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An Extensive X-ray Computed Tomography Evaluation of a Fully Penetrated Encapsulated SiC MMC Ballistic Panel

by William H. Green and Robert H. Carter

ARL-TR-4787 **April 2009**

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
April 2009

2. REPORT TYPE
Final

3. DATES COVERED (From - To)
1 January 2008–30 September 2008

4. TITLE AND SUBTITLE
An Extensive X-ray Computed Tomography Evaluation of a Fully Penetrated Encapsulated SiC MMC Ballistic Panel

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
2182040

6. AUTHOR(S)
William H. Green and Robert H. Carter

5d. PROJECT NUMBER
AH80

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRD-ARL-WM-MD
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-4787

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
X-ray computed tomography (XCT) is an important nondestructive evaluation technique for revealing the spatial distribution of ballistically induced damage in ceramics. The level of detection and resolution of damage depends on the size of the sample and the parameters of the XCT approach (e.g., focal spot size, magnification, etc.). Previous and ongoing work in this area includes assessment of ballistically induced damage in both individual ceramic targets and ceramic armor panels. Ballistic damage in an encapsulated ceramic armor panel with a metal backing has been scanned and extensively evaluated using XCT two- and three-dimensional (3-D) analysis. The purpose of using XCT evaluation in this study was to better characterize and understand all of the detectable damage. This information can be used to correlate damage features and types with the physical processes of damage initiation and growth. XCT scans and analyses of damage in the panel will be shown and discussed. This will include virtual 3-D solid visualizations and some quantitative analysis of damage features.

15. SUBJECT TERMS
computed tomography, nondestructive evaluation/testing (NDE/NDT), ceramics, encapsulated, damage

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			William H. Green
					19b. TELEPHONE NUMBER (*Include area code*)
Unclassified	Unclassified	Unclassified	UU	20	306-410-0817

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1. Introduction

The nondestructive x-ray computed tomography (XCT) technique is a widely applicable and powerful inspection modality for evaluation and analysis of geometrical and physical characteristics of materials. It also presently appears that the non-invasive diagnostic approach with XCT provides the only sufficiently effective modality for high resolution shock and impact damage interrogation, spatial characterization, quantification, visualization and three-dimensional (3-D) analysis. Ceramic materials are currently typically combined with other materials in armor panel structures in order to decrease weight without losing ballistic performance. Encapsulated panels in which the ceramic material is enclosed are an example of this approach. Part of an impact damaged encapsulated ceramic panel was scanned and extensively evaluated using XCT two-dimensional (2-D) (slice) and 3-D analysis. The full capabilities of the XCT diagnostic approach have not yet been reached and the beneficial utilization of this new volumetric impact knowledge has yet to be extensively applied and exploited. Further, this new volumetric damage knowledge has yet to be consistently utilized, if at all, in ballistic damage models for comparison to the models and subsequent analysis.[1,2]

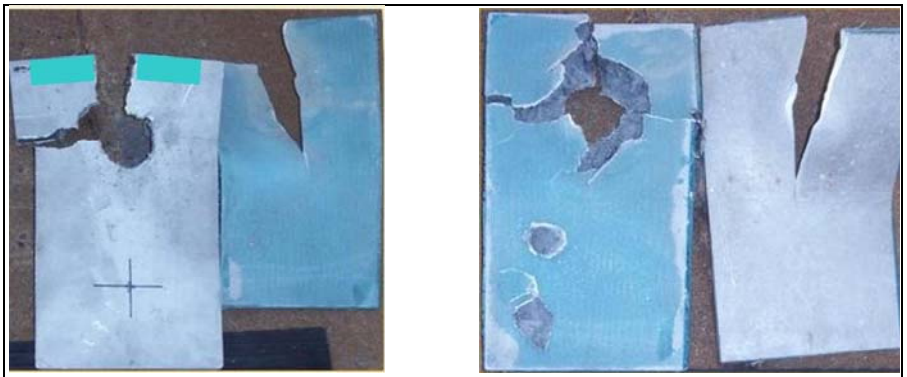
2. XCT

XCT is broadly applicable to any material or test object through which a beam of penetrating radiation may be passed and detected, including metals, plastics, ceramics, metallic/nonmetallic composite material, and assemblies. The principal advantage of XCT is that it provides densitometric (that is, radiological density and geometry) images of thin cross sections through an object in a non-invasive manner. Because of the absence of structural superimposition, images are much easier to interpret than conventional radiological images. The user can quickly learn to read XCT data because images correspond more closely to the way the human mind visualizes 3-D structures than 2-D projection radiology (that is, film radiography, real-time radiography, and digital radiography [DR]). Further, because XCT images are digital, the images may be enhanced, analyzed, compressed, archived, input as data to performance calculations, compared with digital data from other nondestructive evaluation modalities, or transmitted to other locations for remote viewing, or a combination thereof.

[1]Brannon, R.; Wells, J.; Strack, O. *Metallurgical and Materials Transactions A* **2007**, 38A.
[2]Wells, J.; Brannon, R. *Metallurgical and Materials Transactions A* **2007**, 38A, 2944–2949.

3. Specimen Characteristics and Scanning Procedures (DR and XCT)

An ~207-mm (8.1-in) × 361-mm (14.2-in) specimen was sectioned from a larger fully penetrated impacted test panel. The encapsulated specimen included a complete penetration and the surrounding area as well as undamaged material farther away. The backing material was not present on the specimen as received. Figure 1 shows front and back photographs of the specimen with the backing next to it. DRs of the specimen were taken through its thickness using the 420 kV x-ray tube and linear detector array (LDA) setup in centered rotate-only (RO) mode. The x-ray technique (parameters) of the DRs was (405 kV, 2.0 mA) and geometries of source-to-object-distance (SOD) = 750.00 mm and source-to-image-distance (SID) = 940.00 mm.



(a) (b)

Figure 1. (a) Front and (b) back photographs of the specimen with the detached titanium backing next to it (on the right in both images). The upper left section in (a) has fractured away from the rest of the panel and is not included in the x-ray evaluation.

A preliminary series of XCT scans incrementally spaced by 20 mm were taken at the bottom to the top of the specimen. The specimen was held with its faces in a vertical orientation by a portable vice for scanning. Thus, the specimen faces were perpendicular to the horizontal x-ray (collimated) fan beam resulting in through thickness cross-sectional CT images. The vice was suitably stabilized on the scanning turntable. The middle of the penetration cavity was at a height of ~288 mm. The vertical scan positions were based on multiples of 20 mm below, above, and including the 288 position. The undamaged bottom (edge) of the specimen was at a vertical position of about 20 mm and the top position of the remaining upper portion was at about 381 mm. The specimen was scanned using the 420 keV x-ray tube and LDA set up in offset-RO mode. The slice thickness was 0.500 mm and each slice was reconstructed to a 1024 × 1024 image matrix. The field of reconstruction (FOR) diameter was 230.00 mm. The tube energy and current used were 405 keV and 2.0 mA, respectively, and the focal spot was 0.80 mm. The SOD and SID were 750.00 and 940.00 mm, respectively. The first series of scans were done to get a good understanding of the overall changes in damage features throughout the specimen. A second set of scans was done starting below the penetration cavity and ending within the penetration cavity. These scans were vertically overlapping with a slice thickness and increment of 0.500 and 0.450 mm, respectively. This was the majority of the slice (image) data analyzed using 3-D solid and point cloud visualization.

4. Evaluation of Encapsulated Ceramic Specimen

4.1 Digital Radiography Scans

Due to their digital nature, DRs can be processed or "windowed" to accentuate one or some features over others. Figure 2 shows two DR images. In the first the damage itself immediately around and farther away from what is left of the penetration cavity is emphasized, as is the damage in the ceramic tiles below the penetrated tile. It also shows the tile layup very clearly. In the second image the actual perimeter of the penetration cavity itself is emphasized, showing only relatively thin material left intact at the edges making the rest of the image significantly lighter. The diameter of the penetration cavity is ~60 mm.

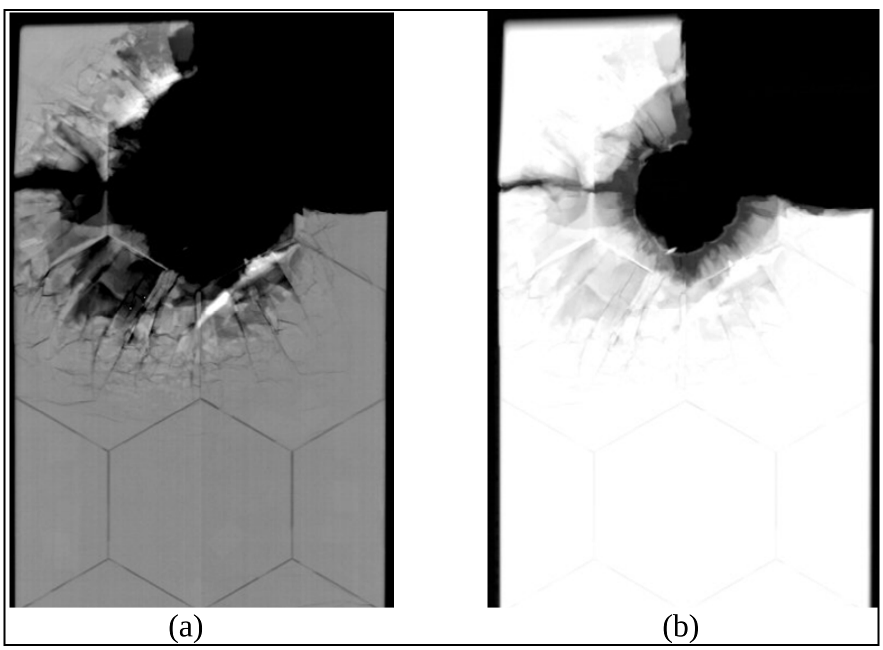


Figure 2. Digital radiographs of the specimen: (a) image emphasizing damage and tile layup and (b) image emphasizing penetration cavity.

4.2 Computed Tomography Scans

Figure 3 shows a series of CT scans (images), starting at a position of 148.10 mm (figure 3a). The scans in figures 3b–j were taken at vertical positions of 167.90 (figure 3b), 188.15, 207.95, 228.20, 248.00, 251.15, 262.85, 288.00, and 308.00 mm, respectively. The darker vertical bands in these images are indications of the area between adjacent tiles. The slightly darker oblong feature with a somewhat crosshatched appearance in the middle of some of the images (lower heights) is an image artifact. It is not an indication of a real physical feature in the specimen. Damage is clearly evident in the top, or back, (exit) side of the specimen at 148.10 mm. There is very slight cracking as far away from the center of the penetration cavity as 160 mm at a scan height of 128.00 mm. The damage is significantly more severe at 167.90 mm, with connected cracking over most of the width of the specimen towards the back side. Cracks are also present in the middle thickness region of the specimen. Multiple cracks are near and adjacent to the bottom, or front, (impact) side of the specimen at 188.15 mm (figure 3c), about 100 mm from the center of the penetration cavity. Braking up of some of the ceramic into rubble as well as bulge in the back face is also present at this height. The amount of rubble is higher with relatively large pieces and the bulging is more severe at 207.95 mm (figure 3d). The ceramic material is clearly cracked through from the front to the back and both the front and back side parts of the encapsulant (case) are also cracked with multiple cracks in the front. The distance between the outer cracks in the front part of the case is about 81 mm.

At 228.20 mm (figure 3e), about 60 mm from the center of the penetration cavity, the rear part of the case is blown open and peeled back and the distance between the two cracks in the front part of the case is about 25 mm. Secondly, at least half of the thickness of the ceramic material no longer has any structural integrity. At 248.00 mm (figure 3f), the rear of the case is peeled back more and there is no ceramic material in the center area between the front and the back of the specimen. The front of the case is also on the verge of being penetrated with a major crack. At 251.15 mm (figure 3g), the case and ceramic material have been completely penetrated, with some residual penetrator material (white) just above and to the right of the hole in the front of the case. The hole in the front of the case and the penetration cavity are larger at 262.85 mm (figure 3h), about 25 mm from the center of the penetration cavity. There is not very much material left at 288.00 mm (figure 3i) being the scan height of the approximate center of impact. Essentially, very little is still intact at this height, including the part of the specimen in the left hand side of the image which was missing. Physically, this was the right-hand side of the specimen as viewed looking at the exit side from the x-ray source perspective (see figure 2). At 288.00 mm and higher, the right-hand side of the specimen is missing having been blown off by the impact and the image at 308.00 mm (figure 3j) is just showing the remaining side.

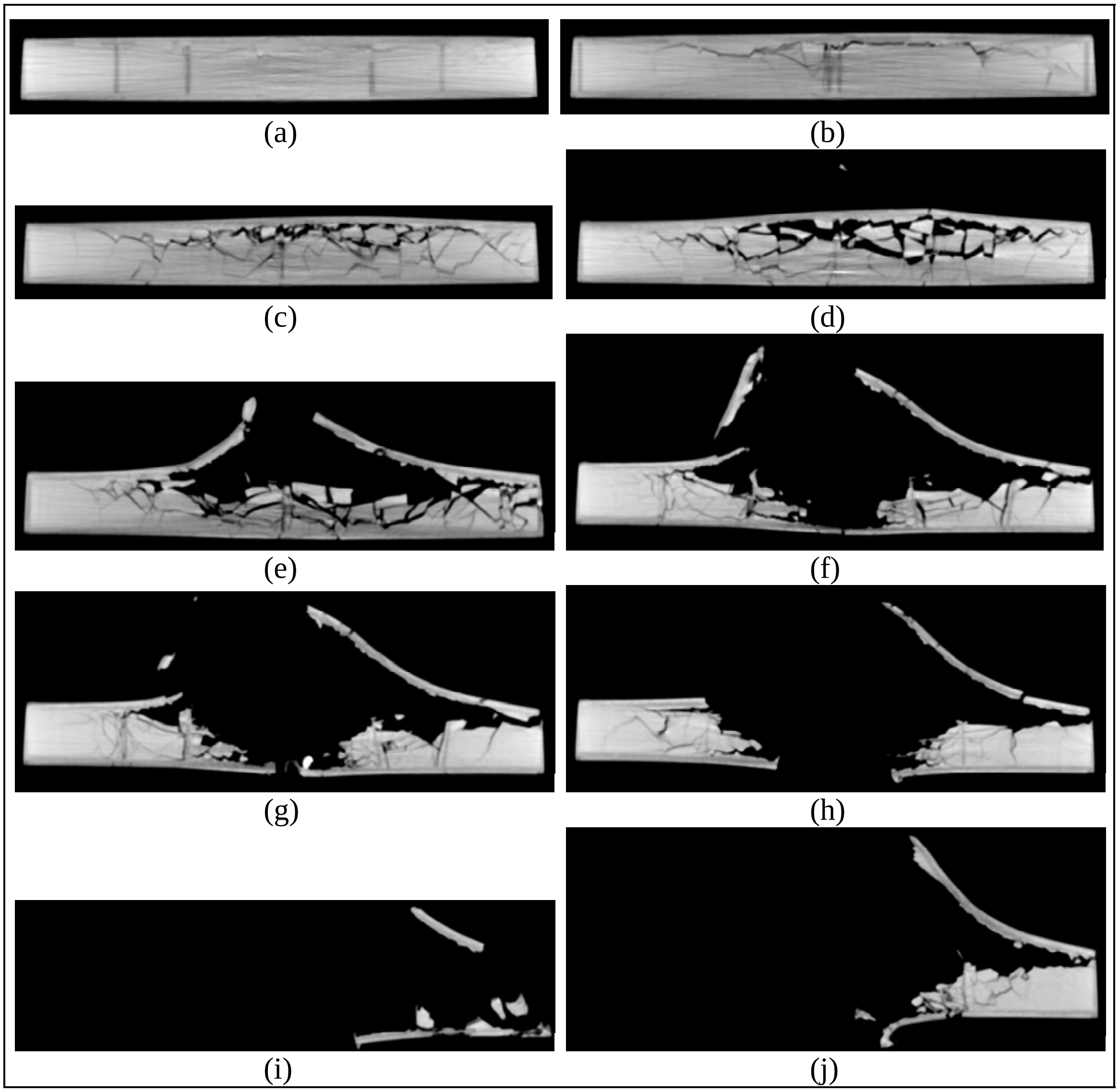


Figure 3. A series of cross-sectional CT scans (images). Scans (a–j) were taken at vertical positions of 148.10, 167.90, 188.15, 207.95, 228.20, 248.00, 251.15, 262.85, 288.00, and 308.00 mm, respectively.

4.3 Three-Dimensional Solid Visualization

The excellent dimensional accuracy and the digital nature of XCT images allow the accurate volume reconstruction of multiple adjacent or overlapping slices. A virtual 3-D solid image is created by electronically stacking the XCT images, which have thickness over their cross sections (i.e., voxels), one on top of the previous from the bottom to the top of the specimen or scanned height to generate its virtual volume. The 3-D solid images of the specimen were created using the second set of overlapping scans from a height of 140.00 mm to a height of 265.55 mm. Figure 4 shows a series of 3-D solid images of the scanned volume with sections virtually removed in (figures 4c–f). The method of virtual sectioning, which is essentially only

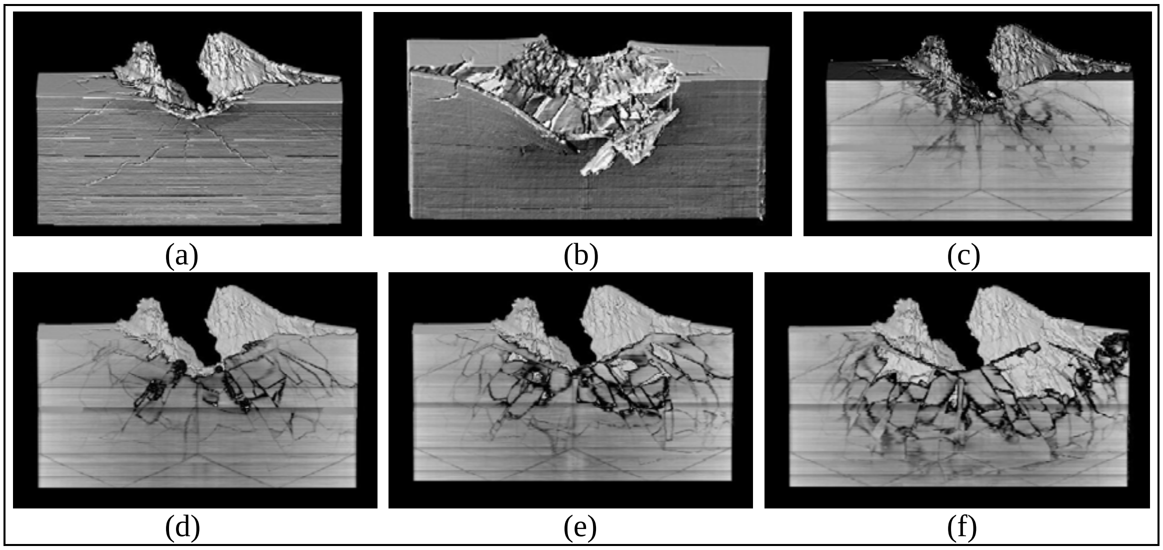


Figure 4. A series of 3-D solid visualization images with material removed from the front face towards the back face: (a) front (impact) side, (b) back (exit) side, and (c–f) front view with 2.2, 6.7, 11.2, and 15.7 mm of material removed, respectively.

showing a portion of each scan, allows viewing of generated surfaces anywhere in the scanned volume in 3-D space. The view in figure 4 is looking at the front of the specimen with it tilted forward, except for figure 4b which is looking at the back of the specimen with that side tilted forward. Figures 4a and b show the entire scanned volume with surfaces and no sections virtually removed. Figure 4b shows the break up and rubble of the ceramic material at the edges of the penetration cavity. It also shows how the overall size of the broken-up ceramic material becomes significantly larger from the front towards the back (exit) side of the specimen. The virtual sectioned surfaces in figures 4c–f are ~2.2, 6.7, 11.2, and 15.7 mm from the front face of the specimen, respectively. The increasing amount of damage around the penetration cavity with increasing distance from the front face is readily apparent. Damage is visible relatively far from the penetration cavity at a height of about 140 mm at the through thickness distance of 15.7 mm (figure 4f). These 3-D solid images and the CT scans they were created from are indicative of the failure of the ceramic material and encapsulation at the back side of the specimen relatively far from the penetration cavity before the specimen was completely penetrated.

The view in figure 5 is looking at the side of the specimen rotated to the right such that the front of it is on the left. The bottom part of the penetration cavity is at the top of the images in the front face. The virtual sectioned surfaces in figures 5a–h are ~9.9, 19.7, 29.6, 39.5, 59.7, 69.6, 90.7, and 125.3 mm from the side of the specimen, respectively. It can be clearly seen how ceramic material cracked and broke away with the case in the back right area (threat view) around the penetration cavity. The surface at 90.7 mm is about at the center of the penetration cavity and the surface at 125.3 mm is at the other side of the penetration cavity. Secondly, damage is visible relatively far from the penetration cavity towards the back of the specimen (right side) at a height of about 140 mm in figures 5e–h.

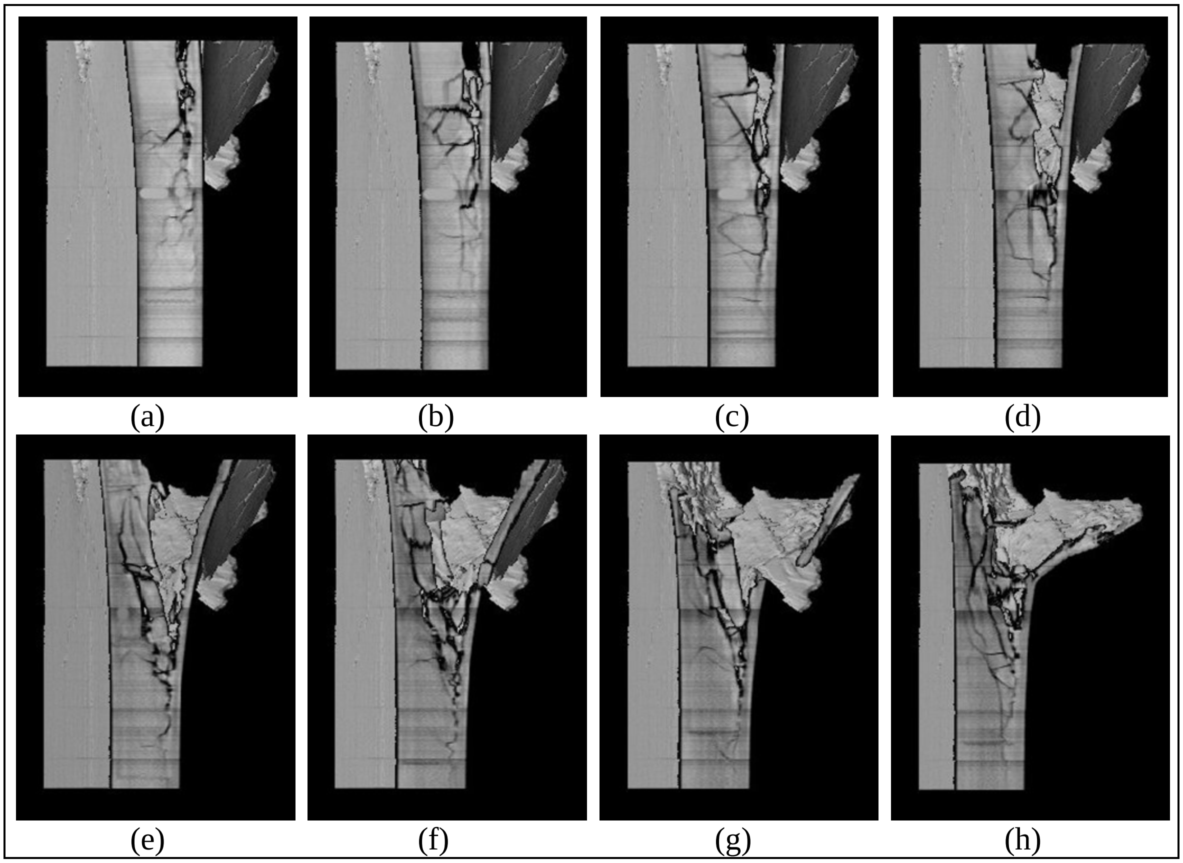


Figure 5. A series of 3-D solid visualization images with material removed perpendicular to the faces from right side as viewed from the front: (a–h) view looking at front and side with 9.9, 19.7, 29.6, 39.5, 59.7, 69.6, 90.7, and 125.3 mm of material removed, respectively.

4.4 Three-Dimensional Point Cloud and Surface Visualization

A 3-D point cloud is a set of points in space that define geometrical characteristics (i.e., shape, size, location) of a specimen or scanned volume and features within it. Location of the points is determined by appropriate (image) segmentation of the feature or features of interest. Figure 6 is a point cloud of the hole in the front of the panel as defined by the DR (figure 2b) with a circle fit to it. The diameter of the entrance hole is 58.40 mm with the center at a height of 282.00 mm. Figure 7 is a point cloud of the overall damage and back face of the specimen in the second overlapping set of scans. The view is looking at the front of the specimen with it tilted forward 50° from a perpendicular line of sight. The back face is the flat looking areas of points to the left and right of the middle "bulge," which is at the front of the specimen, and peeled back case. The points in the bulge include the bowing of the front of the specimen, damage outside of the penetration cavity, and the penetration cavity itself. The presence of damage relatively far from the penetration cavity at the top of the image is shown by the isolated points at the bottom of the image. Figure 8 is a point cloud of the bulge and the damaged case behind it, in which the back face and isolated points have been removed (from figure 7), and is also tilted at 50°.

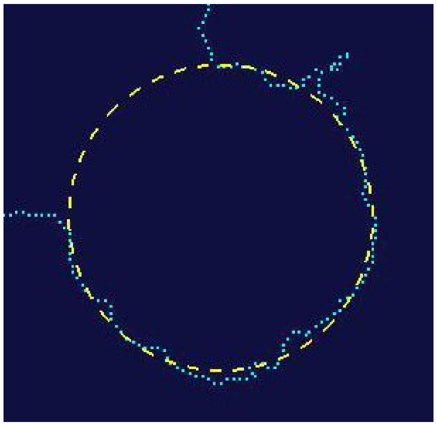


Figure 6. Point cloud of entrance hole.

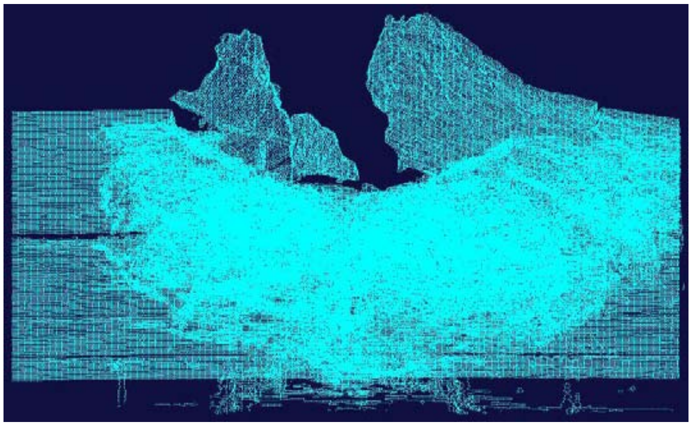


Figure 7. A 3-D point cloud of overall damage and back face.

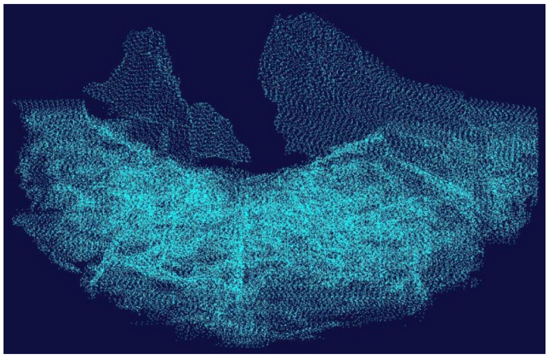


Figure 8. A 3-D point cloud of damage.

Figure 9 is a point cloud created using only the scans that went through the penetration cavity itself. The top image is looking at the top of the specimen in the negative z (–z) direction. The bottom image is only the walls of the cavity in which they are tilted into the page relative to the top-down view in the top image. Free form 3-D surfaces (Non-Uniform Rational Bezier/Basis Spline [NURBS] method[3,4]) were fit to the cavity wall point clouds. These are shown by the wavy surfaces passing through the points on either side of the section of penetration cavity in figures 10 and 11, which are isometric views from rear side and impact side perspectives, respectively, including all of the points to show the specimen edges. Although these surfaces follow the section of penetration cavity quite well, it is useful to take a simpler and more directly informative approach of fitting planes to these point clouds. The fit planes (NURBS) are shown in figures 12 and 13, which are also isometric views from rear side and impact side perspectives including all of the points. The tilt of the two planes defining the section of penetration cavity can be seen more easily than the general behavior of the free form surfaces. The internal angle between the two planes in the physical x-y plane (CT scan plane) is about 125°.

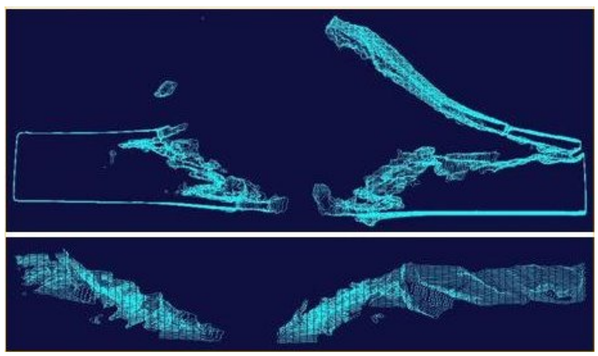


Figure 9. A 3-D point cloud of part of the penetration cavity.

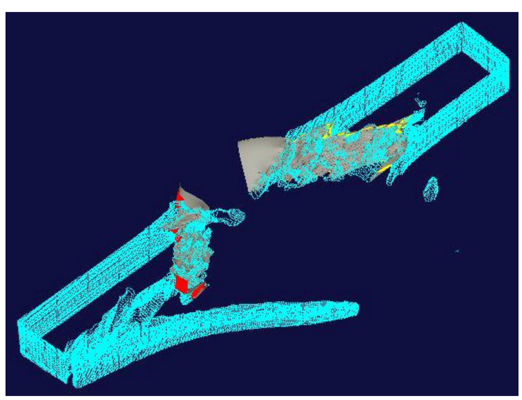


Figure 10. Point cloud of cavity section with fit free form surfaces (NURBS): rear perspective.

[3]Wikipedia, Nonuniform Rational B-Spline. http://en.wikipedia.org/wiki/NURBS (accessed January 2009).

[4]SDRC/Imageware. *Basic Reverse Engineering With Surfacer: Training Guide*; Ann Arbor, MI, March 1999; pp 244–245, 326–327.

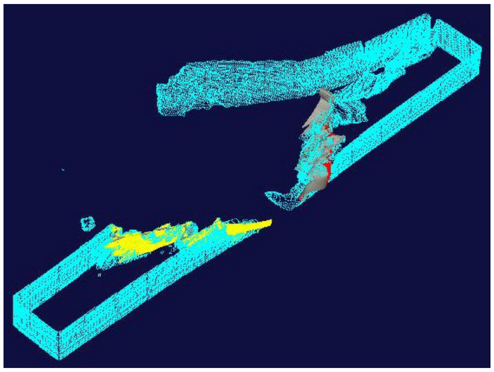


Figure 11. Point cloud of cavity section with fit free form surfaces (NURBS): impact perspective.

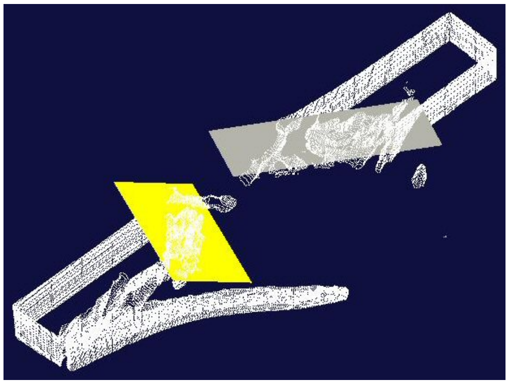


Figure 12. Point cloud of cavity section with fit planar surfaces (NURBS): rear perspective.

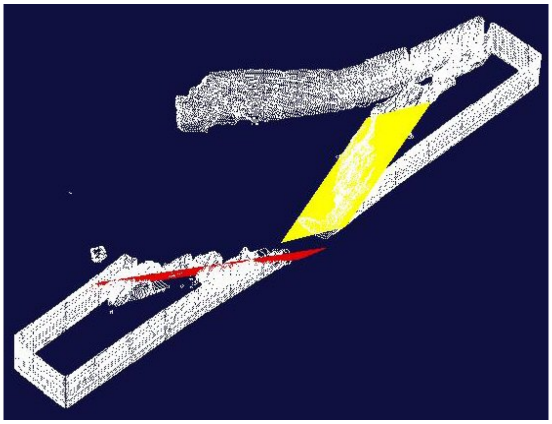


Figure 13. Point cloud of cavity section with fit planar surfaces (NURBS): impact perspective.

The equations (mm) of the left and right planar surfaces in figure 13 (impact side perspective) are

$$0.437x + 0.674y + 0.595z - 136 = 0 \text{ (left)} \quad (1)$$

and

$$-0.47x + 0.608y + 0.639z - 147 = 0 \text{ (right)}, \quad (2)$$

which can be written as

$$x_L = -1.54y - 1.36z + 311 \quad (3)$$

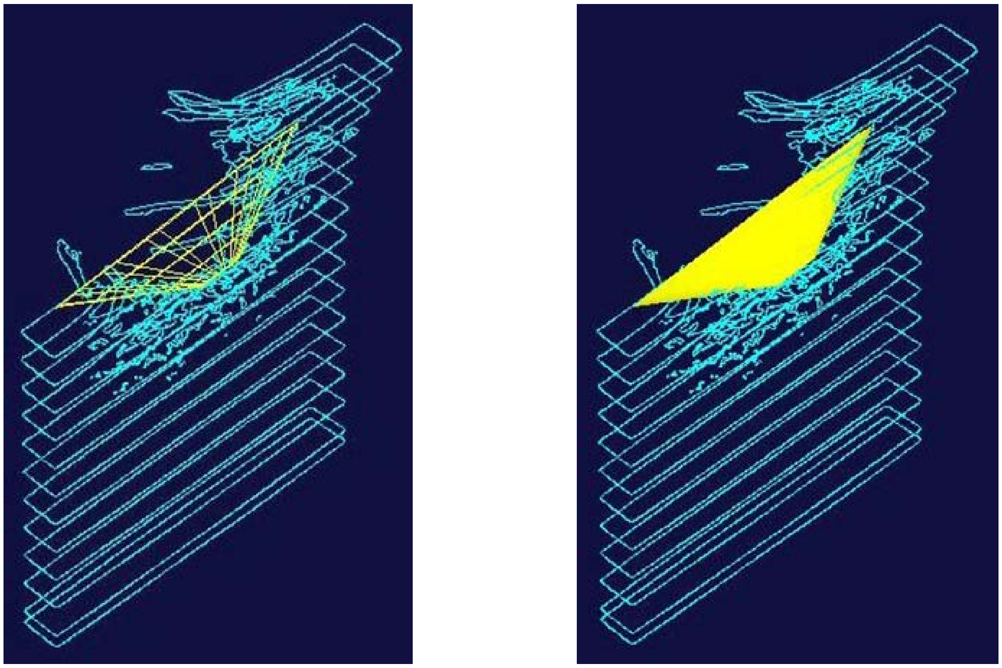
and

$$x_R = 1.29y + 1.36z - 313\,. \quad (4)$$

Table 1 gives the data set of $\{z, y_n, x_{nL}, x_{nR}\}$ for five values of z (vertical position) within the penetration cavity starting near the bottom of the cavity, where three values of y (n = 3) were chosen spanning the through thickness depth (+y direction) of the cavity. The $\{x_{nL}, y_n, z\}$ and $\{x_{nR}, y_n, z\}$ points give the approximate location of the walls of the section of the cavity and provide the fitting data to generate a representative penetration cone surface. Figure 14 shows isometric views from an impact side perspective of the fit penetration cone relative to segmented point cloud representations of selected CT scans, which show the boundaries of the damaged specimen. The penetration cone has an internal angle of 121.9° and an upward tilt out of the x-y plane of 34°. The surface of the cone is mesh shaded in figure 14a in order to maximize the visibility of the points in the vicinity of the penetration cavity. The cone is shaded with an opaque surface in figure 14b in order to emphasize the location, angle, and tilt of the cavity within the damaged structure of the specimen.

Table 1. Data points $\{z, y_n, x_{nL}, x_{nR}\}$on fit planar surfaces.

z Position (mm)	**y_1 Position (mm)**	**y_2 Position (mm)**	**y_3 Position (mm)**	**x_{1L} Position (mm)**	**x_{1R} Position (mm)**	**x_{2L} Position (mm)**	**x_{2R} Position (mm)**	**x_{3L} Position (mm)**	**x_{3R} Position (mm)**
251.60	–15.70	0.00	15.70	–7.14	8.99	–31.35	29.30	–55.57	49.61
255.10	–15.70	0.00	15.70	–11.91	13.75	–36.12	34.06	–60.33	54.37
258.60	–15.70	0.00	15.70	–16.67	18.51	–40.89	38.82	–65.10	59.13
262.10	–15.70	0.00	15.70	–21.44	23.27	–45.65	43.58	–69.87	63.89
265.55	–15.70	0.00	15.70	–26.13	27.96	–50.35	48.27	–74.56	68.58



(a) (b)

Figure 14. Isometric impact side views of fit cone characterizing entire penetration cavity and selective bottom-to-top CT scans of specimen that have been (gray scale) segmented and converted to point cloud representations to show the outer boundaries of the specimen. The penetration cone has an internal angle of 121.9° and an upwards tilt out of the x-y plane (CT scan plane) of 34°.

5. Conclusions

A wide range of ballistic damage in a sectioned encapsulated ceramic panel including complete penetration was scanned and extensively characterized using XCT 2-D cross-sectional (planar) and 3-D volumetric analysis. Several damage features including low severity ceramic cracking relatively far from the penetration cavity, ceramic cracking, fragmentation, and rubble, encapsulation cracking and exit (rear) side peel back, impact (front) face bulging, and penetration cavity size and geometry were captured and discussed. Successive application of XCT 2-D evaluation, volumetric solid visualization and analysis, and volumetric point cloud visualization and derived feature surface analysis provided extensive and important qualitative and quantitative data about damage features. Characteristics of captured damage features provided better understanding of the physical processes of damage initiation and growth.

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