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Final Summary Overview:

Post-Blast Investigative Tools for Structural Forensics by 3D Scene Reconstruction and Advanced Simulation

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Purpose of the Research Effort

Identification of the source of either an accidental or malicious explosion, including determination of the charge weight, composition, and epicenter, is one of the fundamental challenges encountered in post-blast forensic investigations. Current practice for post-blast investigation relies on significant photography and videography of the scene to document evidence, which includes damage to both structural and nonstructural building components from the blast overpressure (U.S. Department of Justice, 2000). However, while the observed damage to these building components contains meaningful information on the blast loading that could be used to enhance post-blast investigations (Sorenson and McGill, 2011), high-fidelity scene reconstruction techniques based on 3D scanning technologies are necessary to provide reliable and sufficiently precise documentation of the post-blast environment to facilitate the back-calculation of explosive properties from the observed damage to building components. Likewise, advanced physics-based simulation tools are necessary to replace relatively crude empirical approaches for determining explosive properties from observed damage with scientifically-based and objective methods. Such computational simulation has transformed related forensic investigative practice through tools specific to arson, blood spatter, ballistics trajectory, and vehicular accident reconstruction.

One primary objective of the sponsored research was to evaluate the use of low-cost scanning technologies for 3D scene reconstruction and other nondestructive inspection technologies that could enhance the collection of post-blast investigative field evidence. Specifically, this research aimed to support an approach of using structural and nonstructural building components as "witness" to blast events, since the extent of permanent set deformation in ductile components, such as steel, and fracture, fragmentation, and debris field formation in brittle components, such as glass, are sensitive to the charge weight, composition, and epicenter of the explosion. Through applied research, the effort aimed to assess the capabilities of both low-cost and measurement grade 3D scanning technologies for the collection of measurements allowing for the characterization of such damages in building components in the post-blast environment.

The second primary objective in this sponsored research effort was to develop the basis of a scientific, physics-based methodology for objective and quantitative determination of charge weight, composition, and epicenter from on-site measurements of the condition of structural and non-structural components damaged by the blast overpressure. Physics-based methodologies introduce engineering simulations to predict the damaged state of these components and provide a means for practitioner hypothesis testing through comparison with field collected evidence. Furthermore, the development and validation of a physics-based methodology could enable automated estimation of charge weight, composition, and epicenter when paired with the high resolution and accurate 3D scene reconstructions produced by modern 3D scanning tools. In this research effort, the initial development, verification, and validation of a Blast Dynamics Simulator, based on an implementation of the Applied Element Method to enable prediction of component behavior through fracture, fragmentation, and development of a debris field, was pursued to provide a basis for introducing such advanced engineering tools into post-blast investigative practice.

Project Design and Methods

The research effort addressed the objectives through extensive field experimentation at an open arena blast testing facility coupled with the development of analytical tools for simulating the response of test specimens under blast loading. This design of the research approach allowed for simultaneously providing a real-world platform for assessing the performance of 3D scanning technologies for scene reconstruction in the post-blast environment as well as providing an extensive experimental database suitable for validating the development of analytical tools forming the basis of a preliminary Blast Dynamics Simulator for post-blast hypothesis testing. In total, 13 blast tests were conducted at the UNC Charlotte Infrastructure Security and Emergency Responder Research and Training (ISERRT) Facility on a test enclosure designed to simulate a small building with a single facade wall comprised of six test specimens. The first seven blast tests were conducted with steel specimens to produce an experimental database with damage characterized by permanent set deformations typical of ductile building materials, while the remaining six blast tests were conducted with tempered glass specimens to produce a corresponding experimental database with damage characterized by fracture, fragmentation, and debris field formation typical of brittle building materials. Furthermore, testing was conducted using both ammonium nitrate/fuel oil (ANFO) mixtures as well as pentaerythritol tetranitrate (PETN) cast booster charges to provide data for damage developed under both low explosive (LE) and high explosive (HE) yields, respectively. A summary of the open arena blast tests conducted within the experimental program of this research effort is provided in Table A1. The steel panels were 3.2mm thick, with the exception of the first set of specimens that were 4.8mm thick. The glass lites were 4.8mm thick tempered glass. Both the steel panels and the glass lites had frontal dimensions of 80cm x 122cm.

Through direct support and in-kind contributions from Union Glass & Metal and GRATEC of Fort Mill, SC, a custom test enclosure was developed for this research consisting of a steel reaction framework outfitted with aluminum mullions that are conventionally used in commercial construction (Figure A1). This reaction framework was designed to support either steel or glass panel specimens and featured additional aluminum panels for the installation of an array of nine flush mount pressure transducers to measure the reflected blast overpressure during each of the blast tests. These measurements of reflected overpressures, as well as measurement of incident overpressure obtained from a pair of free field pencil probe transducers, were used to characterize the explosive yield for each of the explosions as well as provide a quantitative basis for comparison with the blast calculations performed in the developed Blast Dynamics Simulator. In addition to the reaction framework for the panel specimens, a timber enclosure was constructed behind the framework to more faithfully represent the typical conditions associated with a facade of an enclosure building and produce an interior environment within which debris would be contained to generate a post-blast investigative scene. Several notable enhancements of this test enclosure were also introduced to provide means for augmenting the 3D scanning measurements to benchmark both their performance and the predictive accuracy of the Blast Dynamics Simulator predictions against direct physical measurements. A witness panel, which is a two inch thick layer of expanded polystyrene foam with a face layer of half inch thick polyiso rigid, was constructed on the back wall of the enclosure to capture all flying glass debris reaching the rear wall of the enclosure (Figure A2). A new witness panel was installed between subsequent blast tests, as needed, and photographs of the presence, location, and size of high hazard glass debris captured by the witness panel were obtained after each test as one of the physical measurements used to validate computational simulations performed with the Blast Dynamics Simulator. As an additional measure taken to quantify the debris field generated by glass fragmentation, the floor inside the test enclosure was partitioned into nine areas demarcated with tape (Figure A2). Following each blast test and subsequent photography and 3D scanning, the glass debris within each demarcated area was carefully collected using a vacuum and the total mass of the collected glass was weighed. This physical measurement of the mass distribution of the glass debris produced in each test is used as another means for validating the fidelity of the computational simulations. Furthermore, the mass distribution measurements provide a physical reference for correlation with volumetric estimates obtained through post-processing of the 3D point cloud measurements produced by the 3D scanning and scene reconstruction tools. Lastly, each of the six glass lites set in the framework were prepared with a unique color of aerosol paint surface coating. This measure enabled the research team to identify the original panel location associated with glass fragments in the debris fields generated both within and outside the test enclosure. Such opaque surface coatings are commonly used on spandrel glass in buildings. To provide a case typical of transparent vision glass, one test was performed with no surface coating on the tempered glass.

The protocol used to perform the open arena blast testing of both the steel and glass specimens involved first preparing a new set of six panels in the aluminum mullion framework of the reaction frame. A uniform 9.6 N·m (85 lb·in) torque was applied with a torque wrench to tighten the screws securing the pressure plate to the mullions to hold the panels in place. Nondestructive modal testing of each panel was then performed using an impulse hammer and a pair of reference accelerometers to characterize the dynamic properties of each specimen (natural frequencies, damping ratios, and mode shapes) through system identification. These dynamic properties strongly influence the response of the panels under the blast loading and the experimental measurement of these quantities provided a basis for initial verification of the computational routines in the Blast Dynamics Simulator and, subsequently, calibration of the computational models. Digital data acquisition was then prepared to measure reflected overpressures at the nine flush mount transducers installed in the reaction frame and incident overpressures at two free field pencil probe transducers positioned approximately one to two meters from the explosive epicenter. The explosive charges were then prepared by trained and certified personnel in the City of Gastonia Police Department Bomb Squad and detonated in parallel with simultaneous digital data acquisition of the measurement signals.

High speed video of each test was also captured to observe the blast event. The high speed videos document the dynamic response of the steel panels after the application of the blast overpressure as well as the instant of glass fracture and the general trajectory of glass debris following fragmentation of each lite. For the testing of the glass lite specimens, a pair of digital cameras were also mounted on the back wall of the test enclosure to capture images of the initial fracture patterns in the glass specimens during each test. Immediately following the explosion for each of the 12 blast tests, the post-blast scene was documented using conventional photography as well as 3D point cloud scanning, focused exclusively on the deformations in the steel panel specimens and the debris fields both inside and outside the enclosure for the glass tests. As previously noted, supplemental physical measurements were also obtained for reference comparison with the 3D scanning data, including witness panel photographs and mass distribution measurements across the floor of the enclosure. For the panel specimen tests, discrete measurements of the permanent set deformation across a grid of nine points were obtained for each panel using an array of digital dial gages mounted on a temporary fixture mounted to the rear side of the reaction frame.

Post-blast scanning was performed with three 3D scanning technologies that utilize different measurement principles and have significant differences in system-level cost. The first 3D scanning technology used was the low-cost Microsoft Kinect handheld scanner. During post-blast scanning of the steel panel specimens, a first-generation Kinect scanner was used, while the second-generation Kinect scanner was used for post-blast scanning of glass panels and debris. The first-generation device used structured light coding in the infrared bandwidth through projection of randomly located dots triangulated by an infrared camera mounted within the device. The second-generation Kinect scanner uses a time-of-flight measurement that increases the accuracy of the depth measurement and improves the ability of the sensor to perform in direct sunlight (Zennaro et al. 2015). The Kinect scanner was mounted to an articulating servo-controlled robotic arm to control the orientation of the camera and allow for scanning to be performed in a repeatable manner that would also be absent of jitter (Figure A3.a). The Microsoft Kinect Software Development Kit, specifically the KinectFusion routines for real-time dense 3D surface mapping (Newcombe et al. 2011), were used to acquire 3D point cloud measurements from the Kinect scanner throughout the test program.

The second scanning technology investigated was a large format structured light scanner developed as part of this research effort using a high resolution Digital Light Projection (DLP) projector and a 5 megapixel CMOS camera. Structured light scanning is widely utilized in commercial 3D scanning systems, however no commercially available systems were identified that offered the short throw and wide field of view necessary for scanning large areas, such as building walls. Consequently, the hardware for a custom system was developed using an Optima GT1080 HD DLP projector and a Basler puA2500-14um camera with a 5mm focal length lens supported by a mounting fixture and tripod for field deployment. This scanner was developed to operate in the visible light spectrum, so the projected structured light patterns could be visibly observed during scanning, unlike the other 3D scanning technologies used (Figure A3.b). Calibration of the projector-camera pair and reconstruction of the point cloud from gray code sequences of captured structured light images were performed using the open-source library of routines developed at Brown University (Moreno and Taubin, 2012). All calibrations were performed on site using calibration images acquired with a black and white planar checkerboard.

Lastly, a FARO Focus3Dx130 commercial LiDAR scanner was used to acquire high resolution and high accuracy laser-based 3D point cloud measurements as a benchmark reference (Figure A3.c). Following each test, a series of approximately four scans were performed with the LiDAR scanner positioned at different locations to provide field of view coverage both inside and outside of the enclosure. Standard reference target spheres were placed outside of the area of interest but within the field of view of the scanner to assist in registration of the scans, which was performed within the FARO Scene software. Additional post-processing of the 3D scanning point clouds was performed in the open source Cloud Compare software (Girardeau-Montaut, 2015) as well as with project-specific routines scripted in the Matlab technical computing environment.

Data Analysis and Project Findings

For both the experiments performed with the steel and glass specimens, the 3D point cloud measurements obtained in the field with the low-cost scanning technologies were compared with LiDAR reference measurements as well as the supplemental physical measurements of panel deformations and debris field mass distributions. Planar dimensional measurements and depth maps generated with both the Kinect scanner and the large format structured light scanner for the steel panel tests compared favorably with the LiDAR reference measurements, although the higher noise floor for the Kinect scanner and structured light scanner resulted in significant uncertainties at lower magnitude of permanent set deformation (Figure A4). Despite these scanning errors, one conclusion from the research is that the low-cost scanning technologies would generally be suitable for the task of documenting the condition of structural and nonstructural building components in the post-blast environment due to the significant increase in spatial resolution offered by the full-field nature of these measurements relative to discrete contact-based measurements. However, several significant practical obstacles for their field usage were encountered by the research team that severely limit their potential to be accepted into practice. With respect to the large format DLP structure light scanner, since this device operates using light in the visible spectrum and the short throw of the projector necessary for large format scanning results in a low intensity of projected light, this scanner was found to be incapable of operating in the outdoor environment. Consequently, all scans acquired with this technology were obtained from within the enclosure and no scanning of the glass debris field with this technique was possible. The first-generation Kinect scanner was also found to be sensitive to solar radiation, although the second-generation Kinect scanner was generally immune to issues arising from the use of the scanner outdoors. However, the limited field of view offered by this scanner presents significant challenges with respect to scanning large surfaces typical of building systems and glass debris fields. During this research project, this obstacle was address by acquiring a large number of overlapping point cloud scans that were later aligned and registered using the Iterative Closest Point (ICP) algorithm. However, this process required significant manual processing of the point clouds and was found to lead to accumulation of alignment errors that produced distortions and other significant geometric errors in the fully reconstructed scene (Figure A5). Due to the limitations encountered with the low-cost technologies, ongoing work being conducted by the research team has transitioned toward focusing on the use of the high accuracy, high resolution, and wide field-of-view 3D point cloud measurements afforded by the LiDAR scanner as a means for enhancing post-blast forensic investigations.

Toward the project objective of developing the foundation of a Blast Dynamics Simulator to leverage nonstructural and structural evidence in post-blast forensic investigations, the research produced a library of computational routines that have been analytically verified and compare well with experimental measurements. As originally proposed, the software library implements the Applied Element Method (Tagel-Din and Meguro, 1999) for simulating structural response beyond linear elastic behavior, including nonlinear geometric effects, nonlinear material constitutive laws, and fracture, fragmentation, and debris field formation. This method is a relatively new technique for multi-scale structural analysis that has been successfully applied to the modeling of structural damage from blast events (Tagel-Din and Rahman, 2006; Tokal-Ahmen, 2009; Kernicky et al. 2014). Over the course of this research effort, the Applied Element Method formulation has been implemented in an open source library of software routines, written in the Matlab technical computing language and compiled to accelerate performance, that have been prepared to facilitate the simulation of the response of steel and glass facade panels in buildings subjected to air blast loads. Verification of several of the computational features within the developed software library has been performed by comparing the predicted response of simple models to closed-form solutions. A concise summary of specific features of the developed library of routines is provide below:

- Nonlinear geometric effects allow for accurate prediction of structural response through geometrically induced softening and/or stiffening as well as buckling instabilities.
- Nonlinear constitutive material models have been introduced for both ductile materials and brittle materials. For ductile materials, a bilinear elastic-plastic model with kinematic strain hardening has been implemented as well as an advanced constitutive model that additionally accounts for the Bauschinger effects due to cold working during strain reversals. For brittle materials, the ability to automatically detect stress amplitudes exceeding specified material strength thresholds has been implemented to simulate fracture and fragmentation through the removal of the internal springs that form the connectivity between the elements.
- Although model generation and analysis capabilities have not yet been fully generalized, the software library does currently support analyses with different material assignments across the elements in the model. In addition, the element geometry and number of springs assigned

across each pair of elements in contact can be defined by the end user.

- The capability for predicting blast pressures resulting from explosive events was implemented using polynomial approximations to the blast parameters based on the Kingery and Bulmash models (Swisdak, 1994). Consistent with conventional blast effects models, the modified Friedlander open air blast pressure model is used to calculate the reflected pressures applied to individual elements in the model. Additionally, blast loading effects tables were incorporated into the software library to account for the angle of incidence on obliquely loaded elements.
- To support rendering and advanced post-processing of the computational results, the software library was written to prepare output files compatible with the ParaView open source data analysis and visualization platform (Ahrens et al. 2005), widely utilized across a variety of scientific fields for data visualization. Figure A6 presents a screenshot of principal stress results from the Blast Dynamics Simulator rendered in ParaView.

Computational simulations of the open arena blast tests performed with both steel and glass facade panels has been performed to provide insight on the research objective of facilitating hypothesis testing of explosive source location, size, and composition through correlation with physical measurements of the damage to structural and nonstructural building components. Using the measured array of reflected pressure and incident pressure measurements, the TNT equivalence of the PETN and ANFO explosive charges used in the experimental program were determined by correlating the blast effects model programmed into the Blast Dynamics Simulator with the measured pressures. Nonlinear dynamic time history analyses were performed using a model of the six specimens to predict the response of the panels to the applied blast loading and, in the case of the steel panels, the permanent set deformations produced by the loading. These predictions were compared to depth maps processed from the 3D point cloud measurements to assess the predictive fidelity of the simulations. While the presence of permanent set deformations and relative intensity of the permanent set deformations across the panels in the facade generally correlated well with the experimental observations (Figure A7), the Blast Dynamics Simulator was found to under-predict the magnitude of the permanent set deformations in the steel specimens observed in the experimental test program. The nature of this discrepancy is not yet fully understood and could be attributed to a variety of experimental unknowns, including the complex and potentially highly nonlinear behavior of the boundary conditions. However, for this specific case of steel panel specimens, the results imply that additional development of the Blast Dynamics Simulator capabilities paired with extensive experimental validation is necessary prior to transitioning this computational tool and methodology to field practice. Extended development, verification, and validation of the Blast Dynamics Simulator specific to the application to glass lites continues to be an area of active ongoing research being carried out by members of the research team.

Implications for Criminal Justice Policy and Practice

This research provides a foundation for introducing 3D scanning and reconstruction tools for documentation of post-blast forensic scenes, specifically the reconstruction and profiling of blast-induced damage to structural and nonstructural building components. In the long-term, the enhanced scene documentation tools evaluated by the project could facilitate the development of a rich database of scientific data from post-blast investigations that may produce data-driven heuristics for forensic benchmarking and advanced empirical study of explosive effects on conventional building structures in real-world scenarios. The initial development of a Blast Dynamics Simulator in this project can assist in promoting post-blast forensic investigation on an equivalent scientific foundation as currently established in the post-fire forensic arena by producing a means for hypothesis testing of investigator conclusions on explosive charge weight, epicenter, and composition. Currently, the developed Blast Dynamics Simulator provides the capability for evaluating the response of ductile building facade panels to predict the permanent set deformations observed in the post-blast environment as well as the response of glass lites in building fenestration systems to predict the fracture, fragmentation, and development of debris fields when subjected to blast overpressures. Continued long-term development of this library of computational codes could lead to the development of a more generalized software for simulating the effects of accidental and malicious explosions, similar to the Fire Dynamics Simulator and associated Smokeview visualization package used in arson investigations (McGrattan et al. 2013; Forney, 2016).

Scholarly Products

Technical Presentations

Howe, A., Moss, J., Whelan, M., and Weggel, D. (2017) "Experimental Investigation of 3D Scanning and Scene Reconstruction Tools for Post-Blast Measurement of Building Facades," Structures Congress 2017, Denver, Colorado, April 6-8.

Moss, J., Howe, A., Whelan, M., and Weggel, D. (2017) "Simulation of Fracture, Fragmentation, and Debris Field Formation in Glass Lites under Blast Loading using the Applied Element Method," The 14th U.S. National Congress on Computational Mechanics, Montreal, Canada, July 17-20.

Journal Manuscripts - In Process

Howe, A., Moss, J, Whelan, M., and Weggel, D. (in preparation) "Experimental Comparison of 3D Scanning and Scene Reconstruction Tools for Post-Blast Forensic Investigation," to be submitted to the journal *Forensic Sciences Research*.

Whelan, M., Moss, J., and Weggel, D. (in preparation) - "Applied Element Simulation of Nonstructural Building Facade Panels for Enhanced Post-Blast Forensic Investigation," journal to be determined.

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Zennaro, S., Munaro, M., Milani, S., Zanuttigh, P., Bernardi, A., Ghidoni, S., and Menegatti, E. (2015) "Performance evaluation of the 1st and 2nd generation Kinect for multimedia applications," 2015 IEEE International Conference on Multimedia and Expo (ICME), pp. 1-6.

Appendix

Table A1. Summary of Open-Arena Blast Tests Conducted in Research Effort

Test	Specimens	Charge	Standoff	Position of Charge
1	Steel	0.91kg PETN	1.22m	Centered on bottom central panel
2a	Steel	1.56kg ANFO	1.52m	Centered on bottom central panel
2b	Steel	2.54kg ANFO	1.52m	Centered on bottom central panel
3	Steel	3.18kg ANFO	1.52m	Centered on bottom right panel
4	Steel	3.18kg ANFO	1.52m	Centered between bottom central and right panels
5	Steel	0.91kg PETN	1.22m	Centered on bottom right panel
6	Steel	0.91kg PETN	1.37m	Centered on bottom central panel
7	Glass	0.91kg PETN	1.83m	Centered on bottom central lite
8	Glass	0.91kg PETN	5.05m	Centered on bottom left lite
9	Glass	0.45kg PETN	3.05m	0.91m to the left of the left edge of the bottom right lite
10	Glass	0.73kg ANFO	2.44m	0.46m to the right of the right edge of the bottom right lite
11	Glass	0.73kg ANFO	2.74m	Centered on the bottom right lite
12	Glass	0.73kg ANFO	2.44m	Centered between bottom central and right lites

Note: Test 2a did not result in measurable deformations; test specimens were reused in Test 2b

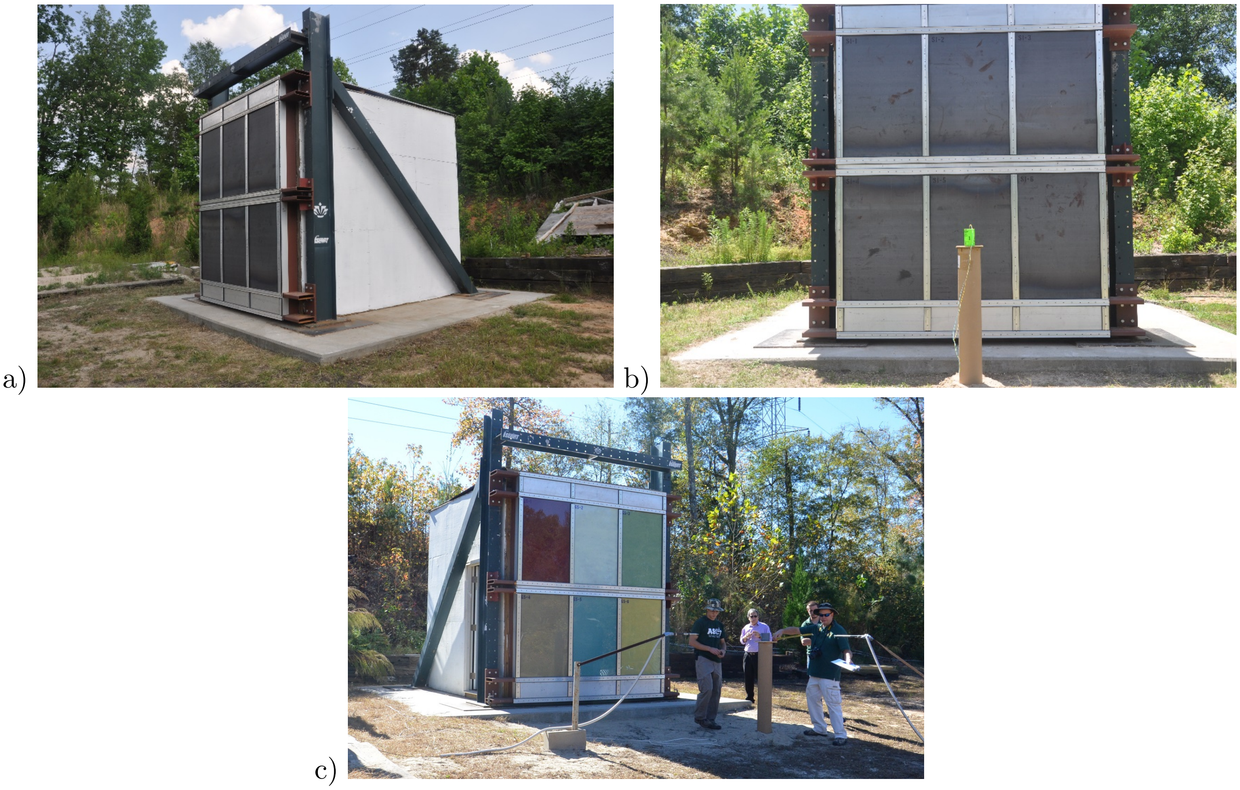

Figure A1. Photographs of experimental test setup developed at the UNC Charlotte ISERRT Facility: a) Reaction frame and enclosure; b) steel panel specimens installed in frame; c) glass lite specimens installed in frame

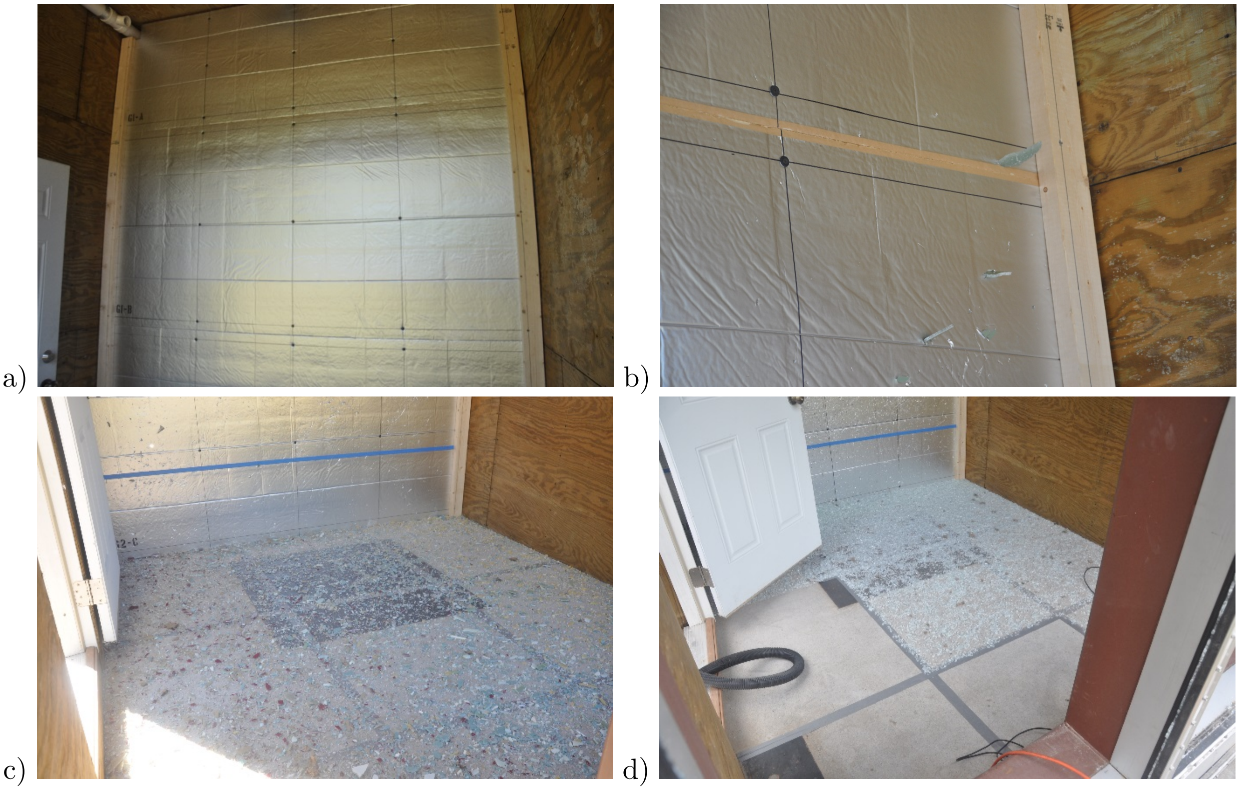
a)
b)
c)
d)

Figure A2. Additional test protocol for glass specimens: a) use of an ASTM F1642-12 witness panel at the rear of the test enclosure to document high hazard glass debris; b) photograph of glass debris captured by witness panel; c) glass debris on floor across nine demarcated areas; d) collection of glass debris from demarcated areas to quantify the distribution of mass of glass debris throughout the enclosure

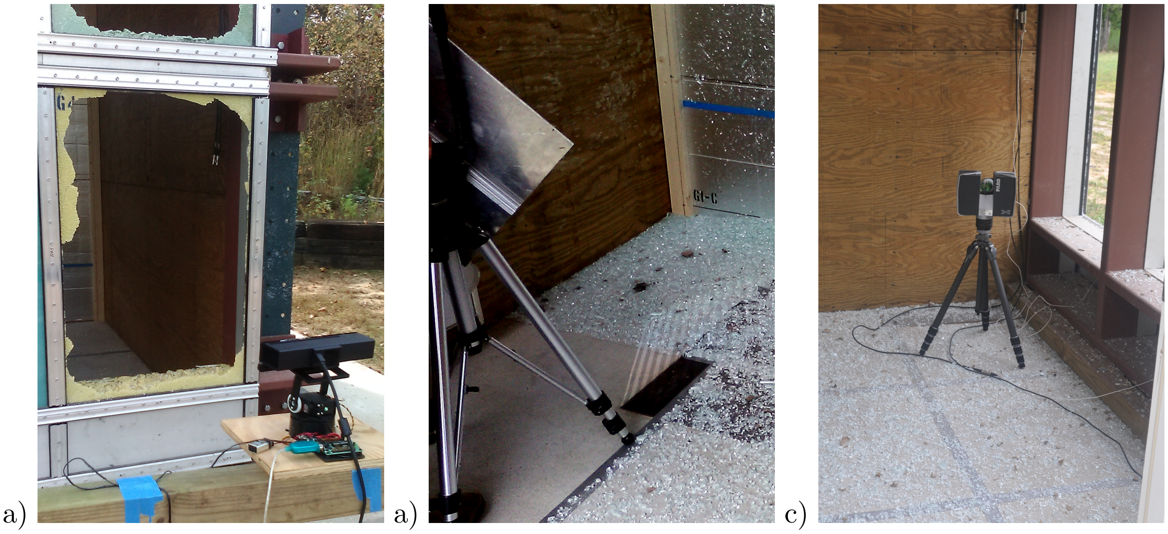
a)
a)
c)

Figure A3. Photographs of the 3D scanning technologies evaluated during the open arena blast testing: a) Microsoft Kinect scanner; b) large format DLP structured light scanner; c) FARO Focus3Dx130 LiDAR scanner

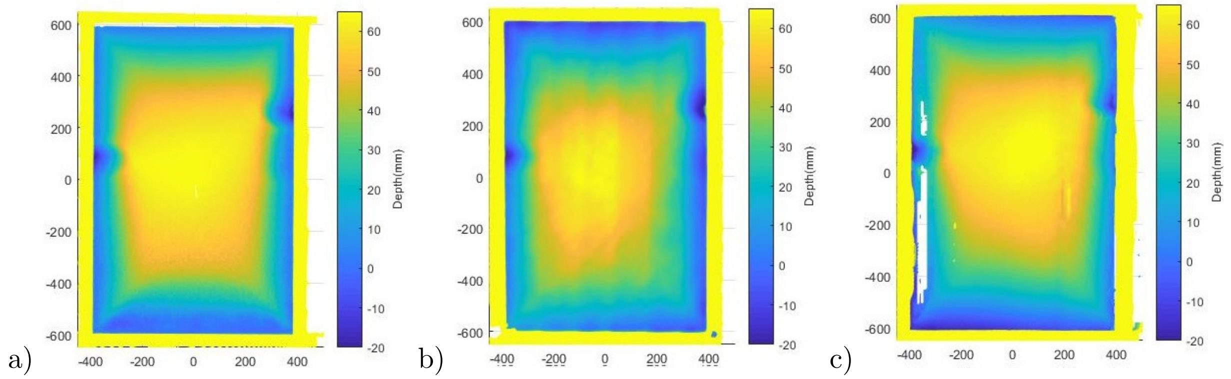

Figure A4. Representative comparison between 3D point cloud depth maps obtained using scanning technologies for the same steel panel specimen: a) LiDAR reference; b) Kinect scanner; c) large format DLP structured light scanner

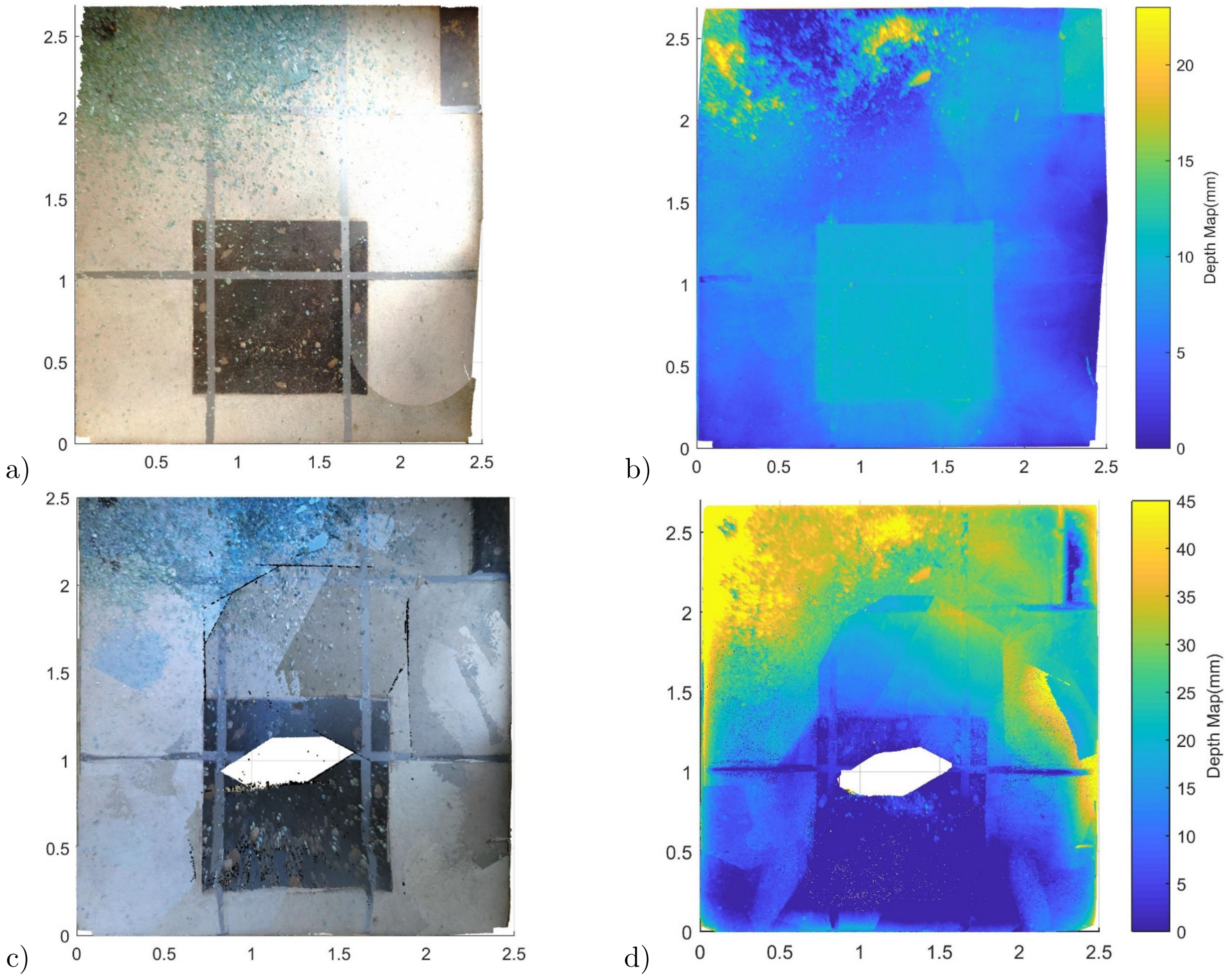

Figure A5. Comparison of 3D point clouds and debris field measurements obtained with LiDAR scanner and Kinect scanner: a) LiDAR point cloud; b) LiDAR depth map; c) Kinect point cloud; d) Kinect depth map

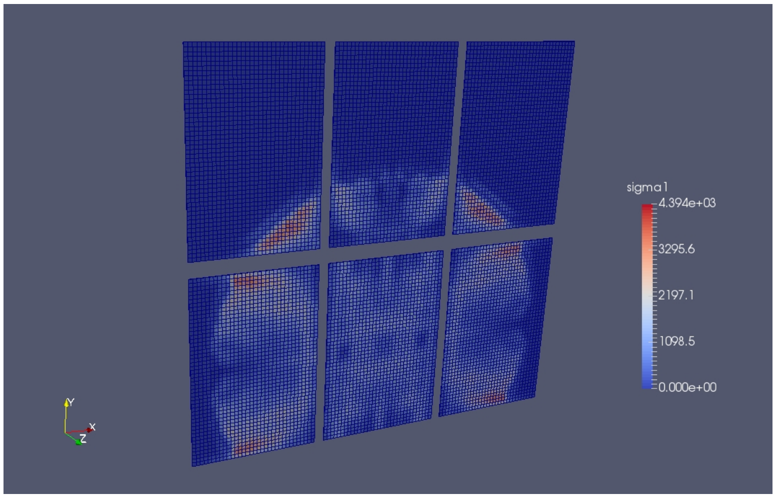

Figure A6. Visualization of Blast Dynamics Simulator results through integration with the ParaView open-source scientific visualization platform

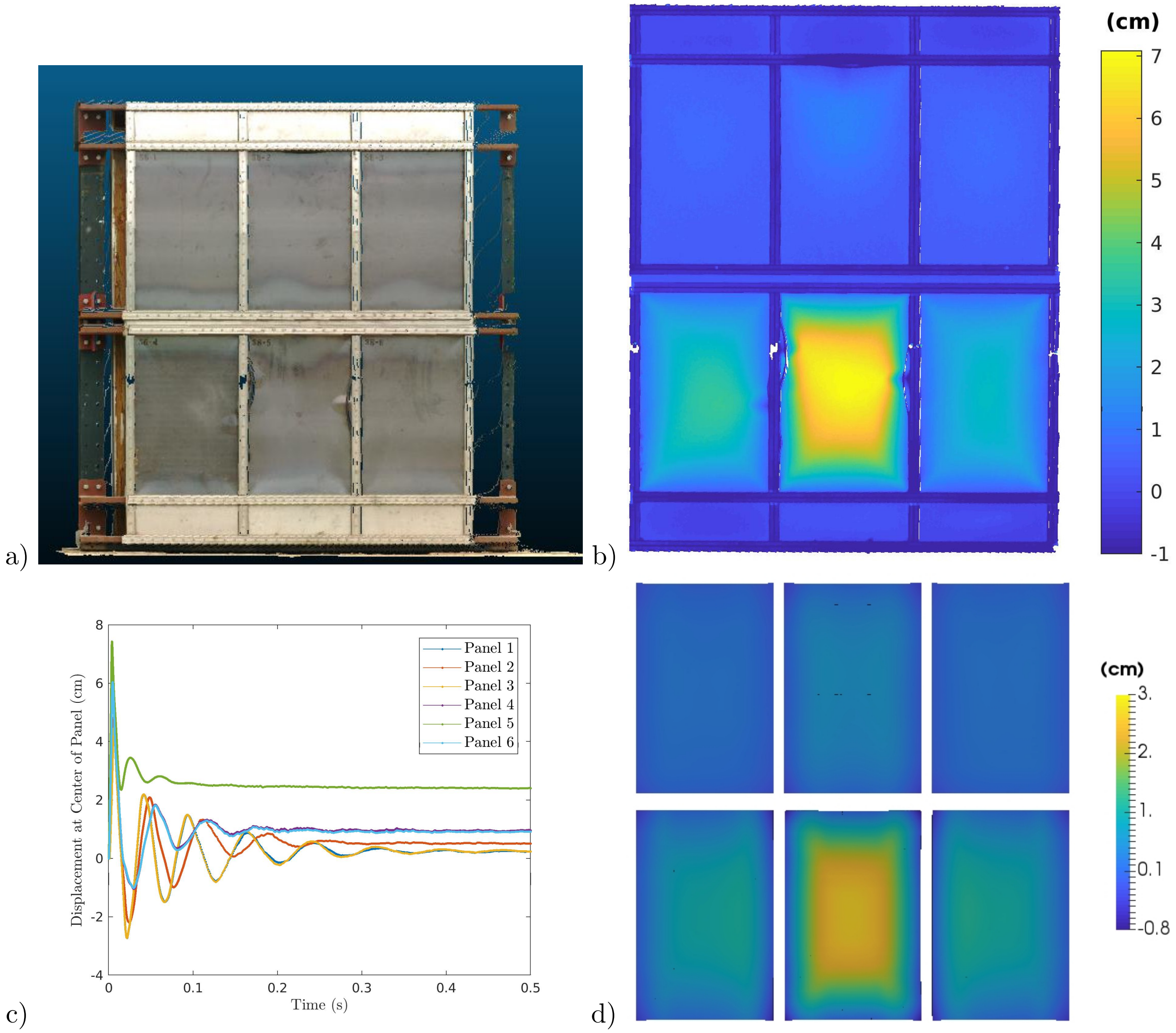

Figure A7. Hypothesis testing of a blast event using the developed Blast Dynamics Simulator: a) point cloud from LiDAR 3D scanning; b) depth map obtained from post-processing of 3D point cloud; c) representative output of the time history for displacements at the center of the six steel panels during a blast simulation; d) representative prediction of permanent set deformations in the steel panels obtained from Blast Dynamics Simulator and rendered in ParaView