

Full-Scale Optical Experiments on the Explosive Failure of a ULD-3 Air Cargo Container

Michael J. Hargather and Gary S. Settles

*Gas Dynamics Laboratory, Mechanical and Nuclear Engineering Department, 301D Reber Building,
Penn State University; University Park, PA 16802, USA*

Joseph A. Gatto

*Transportation Security Laboratory, US Dept. of Homeland Security,
William J. Hughes Technical Center; Atlantic City, NJ, USA*

Abstract

Understanding the failure mechanism of an air cargo container subject to an internal explosion is important to progress in aircraft hardening. Here, full-scale ULD-3 container explosions were imaged using a shadowgraph technique employing a 5m-square retroreflective screen and a high-speed video camera. The experiments revealed that the shock wave from a terrorist-scale explosion can be highly suppressed by typical luggage contents including clothing, paper, etc., even though the blast is otherwise sufficient to destroy the container. While luggage fragments were hurled at high speed through the container walls, there was little evidence of any quasi-static overpressure damage. Another key result is the demonstration of the practicality of optical imaging methods in full-scale aircraft hardening experiments. Future work includes adapting the present optical setup to also record high-speed stress of the cargo container walls, optical refinements including laser illumination to suppress direct light from the explosion, and an effort to better measure the structural failure in order to more exactly define the performance criteria of hardened containers and liners.

Introduction

Terrorist explosives placed in checked airline luggage present a significant threat to commercial aviation. Since the Pan American 103 disaster in December 1988 [1], much effort has been directed toward understanding explosive events inside aircraft and to developing blast resistant cargo containers [2, 3]. Shock loading in the confined space of a cargo container or an aircraft fuselage is a complex combination of shock reflection and pressure loading [4]. In addition to shock reflection, Wilson showed that the luggage itself suppresses the shock, further complicating analysis [5]. The “protective” nature of luggage, however, is not a guarantee of safety due to the variability of charge locations. Differences in container structural loading due to charge location were documented by Gatto and Krznaric, showing a significant decrease in loading as more luggage is placed between the charge and container surface [2]. To improve air cargo container blast resistance capabilities, failure modes of current containers must be documented. A series of tests was conducted in the Fire Safety Test Enclosure (FSTE) of the Army Test Center, Aberdeen Proving Ground, Maryland, during June 2005, to determine container failure modes and to image the shock wave that emanates from a cargo container upon an explosive charge detonation.

Experimental Setup

A survey of cargo containers in use by commercial airlines found that the ULD-3 container represents the most typical container for passenger luggage [6]. A series of tests was conducted with this container type and different explosive charge locations. To document the experiment, an optical shadowgraph system and a high speed digital camera were used to record shock wave phenomena. The shadowgraph system consisted of a 5m square retroreflective screen, illuminated by a 1kW concentrated arc lamp [7]. A diagram of the optical setup within the circular FSTE is given in Figure 1.

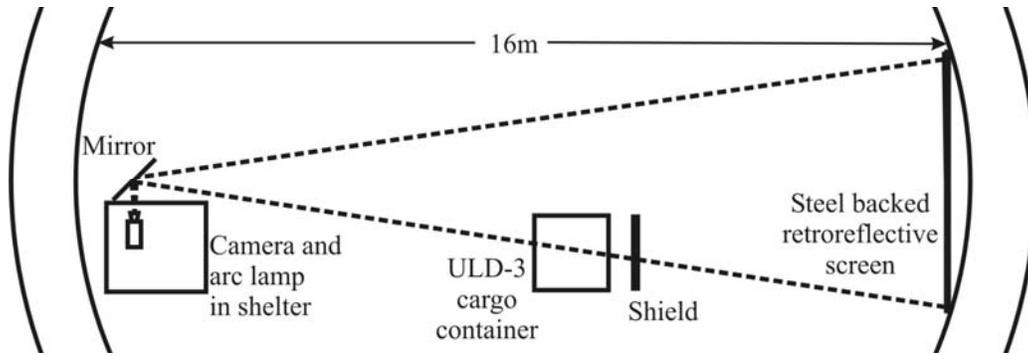


Figure 1: Diagrammed section of the FSTE showing the location of optics and the cargo container. The rest of the circular FSTE was empty.

The ULD-3 was filled to 75% capacity with cardboard boxes for each test. The boxes were partially filled with either paper or clothing and then stacked randomly into the ULD-3. Three tests were performed with charges in two different locations, as shown schematically in Figure 2. Once loaded, the ULD-3 was placed on a scaffold so that the left side and bottom corner could be visualized. A metal shield was installed between the ULD-3 and the shadowgraph screen to protect the screen from shrapnel.

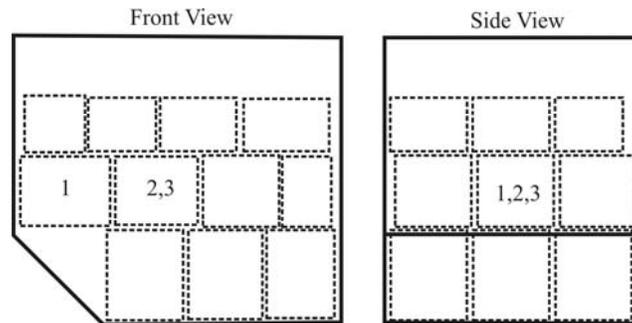


Figure 2: Schematic of the ULD-3 showing general locations of boxes and charges for each test, numbered 1-3.

Frames recorded at 10,000 frames per second, with the Photron APX RS high-speed digital camera, were processed to determine shock speed for shocks that passed out of the container. For comparison, a bare charge was exploded in air with no containment or shielding. By processing these image sets, shock Mach number as a function of radius from the charge center was determined. The bare charge, however, produced so much direct light during the initial stages of explosion that no shadowgraph images were recorded. A second bare charge, placed out of the field of view, resulted in usable data for distances more than about 3m from the charge center.

Discussion of Results

The charge in the first test was placed next to the ULD-3 slant (i.e. closest to an aircraft hull). This was determined to be the most dangerous location because of the proximity of the aircraft structure. Video frames show that the ULD-3 ruptures at the time of shock impact. This can be seen in the series of images in Figure 3. The shock wave emerges from the container, followed closely by material propelled by the explosion. Shock impact is therefore considered the first failure mode.

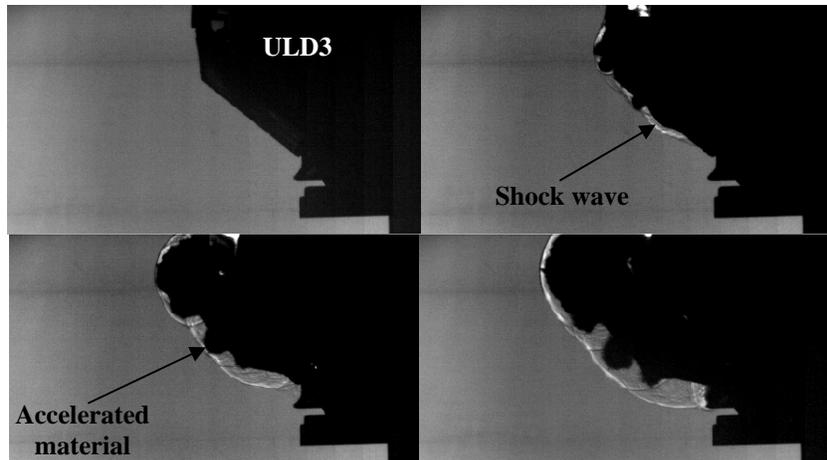


Figure 3: Shadowgraph images of bottom corner of ULD-3 during test 1, frames are $20\mu\text{s}$ apart. The shock wave can be seen emanating from the corner with accelerated material immediately following.

The shock wave from the first test was tracked through the frame sequence using an image processing routine. Its speed as a function of distance from the charge center is shown in Figure 4. Figure 4 also shows the limited data obtained from the bare explosive charge tests and a curve fit extrapolation shown with the dashed line. This figure shows that the cargo and the walls of the container greatly reduce the shock strength of the explosive. The strength of the shock wave as it emerges from the container is about the same as the shock from the bare explosive at a distance of 2m from the charge center. The shock from the container rapidly decays to zero strength (Mach 1).

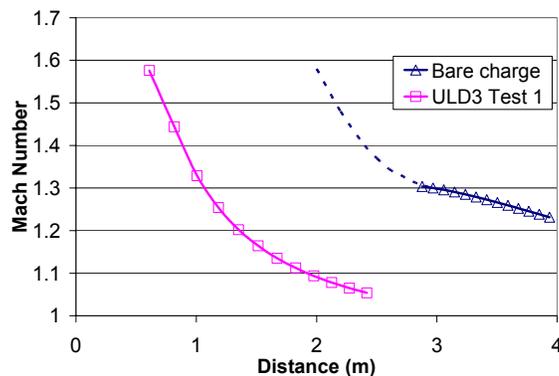


Figure 4: Graph of Mach number as a function of distance from charge center for the bare explosive charge and first ULD-3 test. The bare charge curve fit extrapolation is shown with the dashed line.

For the second test, an extra detonator was placed in the field of view as a timing mark for the initiation of the explosive charge. The timing mark worked well except that the detonator shock wave passed the field of view at almost the exact time that the shock from the container emerged. The presence of the detonator shock prevents drawing clear conclusions about the container shock. One conclusion that can be made is that there was no material explosively-hurled immediately following the shock wave. Material is seen bursting through the ULD-3 wall about $100\mu\text{s}$ after the shock leaves the container. The images show that the container walls deform and break, and fragments immediately exit through the damage. It appears that the damage was caused by the blast accelerated luggage material, representing a second failure mode.

Minutes after the explosion, the ULD-3 from the second test caught fire. This represents another dangerous situation similar to the one that caused the ValuJet 592 crash [8]. Even if the aircraft structure survives the explosive event, luggage material heated by the blast can still cause a fire.

The third ULD-3 test was a repeat of the second test, with the timing detonator relocated. The results were the same, but no fire. The shock wave that emerged from the container was extremely weak, only slightly stronger than a sound wave. The luggage material appears to have suppressed the shock wave almost completely. Fragments, however, were accelerated and burst out of the container after the shock passed. Selected frames from the test are shown in Figure 5.

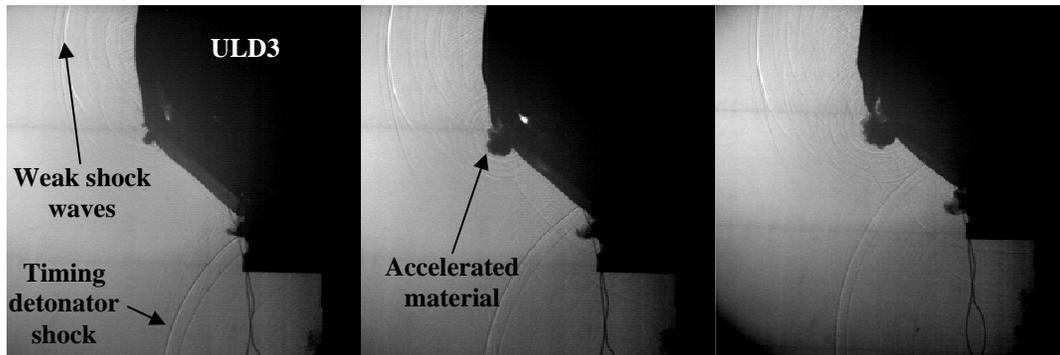


Figure 5: ULD-3 test 3 shadowgraph frames spaced 40µs apart. Explosion of the charge occurred about 180µs before the first frame shown.

Future Work

Two failure modes for cargo containers have been confirmed, shock impact and damage from accelerated material. To further evaluate these failures and to develop techniques for improving cargo containers, more tests should be conducted with added instrumentation. The optical shadowgraphy worked well and can be extended by adding a second system perpendicular to the first to give shock motion in the perpendicular plane. The shadowgraph system can also be improved with pulsed laser illumination to eliminate the problems of direct light fogging. With laser illumination the bare explosive charge can be characterized more fully in terms of a Mach number versus radius profile. The ULD-3 can also be instrumented with pressure transducers to obtain more data to compare with the optical record [2]. Tests with more charge locations could be performed to understand the energy absorption of the luggage and determine weak points in the container construction.

Experiments could also be performed to investigate the high-speed deformation of the container walls. With two high-speed digital cameras in stereo and three-dimensional surface tracking software, deformation histories of the walls can be obtained. A record of wall deformation during an event will help determine wall accelerations and strain rates during the event. This information could lead to materials to better withstand the loads as well as improved structural bracing. The three-dimensional deformation measurements could be applied to walls, edges, or corners where ruptures have been observed. With measurements of deformations, performance standards and criteria could be defined for future containers. The same methods can be applied to the aircraft skin itself.

Other Applications

The optical methods used to image shock waves in this research can also be applied to other research areas. The shadowgraph system is under-used in current counter-terrorism research and could provide more data and greater insight. Two areas of potential are the development of interior and exterior blast resistance.

Scale model tests of shock reflection inside an office building have been performed previously at the Ernst-Mach-Institut [9], but this approach could be expanded and used for blast resistant building development. A 0.5g triacetone triperoxide (TATP) charge was exploded in a small-scale sample building

as an example of this. Shadowgraph video frames from the test are shown in Figure 6. The explosive was placed in the bottom left room, but the shock wave can be seen to reflect throughout the structure, entering every room, but only weakly into the top left room. When the video is viewed at an accelerated play-back rate, the air in the lower left room can be seen to reverberate as shocks repeatedly pass through the room. Vorticies and jets of air can also be seen as shocks pass through doorways and refract into open spaces.

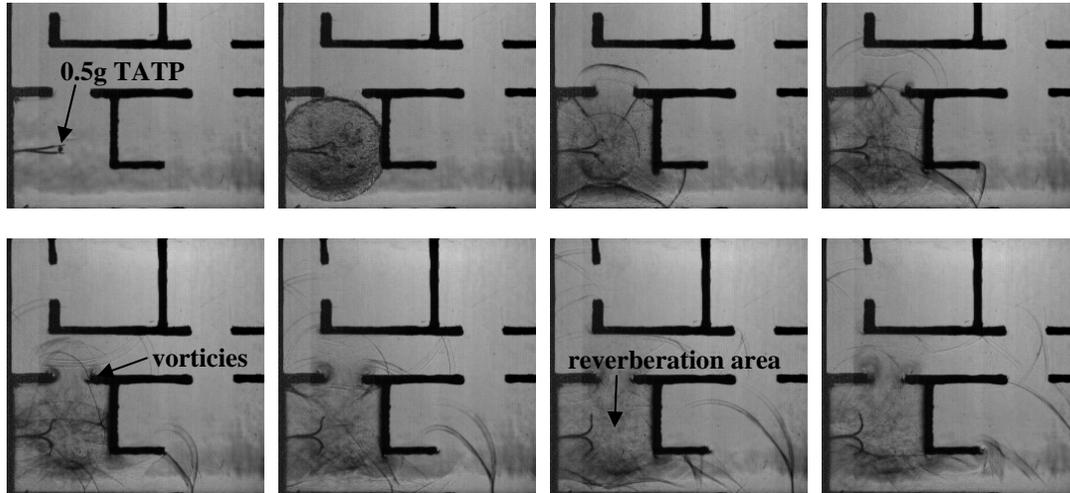


Figure 6: An explosion in a model building, frames are 133 μ s apart.

Exterior building enhancements for blast resistance can also be tested using the shadowgraph system with a high-speed camera. Structural enhancements such as pillars or shock deflection walls could be placed between a street and a building to deflect shock wave energy and reduce damage potential. A simple example showing shock wave diffraction and weakening due to the interaction with pillars (columns) is shown in Figure 7. Present optical methods yield the degree of shock attenuation upon data analysis. Research into optimum spacing and location of pillars or walls could lead to increased blast resistance or survivability for buildings.

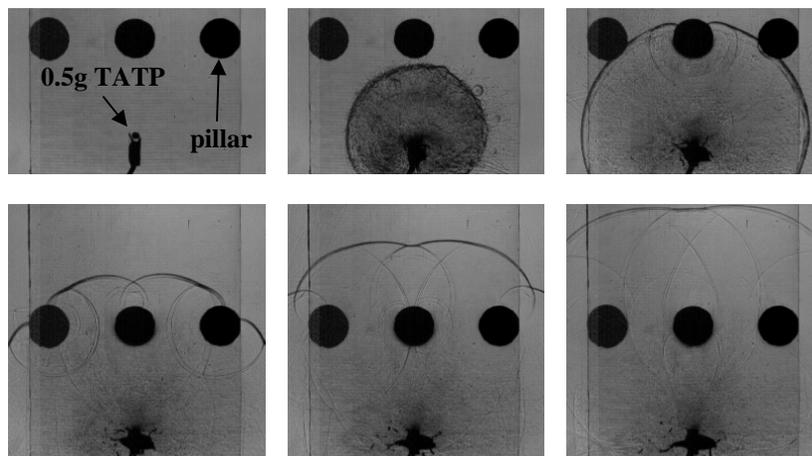


Figure 7: A shock wave diffracting around pillars, frames are 133 μ s apart.

Conclusions

Under-used optical methods exist to properly analyze explosive events and system responses to those events. The shadowgraph technique can be applied to image shock wave motion during explosive events using high-speed digital cameras. Shock wave motion is useful for analyzing the energy released by an explosive and the energy absorbed by materials such as luggage. Optical measurements have

been used to test ULD-3 air-cargo containers to determine failure modes due to a charge detonated inside luggage. Two failure modes have been observed, shock impact and accelerated material rupturing of the container. Luggage was also found to greatly reduce shock wave energy and speed during these tests. The shadowgraph technique is versatile and can be applied to other large- or small-scale explosive tests to improve blast resistance of structures. Three-dimensional surface tracking can also be used in these tests to analyze structure failures and to determine material properties and strain rates during an explosion.

References

1. UK Dept.of Transport, "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. A. and Krznaric, S., "Pressure loading on a luggage container due to an internal explosion," *Proceedings of the 1996 4th International Conference on Structures Under Shock and Impact, SUSI 96, Jul 1996*, Computational Mechanics Inc, Billerica, MA, USA, Udine, Italy 1996, pp. 61-67.
3. Weinstein, E. M., "Design and test of a blast resistant luggage container," *Sixth International Conference on Structures under Shock and Impact, SUSI VI, Jul 3-5 2000*, WIT Press, Southampton, SO40 7AA, United Kingdom, Cambridge, United Kingdom 2000, pp. 67-75.
4. Settles, G. S., Keane, B. T., Anderson, B. W., and Gatto, J. A., "Shock waves in aviation security and safety," *Shock Waves*, Vol. 12, No. 4, 2003, pp. 267-275.
5. Wilson, D. T., "Mitigation of internal blast loading by passenger luggage," FAA, Atlantic City, NJ 2001.
6. Smith, D. J.. The internal airflow in cargo containers and methods to sample it for chemical trace detection. 2005. Pennsylvania State University, Mechanical & Nuclear Engineering Dept. Ref Type: Thesis/Dissertation
7. Settles, G. S., Grumstrup, T. P., Miller, J. D., Hargather, M. J., Dodson, L. J., and Gatto, J. A., "Full-scale high-speed "Edgerton" retroreflective shadowgraphy of explosions and gunshots," 2005.
8. "ValuJet 592: Inquiry and impact: Crash probe eyes oxygen devices," *Aviation Week and Space Technology (New York)*, Vol. 144, No. 22, 1996, pp. 30.
9. Reichenbach, H. and Neuwald, P., "Indoor detonations: visualization and pressure measurements in small-scale models," SPIE, 2001, pp. 92-104.