinary chemical explosives to simulate nuclear blast waves effects according to established scaling laws [19-21]. These experiments illustrate the usefulness of scale-models to simulate – up to a point – full-scale blasts. However, simulating blast effects and structural response simultaneously at model scale is seldom possible. Further, the detailed geometry of an aircraft cabin or luggage compartment is difficult to simulate except at near-full-scale.

The emphasis also shifts dramatically from open-air nuclear-weapons tests to interior shock wave propagation in an aircraft fuselage. Depending on Mach number, the peak overpressure behind a shock wave reflected from a wall can be 28 times the incident overpressure. Even-higher overpressures occur where the wall geometry produces shock focusing [22]. Various recent studies [23-25] amply illustrate that shock motion in interior spaces quickly becomes very complicated, and is poorly understood compared to outdoor blast effects.

### **1.2.5 Aviation Safety**

Finally, we note that explosions onboard aircraft are not always deliberate terrorist acts, but also can be accidental. TWA Flight 800 was lost with all 230 persons aboard due to a fuel-air explosion in its center fuel tank [26]. The overpressure ruptured the tank and damaged the structure sufficiently to cause in-flight breakup of the aircraft. The March 2001 explosion of a Thai Airways Boeing 737 on the ground is thought to have been of similar origin. Likewise the July 2000 Concorde accident resulted from the impact of an exploded tire fragment upon a wing fuel tank, causing “water-hammer” shock waves in the fuel that led to a tank rupture and subsequent catastrophic fire [27].

## **1.3 Objectives of Present Research**

Our principal observation from the above literature review is that optical methods are conspicuously absent from all experiments to date on aircraft hardening. Optical flow visualization and measurement are the most valuable experimental tools in the general study of blast wave propagation [28,29]. Their application to aircraft hardening research does not necessarily require full scale, but a reasonably-large scale is needed if the complicated geometry of the problem is to be well-represented. This rules out table-top optics, but in fact large-scale outdoor optics for blast studies, based on shadowgraphy or background-distortion schlieren principles, have been known since at least the 1950's [28-31].

Optical imaging of blast waves can thus be useful in aviation security studies for several reasons. First, it provides a key physical picture of the phenomena at hand. Second, high-speed images can yield quantitative data such as shock speed and Mach number, from which flow properties behind the shock wave can be found. Finally, such optical data from blast wave experiments may be used to support quantitative data from other (e.g. pointwise) instruments, and to check the accuracy of numerical predictions.

Accordingly, the remainder of this paper describes experiments at Penn State involving full-scale optical imaging of shock motion in aircraft interior scenarios. The primary objectives of this research are to gain a better understanding of blast wave behavior in aircraft environments and to establish the value of optical imaging in full-scale aircraft explosion tests. In that present space does not allow a complete presentation of these experiments, the reader is referred to [31-34] for more detail.

## **2 Experimental Methods**

### **2.1 Full-Scale Schlieren System**

The Penn State Full-Scale Schlieren System is based on the lens-and-grid principle first developed by Schardin [31]. Housed in a university warehouse building, it is the largest indoor schlieren system in the world. As shown in Fig. 1, a large front-lit retroreflective source grid covers one wall of the building. Vertical black gridlines of width 5.08 mm are silk-screened 5.08 mm apart onto the retroreflective material. Opposite this source grid, a large-format camera lens produces a cutoff grid size of 20 x 25 cm, and an image plane slightly larger. The cutoff grid is a precise negative image of the source grid that, when properly aligned, provides multiple schlieren cutoffs for the many source-grid lines that make up this multiple-source schlieren system. The test area, located roughly halfway between the source grid and the lens, is centered 2.4 m above the floor. Its nominal field-of-view is a rectangle 2.3 m high by 2.9 m wide, or about 7.5 x 9.5 feet.

For present purposes, the source grid is illuminated by a Viewstar, Inc. Model 955-5 high-speed-flash light source. A xenon flash tube discharges 5-10 Joules in about 5 sec when a microphone placed an arbitrary distance from the center of the subject explosion provides the electronic trigger signal. While three time-delayed, colored flashes are available from the light source, only a single flash was used in most of the experiments reported here. Front-lighting of objects in the test area is also provided by two additional studio flash-heads located off-axis.

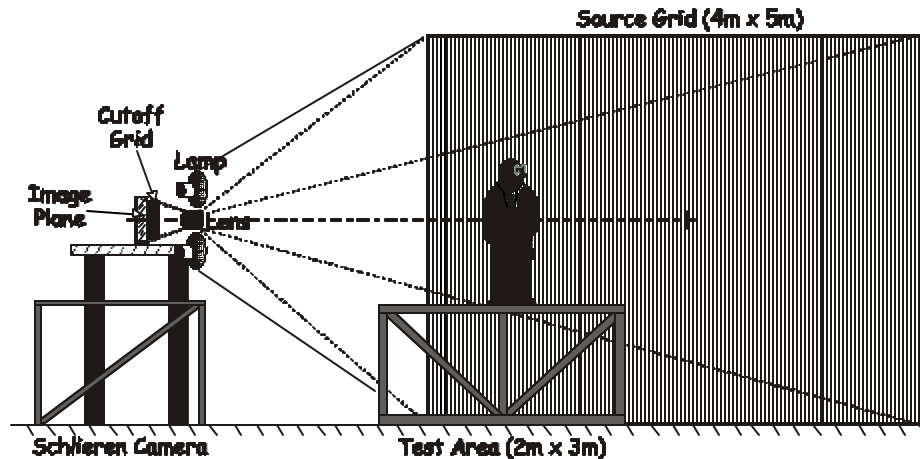


Fig. 1. Schematic of the Penn State Full-Scale Schlieren System

For the still photographs shown here, a Fresnel lens near the schlieren image plane allows re-focusing the test area into a Pentax 67 medium-format camera. Photography is done using 120-size ISO 800 color negative film push-processed to approximately ISO 3200. Photographs are taken in the darkened laboratory with the camera focal-plane shutter open during the explosive event.

## 2.2 Shock Wave Generation

Shock waves were generated by the detonation of an oxygen-acetylene gas mixture in a small (about 10 cm diameter) toy balloon ignited by a nichrome-wire glow-plug. This technique is advantageous in the present case for several reasons. First, it provides a virtually smoke-free blast that does not contaminate the facility. Second, it generates no hazardous shrapnel. Third, it is easily-repeatable in terms of blast strength. Fourth, storage and handling of high explosives is not required. Finally, the detonation of even small amounts of oxygen-acetylene gas mixture, requiring ear protection only, produces shock waves that are clearly visible to the Full-Scale Schlieren System.

Experiments were performed to determine the explosive yield of these gas detonations in terms of a TNT-equivalent mass. It was found that the range of charges tested produced yields equivalent to approximately 1-10 grams of TNT. This knowledge is significant because it provides a means of scaling the blast waves produced by these gas detonations, which may be important in comparing the present experiments with the results of other aircraft-hardening studies.

Resulting shock Mach numbers were also calculated from multi-flash images. This revealed that, for the range of balloon sizes tested, the blast waves had average Mach numbers between 1.0 and 1.2 at a distance of approximately 1 meter from the blast center. Although these are weak shock waves – far weaker than those produced by an actual terrorist bomb – their clear visibility in the Full-Scale Schlieren System justifies their use to study shock wave motion in an aircraft interior environment.

## 3. Results and Discussion

Several mockup aircraft interior settings have been designed and fabricated to represent actual aircraft environments for the purposes of simulating terrorist bombings onboard commercial aircraft. These settings provide a clear optical path allowing shock wave motion to be studied on a realistic scale.

### 3.1 Aircraft Passenger Cabin

Our first experiments consider the scenario of an explosion under an aircraft seat in a side-view of a mockup aircraft-cabin environment. The motivation for this derives from actual terrorist attempts at aircraft sabotage involving bombs placed in the passenger cabin, especially Ramzi Yousef's failed Dec. 1994 attempt to bring down a Philippine Airlines flight with a nitroglycerin bomb under a seat. Baum, et al. [18] numerically

simulated such an explosion in the first class section of a Boeing 747. However, prior the present work, no experiment comparable to this computation had ever been performed.

To simulate the aircraft cabin environment, two rows of actual jetliner seats were positioned in the test area of the Full-Scale Schlieren System (Fig. 2). Two full-sized mannequins were placed in these seats to represent passengers. By the method described earlier, a gas detonation was produced under the front seat row.



**Fig. 2.** Side view of an under-seat blast in the mockup aircraft cabin.

Fig. 2 reveals several aspects of shock wave motion in this scenario. First, the strong initial shock front above the chest of the male mannequin indicates that much of the blast energy is channeled upward between the two seat rows. Second, despite the complicated geometry, a near-spherical wavefront is produced (it can be seen diffracting over the head of the female mannequin). Third, multiple shock reflections are observed between the two seat rows, demonstrating shock reverberation. Finally, the direct light from the explosion is confined to the fireball itself and does not fog or otherwise obstruct the schlieren image. Of course, a terrorist-scale bomb would destroy the seat under which it was placed, but in our simulation only minor scorching damage occurs.

A second set of tests involved a front view of the same passenger-cabin scenario, including a mockup of a full-scale aircraft bulkhead to study the shock wave reflection that would likely occur at the cabin sidewall (Fig. 3) The Pan Am 103 accident report [1] suggested that a shock reflection from the inner hull propagated back into the fuselage, reverberated, and led to extensive damage at remote sites. Multiple shock reflections were indeed observed here, accompanying the spherical primary wave from the blast.

The observation of near-spherical blast propagation, despite the complicated geometry in Figs. 2 and 3, is important in that it suggests the utility of a simplified view of fuselage interior shock wave propagation. Computations [18] also indicated this, though at much lower resolution.



**Fig. 3.** Front view of an under-seat blast in the mockup aircraft cabin.

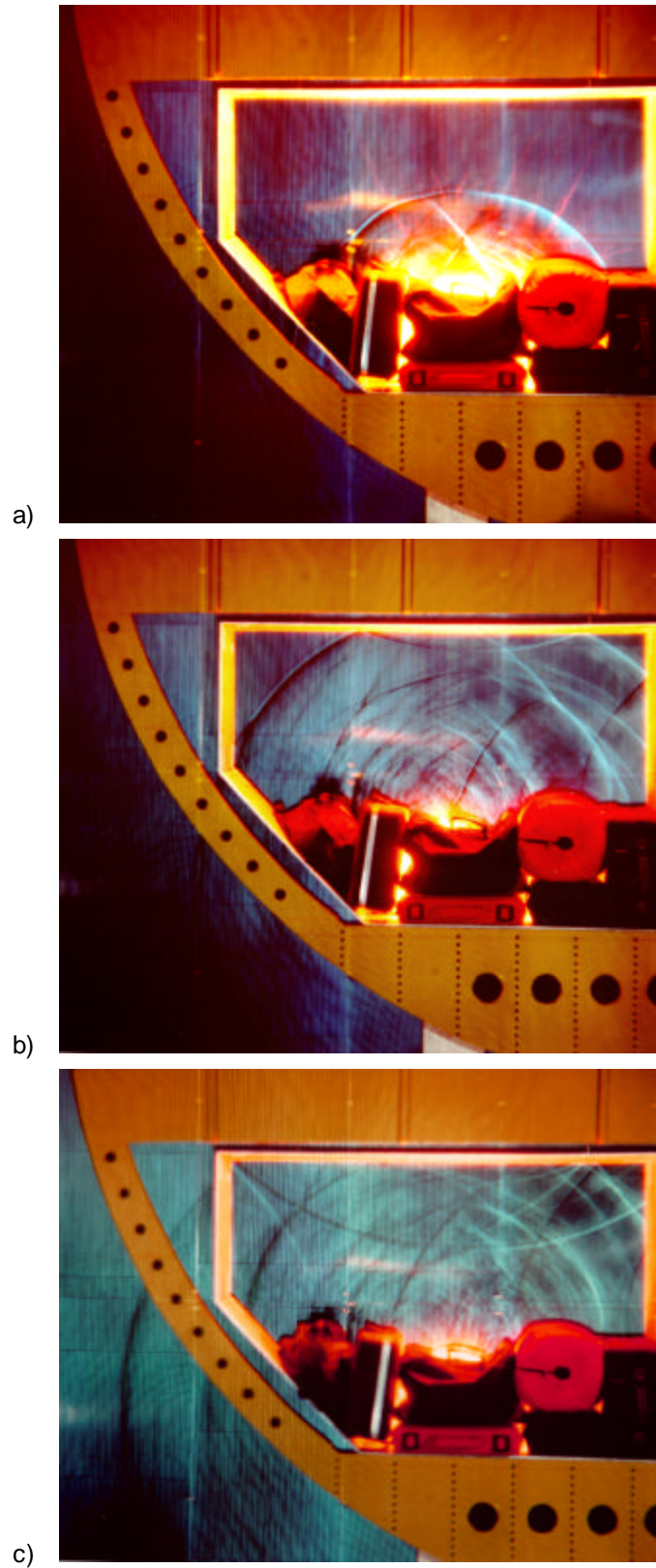
### **3.2 Luggage Container**

A 3/5-scale model of a luggage-container and lower widebody aircraft fuselage cross-section was constructed (Figs. 4-5) and partially filled with typical bags. Explosions beneath the bags were imaged with different microphone (trigger) locations in order to obtain a sequence of images demonstrating the interior shock wave motion. Fig. 4a shows a simple spherical shock front, with interior reflections from the bags beginning to intersect. The delay time following the blast is about 1.5 ms. Fig. 4b shows the shock front just after reflection from the container ceiling, with reflections also occurring at the walls of the container (2.6 ms delay). Finally, Fig. 4c reveals the wave pattern at 3.2 ms delay, with multiple wave reflections leading to a complicated shock reverberation pattern. Several other images in this sequence are omitted for brevity; see [32].

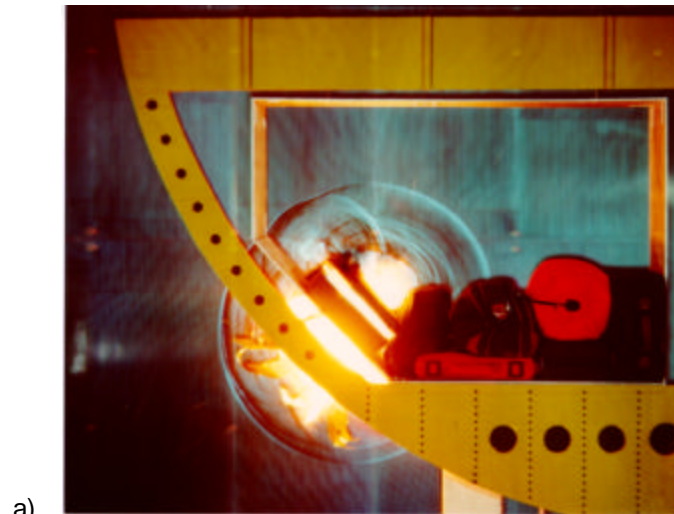
### **3.3 Luggage Container Blowout and Hull Holing**

In another set of experiments, a blowout of the diagonal luggage-container wall and holing of the aircraft hull were simulated. The motivation for this comes from the Pan Am 103 disaster, in which the terrorist bomb was located inside a suitcase near the outer wall of the luggage container, and the hull holing from the explosion led to the loss of the aircraft. To simulate this, the present explosions were positioned along the diagonal luggage-container wall inside a pre-vented hard-shell suitcase. Given the small yield of our explosions, the jagged hull hole also had to be simulated. As in the previous experiment, a sequence of images showing the progression of the blast wave was obtained [32].

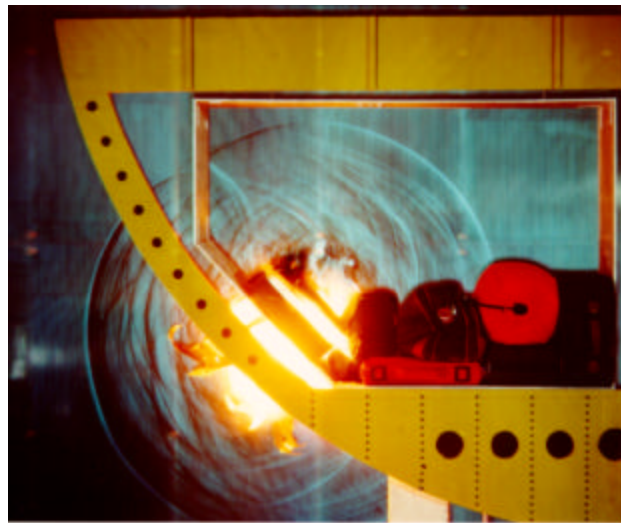
Selected results of these hull-holing tests are shown in Fig. 5. Figure 5a demonstrates the initial release of energy from the explosion at a time delay after blast initiation of about 1.3 ms. Fig. 5b shows the shock patterns  $\frac{1}{2}$ ms later. Here, a series of shock reflections occurs at the upper-left wall of the container and the other interior reflections are expanding. Finally, in Fig. 5c at 3.3 ms delay, shocks have reflected from all four container walls creating a complicated internal wave pattern. Shock motion outside the hull is also clearly seen in all 4 frames, but the high-speed jet of hot gases from the hull hole [14] is not properly simulated in the present experiments.



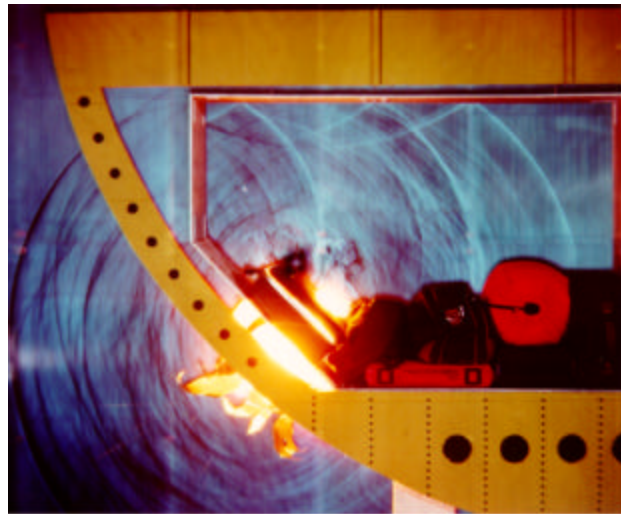
**Fig. 4.** Blasts in mockup luggage container show the progression of shock reflections.



a)



b)



c)

**Fig. 5.** Blasts in a mockup luggage container demonstrating holing of the aircraft hull.

#### 4. Conclusions and Future Work

Shock wave interactions within a mockup aircraft cabin and luggage container have been observed at near-full-scale. The blast wave patterns seen in these experiments indicate several areas of concern in terms of potential damage to actual aircraft structures due to onboard explosions. These results may be used to validate quantitative data from other experiments and numerical aircraft-hardening studies. It is shown that optical imaging on the scale of actual aircraft-hardening experiments is a valuable tool that should not be neglected in the future.

Additional work is now under way along these lines, but is still in a preliminary stage. Using a Cordin Model 377 drum camera, 500-frame image sequences of shock wave motion in these explosive events are being obtained at 45,000 frames/sec. These sequences are digitized and assembled into video clips, effectively slowing the process by a factor of more than 1000 and revealing far more detail than the single frames shown in this paper. Also, quantitative measurements of shock-wave strengths, etc. can be extracted from such drum-camera data. These results will be published in [34] and in a future technical paper. An outdoor optical demonstration in a real aircraft-hardening test is also contemplated.

#### 5. Acknowledgements

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#### 6. References

1. "Report on the accident to Boeing 747-121, N739PA at Lockerbie, Dumfriesshire, Scotland on 21 December 1988." Air Accidents Investigation Branch, UK Dept. of Transport, Aircraft Accident Report 2/90 (EW/C1094), 1989.
2. Gatto, J., "Commercial aircraft vulnerability to terrorism," SPIE CR42, 1992, pp. 77-92.
3. Flitcroft, S. and Harris, S. "Aircraft design: Resisting the blast." *Aviation Security International* 3:1 (1998), pp. 4-9.
4. Morrocco, J.D. "Hardening concepts tested to counter terrorist blasts." *Aviation Week and Space Technology*, June 1997, pp. 44-45.
5. Ashley, S. "Safety in the sky: Designing bomb-resistant baggage containers." *Mechanical Engineering*, June 1992, pp. 81-84.
6. Gatto, J. A., Fleisher, H. J., and Mayerhofer, R., "Effects of pressurization on the damage to KC-135 aircraft subjected to internal blast," FAA Technical Center, Atlantic City, NJ, Dec. 1995.
7. Gatto, J. A., "Experimental data on the pressure loading of a luggage container subjected to an internal blast," FAA Technical Center, Atlantic City, NJ, Feb. 1996.
8. "Blasts in luggage, fragmentation, and blast mitigation," JAYCOR Corp., Applied Science and Engineering Technology Group, San Diego, CA, Oct. 1993.
9. "Blast-resistant containers," Ch. 5 of *Assessment of Technologies Deployed to Improve Aviation Security*, 1<sup>st</sup> Report of NRC Panel, Natl. Research Council, 1999, pp. 28-35.
10. Weinstein, E. "Aircraft hardening: Its place in modern aviation security." *Aviation Security International*, Dec. 2000, pp. 4-6.
11. Lind, C.A., Cybyk, B.Z., and Boris, J.P. "Attenuation of shocks: High Reynolds number porous flows." In *Proc. 22nd Intl. Symp. on Shock Waves*, Imperial College, London, UK, 18-23 July 1999, Paper 5360.
12. Gvozdeva, L.G., Moskvilin, E.A., and Scherbak, N.B. "Interaction of shock waves with brittle porous foams." In *Proc. 22nd Intl. Symp. on Shock Waves*, Imperial College, London, UK, 18-23 July 1999, Paper 4100.
13. Rough, T.S. and Skews, B.W. "Impact of shock waves with porous textiles." In *Proc. 22nd Intl. Symp. on Shock Waves*, July 1999, Paper 1891.
14. Mundy, J.A., Rizzetta, D.P., and Melville, R.B. "Numerical simulation of the jet produced by an internal aircraft explosion." *J. Aircraft* 32:2 (1995), pp. 370-376.

15. Sanai, M., Gefken, P.R., and Simons, J.W., "Blast damage assessment methodology for terrorist bomb attacks on aircraft." SRI International, Menlo Park, CA, May 1995.
16. Bharatram, G., In Moon, Y., Venkayya, V.B., and Schimmels, S.A., "Local panel model analysis of Boeing-707." Flight Dynamics Directorate, Wright Laboratory, Air Force Materiel Command, Wright-Patterson, AFB, OH, July 1995.
17. Chen, V.L., "First successful simulation of on-board explosion will aid in aircraft hardening studies," *Simulation* **68**:2 (1997), pp. 107-110.
18. Baum, J.D., Luo, H., and Löhner, R., "Numerical simulation of a blast inside a Boeing 747." AIAA Paper 93-3091, July 1993.
19. Glasstone, S., "The effects of nuclear weapons," US DOD/AEC, April 1962.
20. Witt, E. F., "Blast transport of debris from scale model buildings," Bell Telephone Labs, Whippany, NJ, Jan. 1979, ADA084641.
21. Naz, P. and Parmentier, G., "Blast waves: Scale models and numerical simulations," Report CO230/91, Institut Franco-Allemand de Recherches de Saint-Louis, ISL, 1991.
22. Loftis, J. E., "Amplification of shock overpressure by reflection within concave corners," MS Thesis, Air Force Inst. of Technology, Wright-Patterson AFB, 1993.
23. Phan, K. C. and Stollery, J. L., "On the effects of shock wave reflection in a confined space," *Shock Waves & Shock Tubes*, Proc. 15<sup>th</sup> Intl. Symposium, 1985, pp. 139-145.
24. Marconi, F., "Investigation of the interaction of a blast wave with an internal structure," *AIAA Journal* **32**:8 (1994), pp. 1561-1567.
25. Neuwald, P., Klein, H., and Reichenbach, H., "Unsteady flows inside structures," SPIE Vol. 2869, 1997, pp. 798-806.
26. TWA 800 Aircraft Accident Report PB2000-910403, NTSB, Washington, DC.
27. Morrocco, J. and Sparaco, P., "Concorde team activates return-to-flight plan," *Aviation Week & Space Technology*, Jan. 22, 2001, pp. 38-40.
28. Dewey, J. M., "Explosive flows: Shock tubes and blast waves," Ch. 29 of *Handbook of Flow Visualization*, ed. W-J. Yang, Hemisphere Pub., Washington, pps. 481-497, 1989.
29. Dewey, J. M., "Shock waves from explosions," Ch. 16 of *High Speed Photography and Photonics*, ed. S. F. Ray, Focal Press, Oxford, UK, 1997, pp. 249-253.
30. Edgerton, H. E., "Shockwave photography of large subjects in daylight," *Review of Scientific Instruments*, **29**(2):171-172, 1958.
31. Settles, G. S., *Schlieren and Shadowgraph Techniques*, Springer-Verlag, Berlin and NY, 2001.
32. Keane, B. T., "The imaging of shock wave motion in aviation security studies," MS Thesis, Mechanical & Nuclear Engrg., Penn State University, May 2001.
33. Settles, G. S., Brandt, A. D., and Miller, J. D., "Full-scale schlieren imaging of shock waves for aviation security research," Proc. 8<sup>th</sup> Intl. Symp. on Flow Visualization, ed. G. Carlomagno, Sorrento, Italy, Sept. 1-4, 1998, Paper No. 30.
34. Anderson, B. W., "High-speed drum-camera imaging of shock-wave motion in aviation security research," MS Thesis, Mechanical & Nuclear Engrg., Penn State University, 2002.