High-resolution X-ray CT Inspection of Honeycomb Composites Using Planar Computed Tomography Technology

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Abstract. In this paper we demonstrate the method and results of using a modified cone-beam reconstruction algorithm (called planar CT reconstruction) to study the variation of the impact damage of a honeycomb composite structure along its depth. We show that with the planar CT technique, the object can be reconstructed with a smaller reconstruction volume size but a higher resolution than that with the conventional CT reconstruction method. We also show that we can directly obtain the impact damage patterns along the different depths of the structure without using expensive visualization software.

1. Introduction

Impact damage is a common cause of the flaws such as disbond, delamination, crushed honeycomb, and internal cracks associated with honeycomb composite structures. These defects are detected by many techniques such as Radiography, X-ray Computed Tomography, Shearography, Thermography, Electronic Speckle Pattern Interferometry (ESPI), and Ultrasonics [1-2]. Each technology has its own advantages and limitation and it is generally not easy to comment that one technology is superior to others without considering the particular study environment and requirement. For example, X-ray computed tomography may not be as convenient and efficient as ultrasonic and thermography in applications of in-service defects inspection, but it would be a good choice in studying the internal structure damage of a complicated structure such as honeycomb composite in a lab environment. The clear and unique 3D details of the inspection results obtained with modern micro-CT system cannot be compared by other technologies in many cases.

In this study, we present using X-ray computed tomography to study the impact damage of a honeycomb composite sample. The objective is to evaluate the damage pattern at different depth inside the sample. Fig. 1 shows the X-ray images of the object's top view and side view, from which we can find that the sample has a planar but curved shape, and the impact damage location is at the central area of the sample. We scan this sample following the standard procedure with a modern micro-CT system. However, instead of performing the conventional CT reconstruction to the scanned data and then visualizing the results with the existing powerful but expensive visualization software, we demonstrate that, by using our novel planar CT reconstruction algorithm (modified based on the popular cone-beam filtered back-projection reconstruction algorithm [3]), we can conveniently

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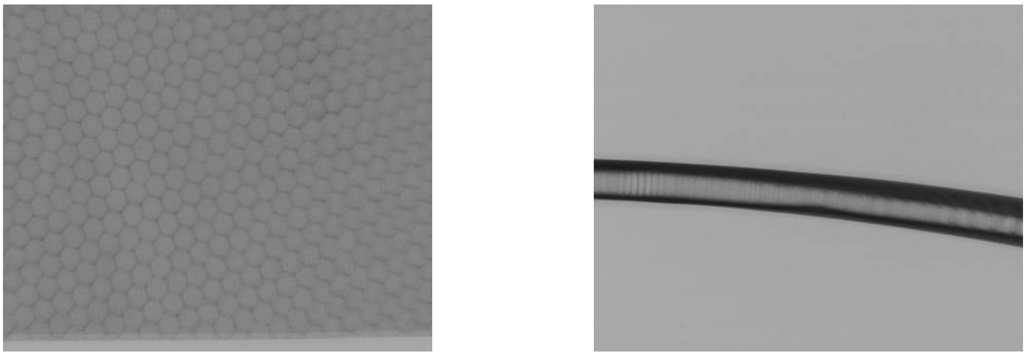
obtain the variation of the impact damage along the depth of the honeycomb composite structure without using the powerful but expensive visualization software, although the structure has a curved shape.



(a) Top image (b) Side image

Fig.1 Top view (a) and side view (B) of the object.

2. Methodology

Due to the curved-shape of the sample, when mounting the sample to the rotary system of the CT system, it usually has a relation to the rotation axis (Z) and the detector (represented as XZ plane) as shown in Fig. 2. In this illustration, the shaded area is the region-of-interest, i.e. the impact damage location in the sample. α is the angle between the primary dimension of the object cross-section and one dimension of the detector (usually used as the default reconstruction reference angle and set as zero), and β is the axial tilting angle between ROI and the axis-of-rotation (here we have ignored the small local variation of the slope in the ROI). To make these definitions clearer, we show them separately in Fig.3.

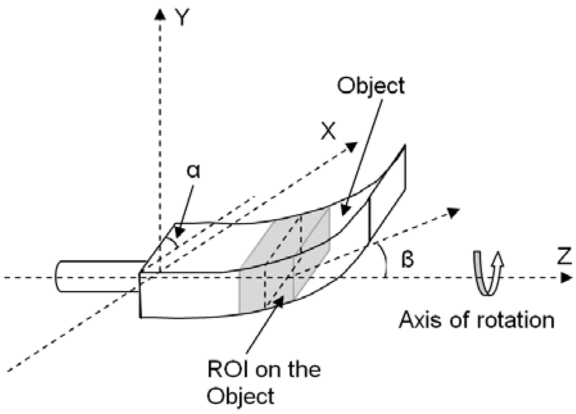


Fig.2 Illustration of the scan start orientation of the object (shaded area is where the internal impact damage occurs)

Because α and β are generally not zero, with traditional CT reconstruction method, the ROI of the reconstructed object will be obliquely oriented with respect to the reconstruction volume, as illustrated in Fig. 4(a). To obtain the impact damage pattern along the thickness dimension in this region, one has to use visualization software such as I-View or Volume Graphics. Both of them are powerful but expensive. However, even with these visualization software, in order to obtain the impact damage variation along the depth of the sample, one still needs a tedious and time-consuming process to carefully define a clipping plane which is parallel to the local plane of the ROI.

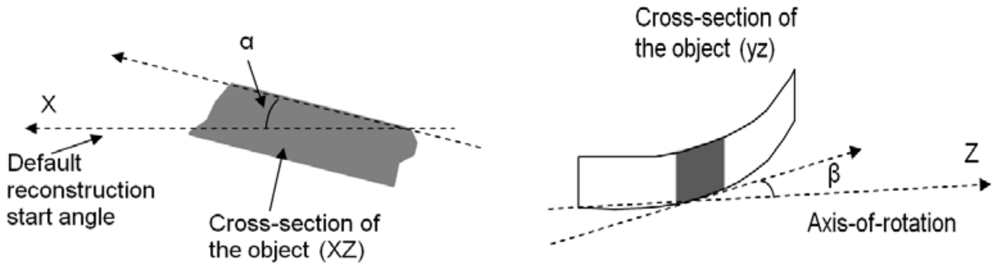


Fig. 3 Definition of angles α and β

If we can reconstruct the object with an orientation illustrated in Fig. 4(b), that is, the local ROI is well-oriented with respect to the reconstruction volume, we can directly see the impact damage pattern varying along the depth of the ROI by simply displaying the results slice-by-slice along the thickness (vertical) dimension of the reconstruction volume. Here well-orientation means that the primary plane of the reconstructed object is parallel to one plane of the reconstruction volume. This idea is now becoming realistic with the novel planar CT developed in SIMTech. The confidence of using planar CT for a possibly better solution to this application comes from two observations: Firstly the object is basically a planar object and secondly the local slope variation is relatively small and should not have meaningful inference to the inspection results and analysis if treated as a flat region.

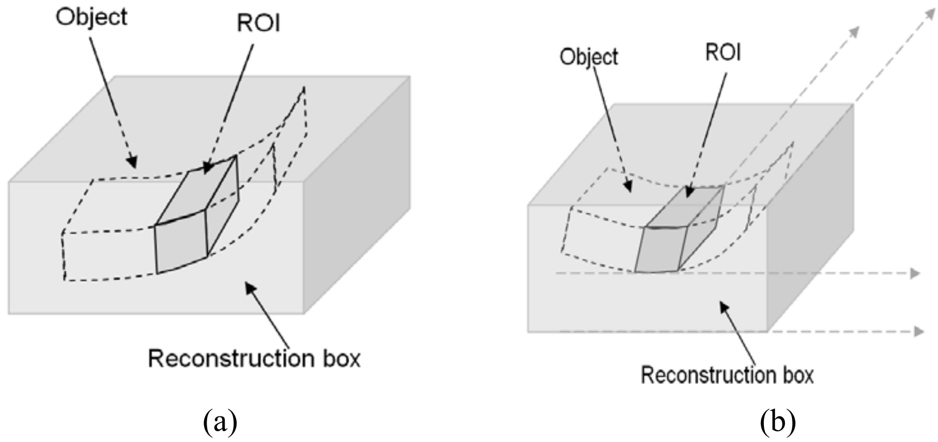


Fig.4 The general situation of the reconstruction result (a) and that with α=0 and β =0 for ROI, when a conventional reconstruction method is applied

The detail of the novel planar CT reconstruction technology can be found in reference [4, 5]. Here we just highlight the three key steps involved in this technology.

2.1 Automatic determination of the centre-of-rotation of the scan.

Centre-of-rotation (also called central ray) must be determined before starting the reconstruction process. Its accuracy has significant impact on the reconstruction quality. The common practice several years ago was to scan a wire phantom at the same position of the object to-be scanned. This is obviously tedious and a waste of resources, including both manpower and machine. To solve this problem, the authors developed two patented technologies which allow the determination of the centre-of-rotation directly with the central-beam sinogram of the scanning data of the object. The earlier published one [6] makes use of the geometrical relationship of the system and the two longest edge points of the object or an obviously high-contrast feature to calculate the centre-of-rotation. This method generally works well, but suffers from low boundary contrast or high-magnification scan (it means the detector doesn't always cover the whole object during the scanning). The later published solution [7] overcomes these weaknesses of the previous method. Its basic idea is based on the fact that on the object's central cross-section which is defined as the beam perpendicular to the detector plane, any line on this cross-section has and only has two times to be aligned with the source during the whole scan. Giving any pixel (which represents one ray from the source or one line on the object's central cross-section) on the central cross-section sinogram, its second aligned pixel and the associated rotation angle can be calculated with an assumed centre-of-rotation value. Suppose the detector is a continuous sensor, then only for a true centre-of-ration value, the graylevels of the two pixels will be the same. Of course this statement is compromised with a discrete detector column. However, by computing a number of pixels, for example, 1/3 or half of all the pixels on the central-beam sinogram from 0 degree to 180 degree for a 360-degree scan, this problem can be eliminated. This new method has been proven to be robust and accurate through our daily CT scans, and takes less than 1 second with a C++ software on a general duo-core PC.

Fig.5 is the central-beam sinogram of the honeycomb composite structure with a determined centre-of-rotation indicated on it.

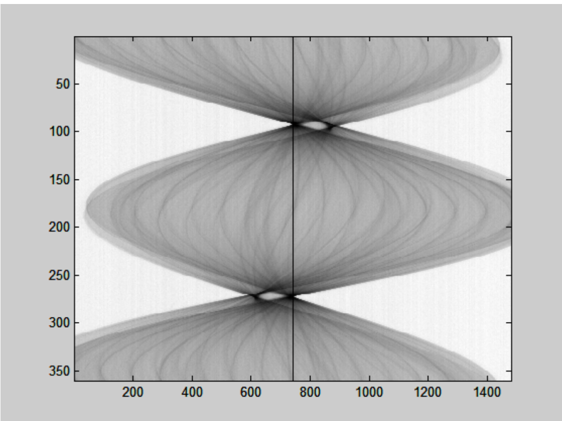


Fig.5 Automatic centre-of-rotation determination

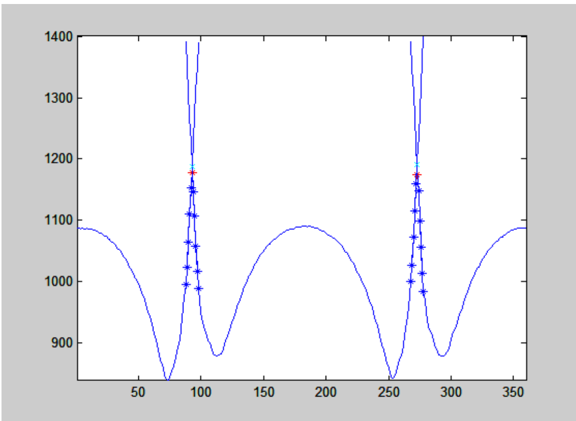


Fig.6 Automatic determination of the narrowest-projection angle

2.2 Automatic determination of the four parameters for planar CT reconstruction.

The second important step is to determine the four key parameters that are required for planar CT reconstruction, i.e. the scan-start-angle, the axial tilt angle, the projection thickness of the object and the centre-position of the thickness.

The scan-start-angle is determined by first converting the central-beam sinogram from fan-beam to parallel beam, and then by curve fitting the edge points of the sinogram on both sides of the estimated narrowest position in the sinogram, the intersection of the two fitted lines is actually the projection angle that gives us the narrowest projection shadow (Fig. 6), from which we can easily calculate the scan-start-angle, i.e. the α in Fig.2.

Then we perform a simple edge-detection on the projection image that has the narrowest shadow and use the edge data to determine the axial tilt angle (i.e. the β in Fig.2). We can also determine the projection thickness, t, of the object and its centre-position, as illustrated in Fig. 7. The accuracy of these two parameters is not important because they have nothing to do with the reconstruction quality. It will only slightly affect the size of the planar CT reconstruction matrix.

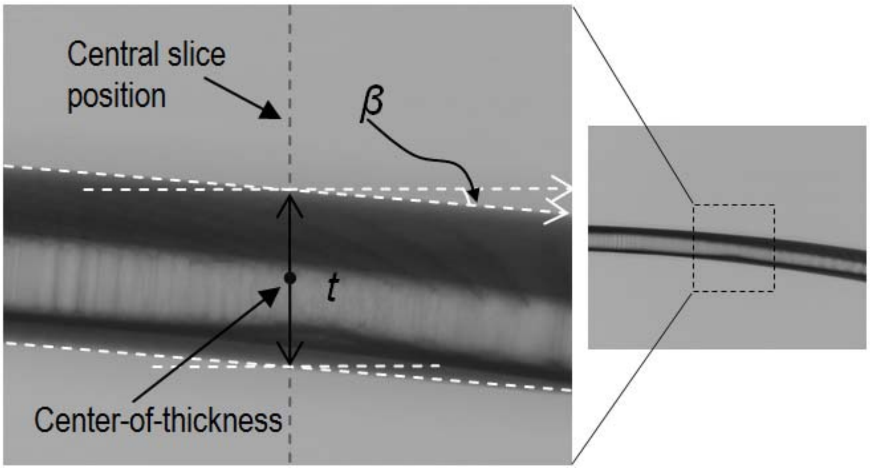


Fig.7 Automatic determination of the axial tilting angle, the sample thickness under the set magnification, and centre position of the object thickness

2.3 Definition of the planar CT reconstruction matrix.

With the all parameters determined, we can now define the planar CT reconstruction matrix. However unlike with traditional CT reconstruction, we define the reconstruction matrix along the object's orientation instead of the rotation axis. Fig.8 illustrates the major difference between a convention reconstruction matrix definition ($A(i, j)$) and the planar CT reconstruction matrix definition (B(m, n)) in a situation that the axial tilt angle is zero, from which one can easily see why planar CT can reconstruct a planar object with a smaller matrix but even a higher resolution in the thickness dimension.

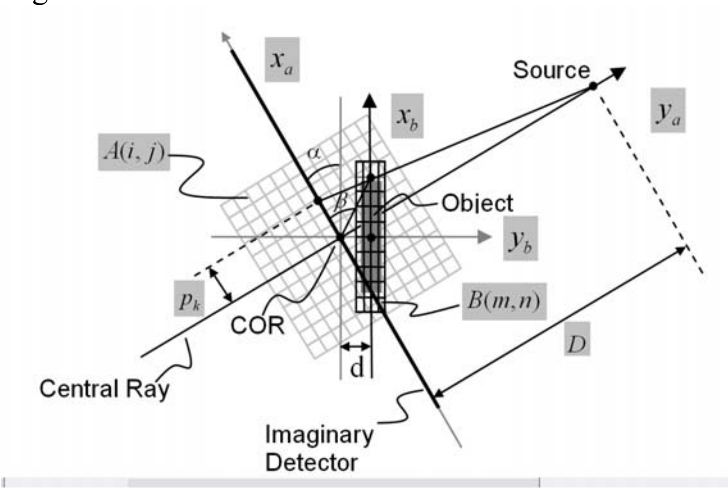


Fig.8 Illustration of the difference between a convention reconstruction matrix definition and the planar CT reconstruction matrix definition

3. Results and Discussion

Our X-ray CT machine is Comet/Feinfocus Fox 160.25. It has an open tube with a spot size as small as 700nm, and a 200mm x 197mm direct digital detector (Varian Paxscan 2520). The detector has 1408 rows and 1888 columns and each pixel has a size of 127µm. The rotation axis is aligned with the column direction. The scan is conducted with a tube voltage of 110KV and a tube current of 12µA (according to the system specifications, the corresponding spot size is estimated to be 1 or 2 microns with this setting). The source-to-image distance (SID) and the source-to-object distance (SOD) are respectively 693mm and 286mm. A 360° scan was conducted with an angular step size of 1°.

The central-beam sinogram is used to determine the centre-of-rotation and the scan-start-angle of the scan. Then the image with the narrowest projection is used to determine the rest three parameters, i.e. the axial tilt angle, the object's projection thickness and the centre position of the thickness. As discussed before, in general case if the object is flat, either the whole image or part of it can be used for axial tilt angle determination. However, in this study, due to the curved nature of the object, we use the ROI for this purpose, as shown in Fig. 7. All the determined parameters are summarized in Table 1.

Centre-of-rotation	Scan-start-angle	Axial tilt angle	Object thickness	Centre-of-thickness
742.1 pixel	**-1.96** degree	**5.42** degree	**193** pixel	**823.5** pixel

Table 1 the determined parameters for planar CT reconstruction

The object is reconstructed using our planar CT algorithm written in Matlab software. This method can be treated as a modified version of the popular filtered back-projection cone-beam reconstruction algorithm. The reconstruction volume is (154 × 512) × 600, with the resolution in the thickness dimension being two times that in the lateral directions.

Fig.9 shows in one figure the three typical orthogonal views and the one 3D view as well, obtained with Volume Graphics VG Studio 2.0. One can see that with the planar CT reconstruction, the reconstruction volume is much smaller than that with the traditional reconstruction method. This benefit will significantly increase as the planar object becomes thinner.

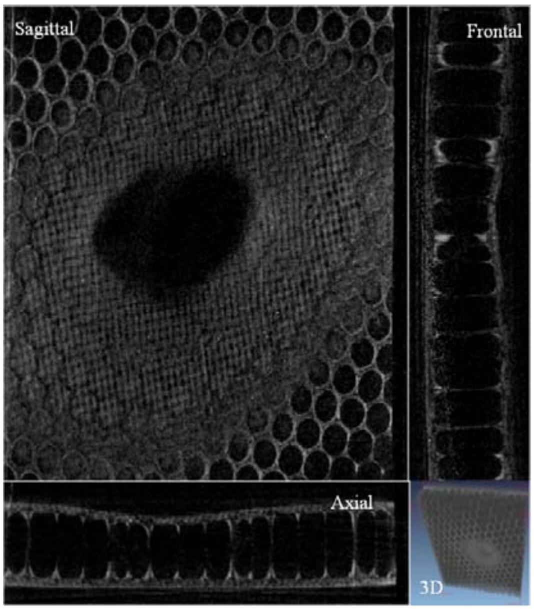


Fig. 9 3D and the three orthogonal views

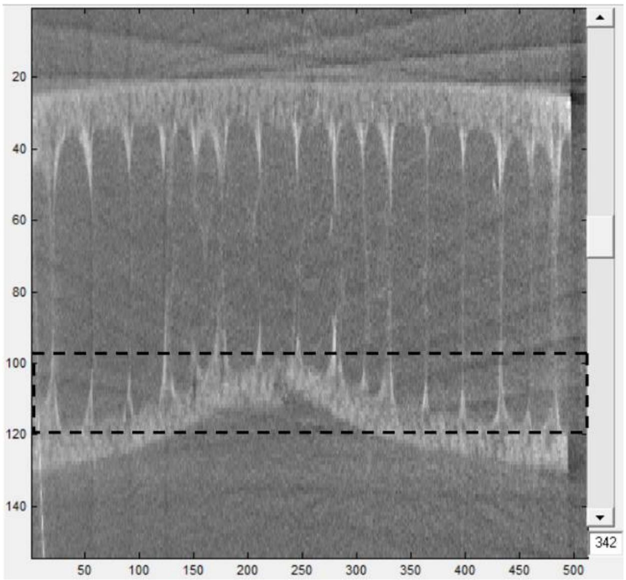


Fig.10 An axial view with an the damaged region indicated

The direct reconstruction results are conventionally called axial slices, from which one can also easily generate other two sets of orthogonal views called sagittal views and frontal views. However, generally these views have limited meanings if a complicated planar object such as a stacked IC is inspected and this object is reconstructed with an oblique orientation with respect to the reconstruction volume. Actually that is one of the many situations that visualization software can play an important role. Now with the results obtained with the planar CT reconstruction, even without using visualization software, we can obtain the information of the impact damage varying along the depth of the sample. This is because the reconstructed ROI of the object is now well oriented in the reconstruction volume, each frontal view represent a pattern approximately perpendicular to the primary plane of the ROI.

Fig. 10 shows one axial slice, in which the impact damage area is indicated in dotted box. By analysing the frontal views slice by slice, one can observe the variation of the impact damage along the depth of the object. Limited by size of the paper, Fig. 11 just shows 12 images with a 2-pixel step.

4. Conclusion

We present in this paper the method and results of using a modified cone-beam reconstruction algorithm for CT inspection of the impact damage of a honeycomb composite structure which has a curved shape. We demonstrate that by reconstructing the local region-of-interest to be well-orientated with respect to the reconstruction volume, one can easily obtain the variation of the impact damage pattern along the depth of the object without using the expensive visualization software. We believe that this method can also be applied to some other similar applications such as studying a planar multilayer object which is in a curved structure.

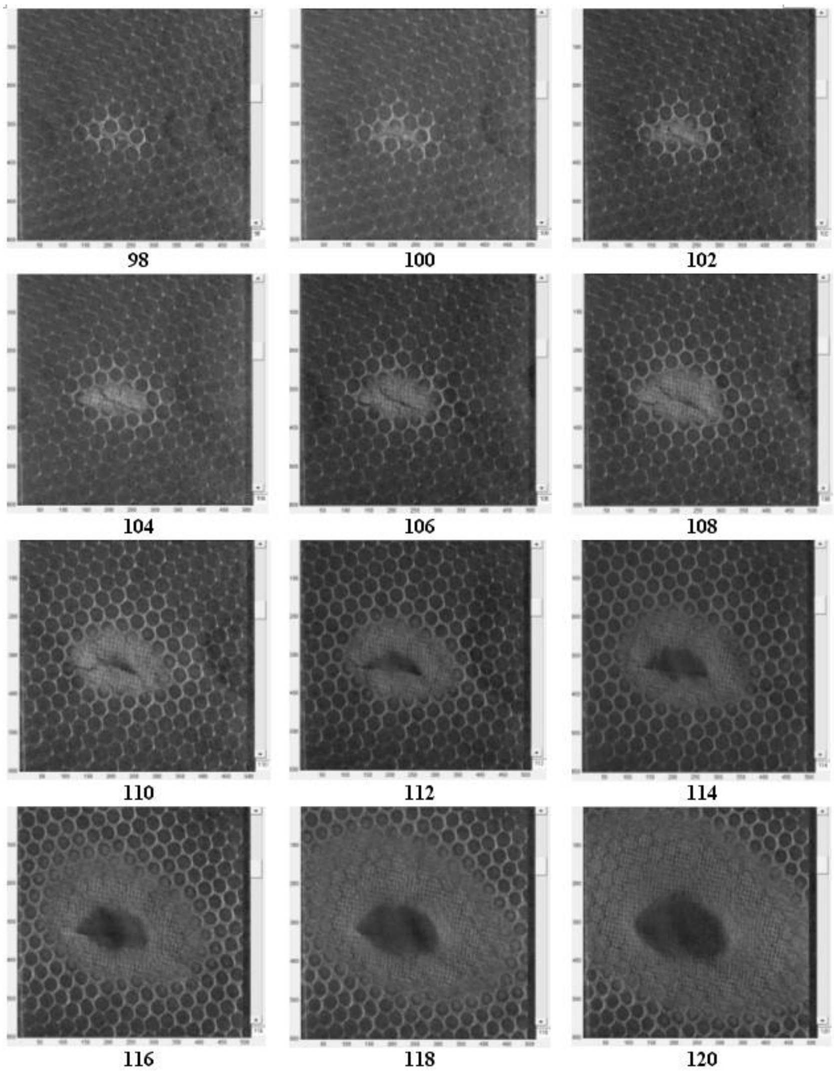


Fig.11 Slices show the impact damage changing over the depth

Reference

[1]. Kisoo Kang, Manyong Choi, Koungsuk Kim, Yonghun Cha, Youngjune Kang, Dongpyo Hong, and Seongmo Yang, "Inspection of impact damage in honeycomb composite plate by ESPI, Ultrasonic testing, and Thermography ", *12th A-PCNDT– Asia-Pacific Conference on NDT*, Auckland, New Zealand , 2006

[2]. M.A. Abou-Khousa1, A. Ryley1, S. Kharkovsky1, R. Zoughi1, D. Daniels2, N. Kreitinger2 and G. Steffes, "Comparison of x-ray, millimeter wave, shearography and through-transmission ultrasonic methods for inspection of honeycomb composites", *American Institute of Physics*, 2007

[3]. Jiang Hsieh. Computed tomography. Bellingham, Washington: SPIEPRESS, 2003.

[4]. Tong Liu and Jian Xu, "Differential reconstruction for planar object in computed tomography", *Journal of X-ray Science and Technolog*y, **17**, 101-113, 2009

[5]. Tong Liu, Lay May Sim and Jian Xu, "Targeted reconstruction with differential planar computed tomography", *NDT&E International*, **43**, 116–122, (2010)

[6]. Tong Liu and Andrew A. Malcolm, "Comparison between four methods for central ray determination with wire phantoms in micro-computed-tomography systems", *Optical Engineering*, **45**(6), 066402, 2006

[7]. Tong Liu, "Direct central ray determination in computed microtomography", *Optical Engineering* **48**(4), 046501, 2009