

EXPLOSIVE TESTING OF WINDOW SYSTEMS

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ABSTRACT

The increased threat of terrorist attacks over recent years has brought to light the need for enhanced physical security features to be incorporated into occupied facilities. Such features may include the use of hardened window systems designed to reduce the level of hazardous glass fragments generated during an explosive event. Historically, the majority of building occupants seriously injured or killed in blast events sustained these injuries due to flying glass fragments from the building's exterior window systems. This has prompted many Federal agencies to mandate explosive testing to pre-qualify window systems prior to being installed in their facilities. Explosive testing can reveal many deficiencies in new technologies and improperly designed window systems, in addition to providing valuable data for improved analytical methods and software validation. With many involved parties, explosive testing is a highly orchestrated process that requires much planning, but yields great benefits for the occupants of blast-hardened buildings in the form of proven hazard mitigating window systems.

INTRODUCTION

Explosive testing of window systems has increased dramatically in recent years as a result of the increased threat of terrorist attacks. Historically, many building occupants who are seriously injured or killed in blast events received their injuries due to flying glass fragments from the building's exterior window systems. Each year, a multitude of explosive tests are conducted to help increase the safety of the building occupants in the event of an explosive attack.

Tested systems have included project-specific applications, as well as commercially available product lines. A sampling of tested window systems includes:

- Butt-glazed (ribbon) window systems
- Punched window systems
- Window cable-catch systems
- Operable and fixed window systems
- Curtainwall window systems
- Blast curtains
- Energy absorbing window systems
- Polycarbonate window systems
- Thick interlayer laminated window systems
- Window security film (daylight, wet-glazed, and mechanically attached)
- Wet-glazed window systems.

Designs based on many of these tested systems have been implemented in buildings throughout the world to help reduce hazard to the building occupants in the event of an explosive attack.

BENEFITS OF EXPLOSIVE TESTING

Explosive testing can be a useful tool for evaluating the response of a window system to actual blast loads. These types of tests can provide:

- Proof of novel concepts.
- Validation of a product.
- Product and project-specific verification/validation of a particular design for a particular loading and a given performance level.
- Data to develop/improve/refine products and analysis tools.

New technologies and designs are continually being developed for reducing glass fragment hazards to building occupants. In some instances, these ideas look promising on paper, although their performance during an actual explosive event may be lackluster at best. Alternatively, a tested system may also far exceed expectations. Because of the real-world results that these tests provide, the explosive test bed has become a ‘proving ground’ for both newly developed technologies as well as project-specific designs.

An added benefit of this type of testing is that the results obtained may be used to develop new analytical methods, as well as provide additional validation of existing methods. A good example of this is the continuing development of the WINGARD computer code for the U.S. General Services Administration. This code predicts the glass hazards generated by an explosive event, and it is continually being improved as the library of test results expands.

TEST OBJECTIVES

There are two major categories of test objectives:

- Proof testing
- Data collection

Although these objectives have differing ultimate goals, they share many common benefits. For example, although the ultimate goal of a proof test is to obtain a “pass/fail” rating for a given specimen and load combination, data collected from the test is also useful for other purposes, such as development and validation of analytical methods and software, as well as improvement of a tested product. Such additional benefits may include:

- High-speed video footage for analyzing the time-dependent response of window systems.
- Pre-test and post-test photographs and measurements for analysis/comparison of response between tested window systems, including failure modes and details.

Similarly, testing conducted for the primary purpose of collecting data may also provide a “pass/fail” rating as a byproduct of the test.

TEST METHODS

Explosive testing is typically performed using one of two different methods: Shock tube testing and large-scale arena testing. There are several pros and cons involved with each type of testing:

Shock Tube Testing

During shock tube testing, the test specimen is mounted at the end of a large tube. A pressure pulse is generated at the opposite end of the tube, which travels down the tube and impacts the test specimen. The pros and cons involved with shock tube testing are as follows:

Pros:

- Less expensive than large-scale arena testing when testing limited samples.
- Readily reproducible loads.
- Can be conducted quickly.

Cons:

- Generally limited to one specimen per test.
- Generally limited to relatively small test specimens.
- Difficult or impossible to achieve realistic open-air blast waveforms (the positive phase impulse may be too high and negative phase effects cannot be consistently replicated).
- Difficult to obtain high-quality video for scientific or marketing purposes.

In general, shock tube testing can be a useful tool for conducting expedient and inexpensive testing through the use of single, small test samples.

Large-Scale Arena Testing

Large-scale arena testing is conducted on an outdoor test bed using high-energy explosives and full-scale test specimens. The pros and cons involved with large-scale arena testing are as follows:

Pros:

- Large size (often full-scale) specimens may be evaluated.
- Multiple specimens may be evaluated simultaneously reducing overall cost per specimen.
- Replicates actual explosive environments resulting in realistic blast loading including both positive and negative phase.
- High quality video footage of the response is typically obtained providing good scientific data, as well as dramatic marketing/demonstration video.

Cons:

- More expensive than shock tube testing when testing only one or two samples.
- Adjustments to the test structure and/or charge size may be required to avoid reduced impulse due to clearing effects when using smaller test structures.
- May require longer lead times in test planning.
- Some variability in results due to real-world environment.

In general, large-scale arena testing can be a useful tool for documenting the response of multiple full-scale test samples in a real-world explosive environment.

TEST STANDARDS

Currently two independent test standards exist for explosive testing of window systems in the U.S.:

- U.S. General Services Administration (GSA) Test Standard (GSA-TS01-2003)
 - Used by GSA and other non-DoD agencies using the ISC Security Design Criteria.
 - Available at no cost from the GSA (<http://www.oca.gsa.gov/>).
- ASTM Test Standard (ASTM 1642-04)
 - Widely used by some DoD components.
 - Available for purchase from ASTM (<http://www.astm.org/>).

No universally accepted blast test standard currently exists in the U.S. for typical building components other than window systems.

The GSA Test Standard

The GSA test standard was developed to ensure an adequate measure of standardization and quality assurance in the testing of window systems. It includes the following:

- A listing of terms and definitions associated with explosive testing of window systems.
- Performance Criteria/Hazard Ratings.
- A listing of test requirements, which include:
 - Allowable test methods (shock tube or high-explosive arena testing).
 - Blast load and explosive charge requirements.
 - Test site and reaction structure requirements.
 - Data collection and documentation requirements.
 - Test specimen requirements.
 - Test report requirements.

Although most of the testing conducted by the Southern Division conforms to the GSA Test Standard, testing to the ASTM Test Standard can also be performed through only minor modification.

TEST PLANNING AND SETUP

With multiple parties involved, explosive testing is a highly orchestrated process that requires much planning and coordination. Each test project begins with discussing the goals of the test with the client. During these discussions, decisions are made regarding the selection of window samples, test load environment and the timeframe for testing. At this time, pre-test load calculations are also performed. The target loads are typically selected to achieve either a specified level of response for the test sample, or a specified load (pressure and/or impulse) required by a particular guideline or project. During this procedure, charge weight and standoff combinations are optimized to achieve the desired load on the test samples. These calculations include altitude corrections to adjust for the altitude of the test bed. For example, a comparison of pre-test predictions and actual (recorded) test loads from the field test of a cylindrical pressure vessel are provided in Figures 1 and 2. The pre-test load distribution predictions are illustrated

graphically in each Figure. The predicted and measured peak loads compare very favorably.

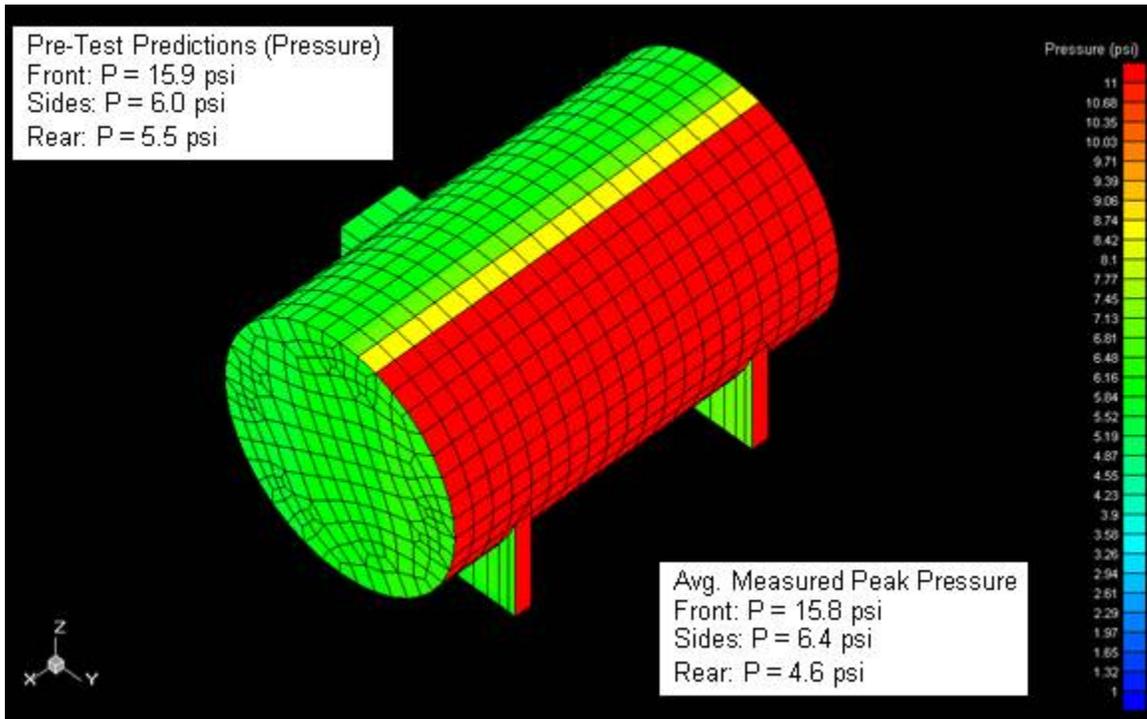


Figure 1. Pre-Test Pressure Predictions vs. Measured Values Across Test Specimen.

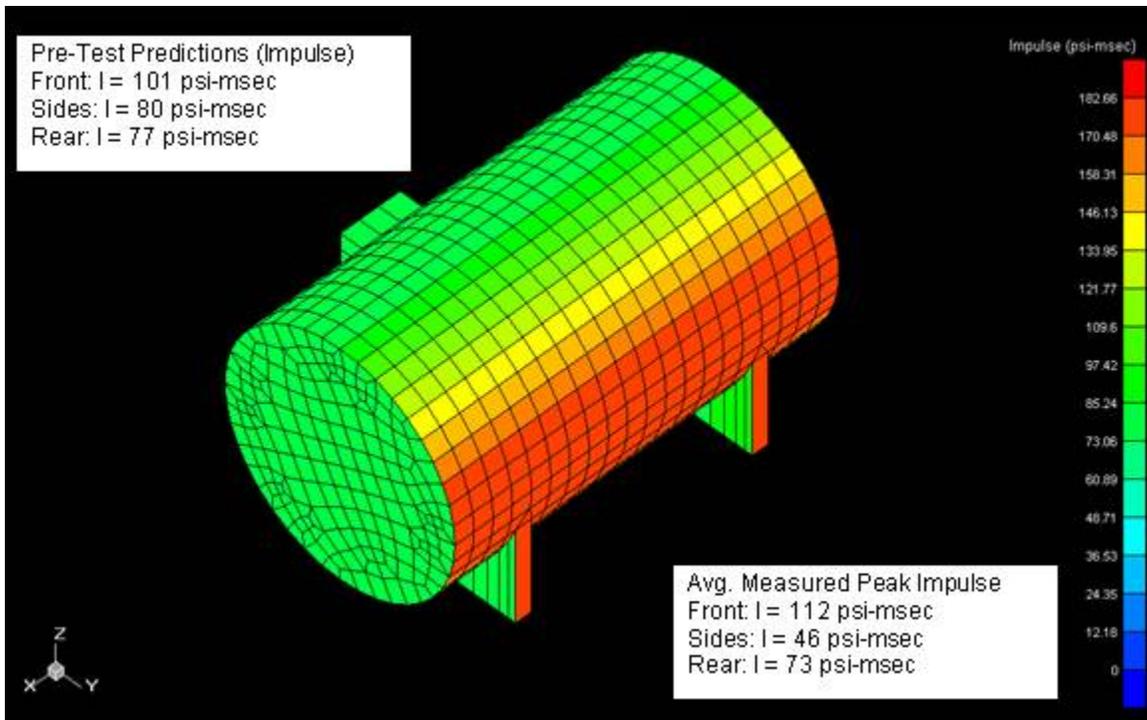


Figure 2. Pre-Test Impulse Predictions vs. Measured Values Across Test Specimen.

Once this information has been determined, coordination of the testing begins. Logistical planning must begin long before testing occurs to be sure that everyone's schedules correspond and that all test specimens are constructed and delivered on time.

Immediately prior to testing, essential personnel arrive on-site to begin test setup. This process can take up to several days. Some of the items included in test setup include:

- Calibration and installation of electronic instrumentation
- Installation of high-speed video cameras and lighting
- Verification and installation of window systems
- Cleanup of test structures and repair of any damage from previous tests
- Preparation of the test setup/test bed in accordance with the appropriate test standard (GSA or ASTM).

Preparation of the test bed typically includes excavating a pit at the charge location which is then filled with clean sand. This preparation reduces the chance of any rocks being ejected from the crater during the blast event. The sand from the test bed and the pit typically has little, if any, influence on the effects of the test. Explosive charges for these types of tests are typically contained in a cardboard Sonotube with a thin plywood base. The Sonotube charge container disintegrates during the blast event, removing the possibility of undesirable fragmentation.

TEST EXECUTION

Test execution is also a highly choreographed process. It begins with a series of 'dry-runs' which check the following systems prior to each test to assure that all systems are performing as intended:

- Firing system
- Pressure gauges and data acquisition equipment
- Cameras and lighting

Once the dry runs have been satisfactorily completed, pre-test measurements and photographs of each window are taken and the location of the explosive charge is marked (Figure 3). The test bed is then cleared of all non-essential personnel and the ordnance technicians begin construction of the explosive charge. After the charge has been constructed, all personnel are ushered to a protected area, the firing system is charged, and the countdown sequencer is started. Once started, the sequencer counts down to zero, at which time the system fires and the explosives are detonated. All of the electronic test systems (firing system, gauges, data acquisition equipment, lights, and gauges) are typically synchronized and controlled through the sequencer. After the detonation, the ordnance technician checks the test bed to assure that all explosive material has been ignited. He then signals that it is safe for personnel to re-enter the test bed for post-test viewing and data collection.



Figure 3. Marked Location for Explosive Charge.

DATA COLLECTION AND PRESENTATION

Data collection and documentation is at the core of any testing program. Multiple types of data are collected during each test series:

- Load-duration time-history at multiple locations
- Charge size and type
- Charge standoff to each specimen
- Time of detonation
- Ambient temperature at time of detonation
- Selected pre and post-test measurements of the window systems

To supplement the measured data, the response of each test window is fully documented using high-speed video as well digital still photography. Figure 4 shows the progression of window failure as captured through high-speed video during an explosive test.



Figure 4. Video Footage of Window Test.

Upon completion of the test series, the load-duration time-history data is processed and plotted as exemplified in Figure 5. The data is then compiled and compared to pre-test load prediction calculations to help fine-tune current load prediction methods.

All of the test data and gathered documentation is then incorporated into a comprehensive report that fully describes both the test procedure along with the test results. Also included in the report is a copy of the specific test method that the test followed, along with details such as manufacturer drawings of the tested systems and any relevant specifications.

As a supplement to the test report, the client is also presented with a video summarizing the results of the test.

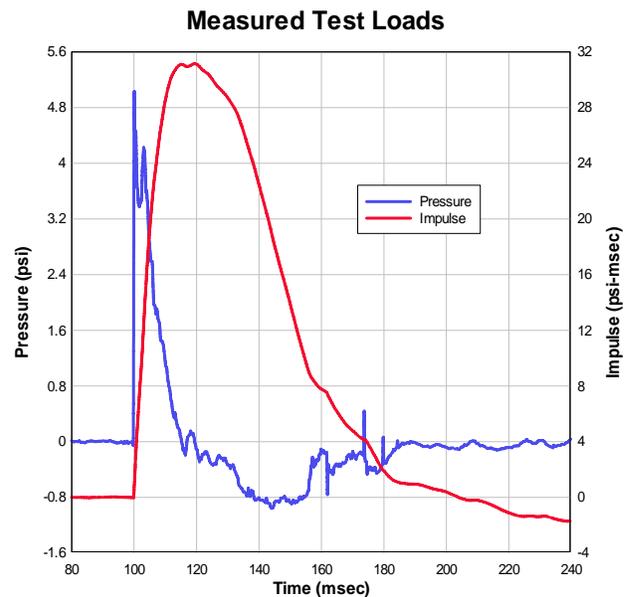


Figure 5. Load-Duration Time-History Plot.

RECENT TEST FINDINGS

Many window blast-mitigation technologies have undergone explosive testing to a certain degree at some point during their development. Lessons learned have resulted in many technologies undergoing extensive refinement based on the results of explosive testing. Some recent developments resulting from explosive testing include:

- Failure of standard connections in blast-resistant muntin window systems
- Failure of attachment screws in glass screen wall
- Documented response of thick laminate window systems
- Documented response of steel sub-frames in blast-resistant window systems

Muntin Window Systems – Blast-resistant muntin window systems consist of a heavy laminated glass pane (similar to a car windshield) backed by a structural tube system, which is welded to an outer steel frame. This is a fairly new type of blast mitigation window system that was designed for the Federal Government and has been implemented in a number of buildings. Recent explosive tests exposed a weakness in the end connections of the structural tubes with the occurrence of a brittle fracture failure (Figure 6). This failure was unexpected, as the system was designed using standard methods to withstand this level of loading. New methods of attachment for these end connections have been proposed.



Figure 6. Failure of Standard Muntin End Connection.

Screen Wall Attachment Screws – Recent explosive tests were conducted to evaluate a concept window design for new 8-story Federal office building. The facility is to have an architectural steel exoskeleton and glass screen wall covering the majority of the building exterior. Designers specified attachment clips and screws rated for hurricane-level loads for attaching the screen wall to the exoskeleton. When tested in an explosive environment, the upper attachment screws failed, resulting in the upper glass screen wall panel falling to the ground (Figure 7). These panels falling from the upper floors of the building would have exposed the building occupants to hazardous conditions during evacuation of the facility. Upgraded attachment screws were then re-tested and found to perform adequately.

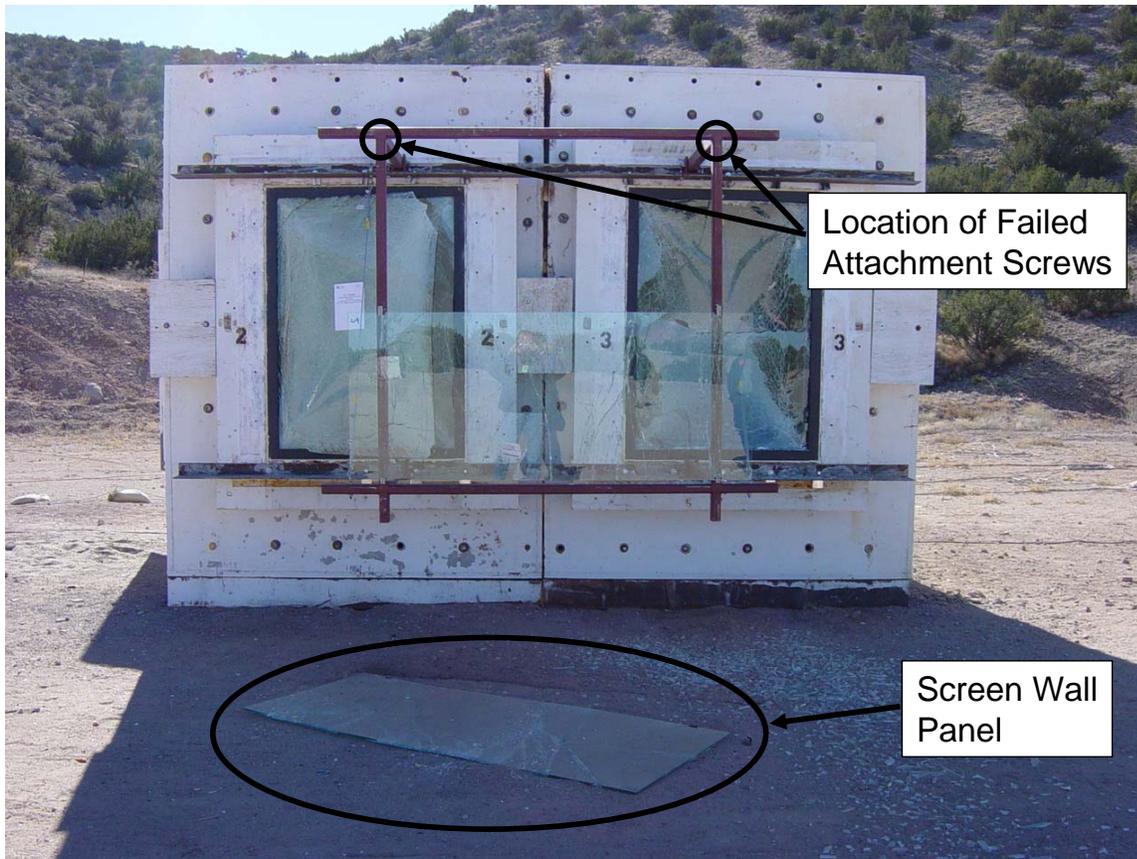


Figure 7. Failure of Screen Wall Attachment Screws.

Thick Laminate Window Systems – Thick laminate interlayer window systems are typically used in hurricane-prone areas. The thick laminate interlayer provides increased strength to the window, as well as mitigation of projectile penetration. Explosive tests were recently conducted on these types of windows to document their performance when exposed to an explosive environment (Figure 8). The data gathered during the tests was used to develop new analytical models which were then incorporated into the latest version of the GSA-sponsored computer program WINGARD. This enhancement of WINGARD will help analysts and designers predict the response of these window systems under blast loads, thereby providing additional options for blast hardening of new and existing buildings.



Figure 8. Post-Test Photo of Thick Laminate Window System Response.

Steel Sub-Frame Response – Explosive tests were recently conducted on window upgrades planned for a prominent Federal office building. The test loads caused deformation of the window’s steel subframe that exceeded the response limits allowed for the system (Figure 9). A finite element analysis (FEA) of the system was performed and exposed a weakness in one of the corner connections of the frame (Figures 10 and 11). An appropriate upgrade was developed for the window manufacturer to help correct the deficiency.



Figure 9. Post-Test Photo of Frame Deformation.

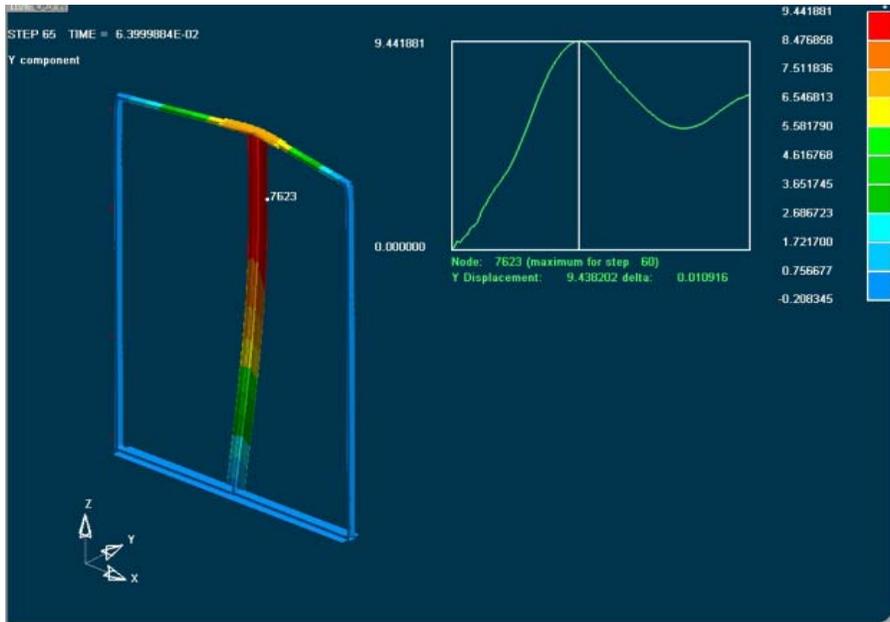


Figure 10. FEA Displacement Results for Test Window.

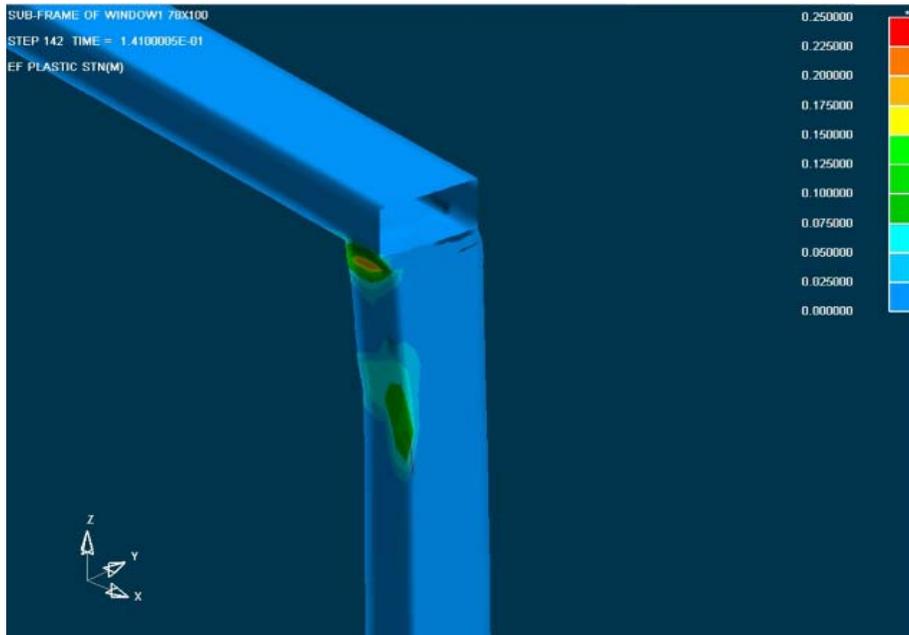


Figure 11. FEA Strain Results for Test Window Connection.

CONCLUSIONS

Explosive testing of window systems provides a valuable service, with many of the tested systems having been implemented in buildings throughout the world. This added level of protection helps to increase the safety of the building occupants in the event of an explosive attack. With many involved parties, explosive testing is a highly orchestrated process that requires much planning, but yields benefits for both those planning the security upgrades for a particular facility and for the occupants of that facility.

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Applied Research Associates, Inc. conducts numerous explosive tests each year including tests of window systems, doors, wall systems, portable hardened facilities and other items. Since the April 19, 1995 bombing of the A.P. Murrah Federal Building in Oklahoma City, ARA's Security Engineering & Applied Sciences Sector has performed explosive testing on several hundred different window specimens for numerous U.S. Government agencies, as well as U.S. and foreign corporations. Contact Mr. Joseph L. Smith, Sr. Vice President (jsmith@ara.com), Mr. James Brokaw (jbrokaw@ara.com), Principal Engineer and Group Leader, or the authors of this paper for additional information.