THREE DIMENSIONAL INDUSTRIAL METROLOGY USING X-RAY COMPUTED TOMOGRAPHY ON COMPOSITE MATERIALS

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Abstract

Composite materials are forecast to double their demand by 2015. For instance, in the aerospace sector, roughly 50% in weight of parts for commercial aircraft like Airbus A350 XWB or Boeing 787 Dreamliner are manufactured in polymer reinforced composites. Furthermore, due to design and structural purposes, even larger and more complex geometries are required.

Conventional metrologic methods like coordinate measuring machines are capable of producing highly accurate dimensioning of composite parts. On the other hand, inner surfaces are difficult to access and alternative dimensioning methods are required. X-ray Computed Tomography (XCT) is being used over the last decade as a suitable solution for industrial metrology. Using this method, inner and outer fully 3D mapping of geometry can be performed, and in some cases, even reducing cost and testing time. However, to improve accuracy and fidelity, systems must be calibrated prior to inspection according to the specimen requirements.

This work reports on a dimensional analysis of a CFRP sandwich part, together with the application of calibration method for an XCT system. A reference standard has been dimensioned using a XYZ coordinate measurements and then analysed by XCT. Records from test inspections after calibration are reported as well.

1. Introduction

CT systems for metrology analysis of composite materials offers extremely precise and complete 3D mapping of inner and outer surfaces of component. Cavities, undercuts, hidden radii and bonded joints are typical hardly achievable component features for traditional metrology based on coordinate measuring systems. In addition, a CT scan of a specimen results in a very high number of measurement points (typically in the order of magnitude of 10^5 to 10^6), which can then be used by statistical methods to analyze if part meets requirements [1-6].

Before carry out a metrological inspection, a real estimation of the uncertainty of the XCT measurements and correct the major sources of error must be executed. The main sources of errors XCT inspections are the surface determination of component and the voxel size acquisition [5]. In order to solve these problems, several methods are currently available on literature [6]. Between those, the calibration routine by means of a reference object is one of the more promising in terms of accuracy, speed and, in addition, it gives a real experimental data.

In this work, a practical route to perform calibrated measurements, reaching high accuracy on complex geometries by means of reference standards parts is presented. An example of XCT metrology application on a CFRP honeycomb structure is presented.

2. Experimental

The following testing methodology has been employed: (i) Inspection of reference standard object with same tomographic set up than component of interest; (ii) XCT voxel size calibration; (iii) Determination of maximum permissible length; and (iv) geometrical size errors. Detailed information of reference part, procedure for CT calibration, application CFRP sandwich and measuring procedure is reported.

2.1. Reference Standard Specimen

A 7075 aluminum reference object (Figure 1) has been used for voxel size calibration. This item is known as “Hollow Stepped Cylinder” (HSC) and it is built following the recommendations of the guideline VDI/VDE 2360 [7]. The HSC have been manufactured with a ± 0.01 mm of tolerance and then coordinate measurement machine (CMM) calibrated. View of the reference calibration specimen and drawing are presented in Figure 1.

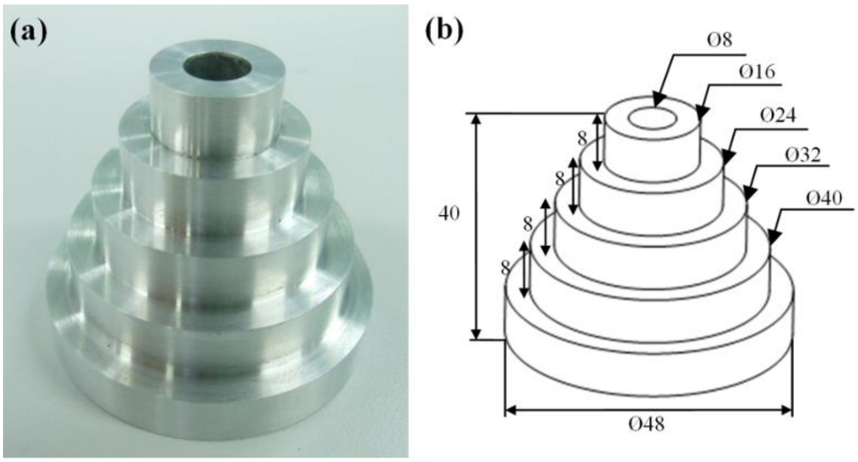

Figure 1. Reference Hollow Stepped Cylinder (HSC) part for system calibration (a) view; and (b) drawing [mm].

2.2. CFRP Honeycomb structure

A sandwich part composed of CFRP skin / Kevlar honeycomb core has been employed as application example for dimensioning different features along its structure. The element sizes about 100 x 100 x 40 mm (LxWxH). A view is presented in Figure 2.

2.3. Equipment

Metrological investigation has been carried out by CT system model “VJT-225 µ-CT” manufactured by VJ Technologies (Figure 3). Their main technical characteristics are: (x1) X-ray tube 225KV @ 30 mA, 4,500W; (x1) Digital detector of 2048 x 2048 pixels^2;

(x1) Shielded vault of 4,000 x 3,032 x 2,827 mm3 (LxWxH) and VGStudio software for 3D reconstruction and dimensioning.

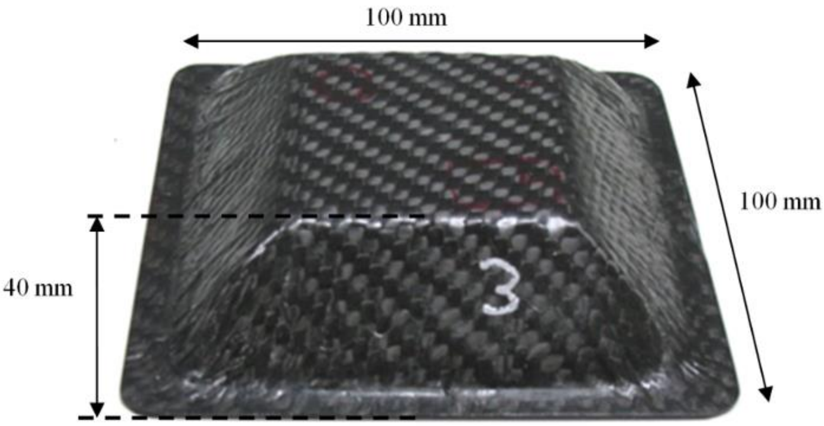

Figure 2. CFRP honeycomb sandwich structure.

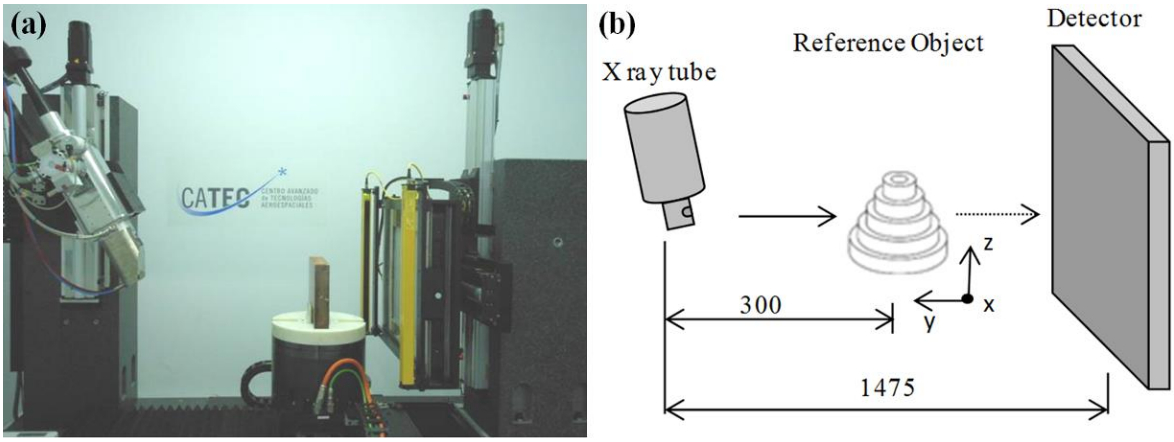

Figure 3. (a).view of XCT system at CATEC facilities; (b) Set-up for the inspection of HSC.

2.4. Voxel size calibration

Once reference standard specimen is inspected and reconstruction data is acquired, the calibration methodology is driven by the next 4 steps [2]: (i) adjustment of the surface edge threshold: Once a threshold value is selected, the diameter ratio (Equation 1) must be compared with the reference (DR). The threshold would be adjusted until obtain the same DR as in the reference measurements, (ii) Measurement of the outer (Do) and inner (DI) diameter in the tomographic reconstruction, (iii) Calculation of the scale factor (SF) correction through the relation between the reference (LREF) and tomographic (LXCT) diameters (Equation 2), and finally, (iv) Global application of the scale factor correction and final measurement of the diameters.

$$D_R = \frac{D_O}{D_I} \tag{1}$$

$$SF = \frac{L_{REF}}{L_{XCT}} \tag{2}$$

2.5. Maximum permissible length error

The maximum permissible length error ($E_{L,MPE}$) [7] is calculated through the difference between the tomography and the reference lengths (Equation 3). By means of the statistical study of the HSC length errors points, a linear tendency of the maximum permissible error are calculated (Equation 4). Expressions of the above are defined as:

$$E_L = L_{XCT} - L_{REF} \tag{3}$$

$$E_{L,MPE}[\mu m] = \pm\left(A + m \cdot L[mm]\right) \tag{4}$$

where, E_L is the length error, L_{XCT} is the measure obtained by tomography, L_{REF} correspond to measured length of reference object and $E_{L,MPE}$ is the maximum permissible error according to equation 3. Finally, A is the intersection point of the $E_{L,MPE}$ line with the vertical axis, m is the slope of the straight line and L is the length in millimeters.

2.6. Maximum geometrical size error ($G_{S,MPE}$)

$G_{S,MPE}$ [7] is obtained by the difference between tomographic and reference diameters, outer and inner features (Equation 5). The maximum permissible value is fixed by the maximum difference in the analysis (Equation 6) by:

$$G_S = D_{XCT} - D_{REF} \tag{5}$$

$$G_{S,MPE} = B \tag{6}$$

where, G_S is the geometrical size error, D_{XCT} is the tomography diameter, D_{REF} is the diameter of reference and B is the maximum diameter difference multiplied by a security coefficient (for this work 1.2).

3. Results & Discussion

This section reports on the obtained results regarding the calibration process as well as the metrological investigation in CFRP honeycomb structure.

3.1. Voxel size calibration

The HSC have been inspected using a 3 mm aluminum filter, at 220 kV and 100 µA. A 40 µm voxel size has been obtained. Three dimensional reconstruction of the part and representative cross sections are presented in the Figure 4.

		Before Voxel Size Calibration		**After Voxel Size Calibration**	
	REF (mm)	**XCT (mm)**	**G_S (µm)**	**XCT (mm)**	**G_S (µm)**
D_{O1}	48.001	48.012	11	47.996	-5
D_{O2}	40.001	40.016	15	40.003	2
D_{O3}	32.000	32.014	14	32.003	3
D_{O4}	24.005	24.014	9	24.006	1
D_{O5}	16.005	16.022	17	16.017	12
D_I	8.000	7.996	-4	7.993	-7

Table 1. Scale factor calculation and length error after the voxel size correction.

First, the surface edge is adjusted with the reference diameter ratio. The outer diameters and inner diameters of the HSC are measured by fitting a virtual circle using a least square method. Once the scale factor is applied to the whole volume, the diameters and steps lengths are measured again. The recorded results are presented in Table 1, together with the calculated errors defined by equation 5.

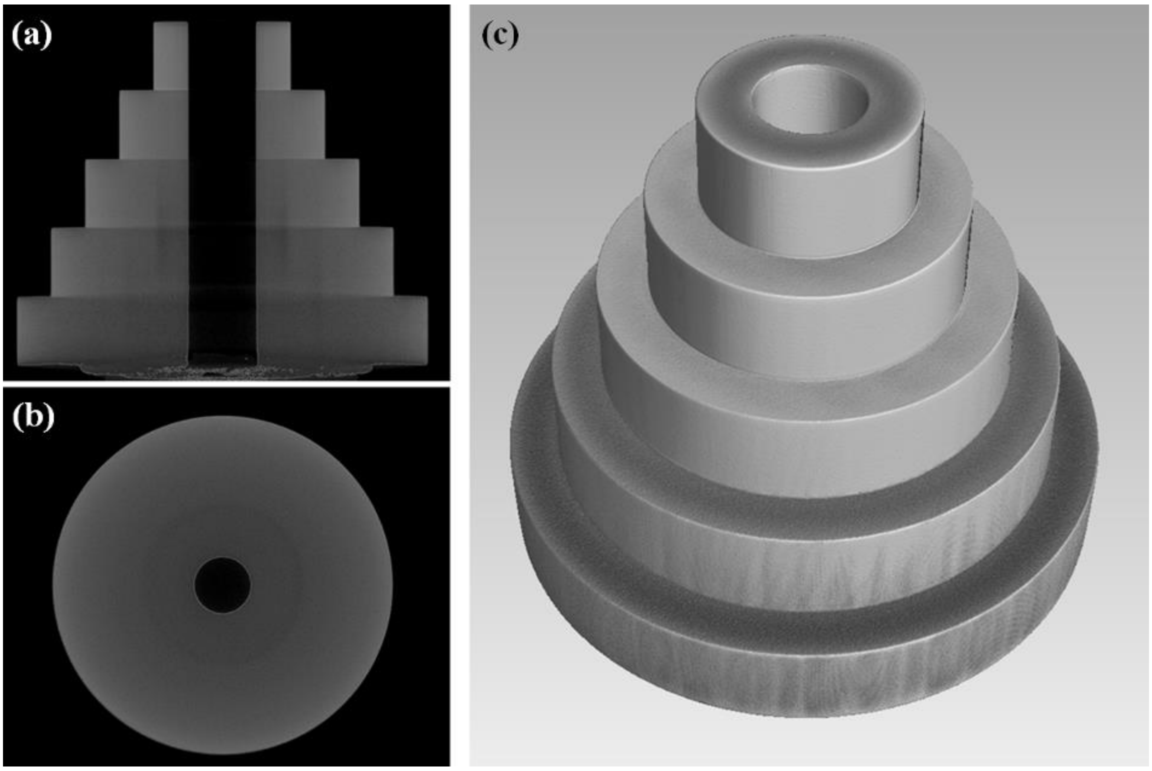

Figure 4. Tomographic views of the reconstructed HSC standard: (a) Front and (b) top cross sections; (c) three dimensional view.

3.2. Maximum permissible length error

According to the procedure presented above, the calibration curve for the maximum permissible length is calculated as $E_{L,MPE} = \pm(39 + 0.65 \cdot L)\mu m$. Figure 5.a shows HSC cross section (parallel to main part axis) from where measures from stepped planes are obtained. The length error E_L against the measured distance is depicted in Figure 5.b. Between those records, the tendency line is drawn together with the envelope (depicted in dash-line). The maximum permissible error lines (continuous line) is calculated applying a security factor (1,2 in this case) to the envelope. Finally, Table 2 shows the summarized information after data analysis by comparison of XCT and CMM measurements.

Length	**XCT (mm)**	**REF (mm)**	**E_L (µm)**	**Lenght**	**XCT (mm)**	**REF (mm)**	**E_L (µm)**
P1-P2	7.958	7.975	-17	P2-P4	16.020	16.015	5
P1-P3	15.991	16.010	-19	P2-P5	24.095	24.055	40
P1-P4	23.979	23.990	-11	P3-P4	7.988	7.980	8
P1-P5	32.053	32.030	23	P3-P5	16.063	16.020	43
P2-P3	8.032	8.035	-3	P4-P5	8.075	8.040	35

Table 2. Length error calculation from measures between the HSC stepped planes.

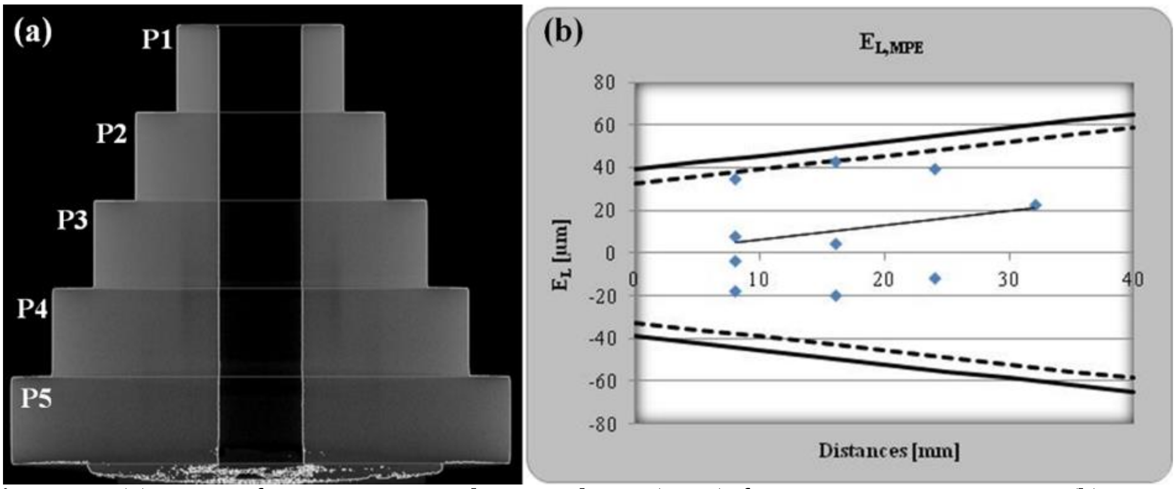

Figure 5. (a) View of cross section indicating planes (P1-5) for comparative measures; (b) Length error graph after voxel size correction, where each record represents the error of specific distance against CMM measures.

3.3. Maximum geometrical size error ($G_{S,MPE}$)

The maximum geometrical error, according to calculations presented in section 2.6, has been determined as 17µm (Table 1, before voxel size calibration). A three dimensional XCT reconstruction of the standard, and maximum geometrical size error for the acquired data is presented in Figure 6. The $G_{S,MPE}$ is a constant limit (see continuous line in Figure 6.b) obtained through the application of a security factor (1,2) to the maximum G_S (dash-line) recorded in the tests.

$$G_{S,MPE} = 20\mu m$$

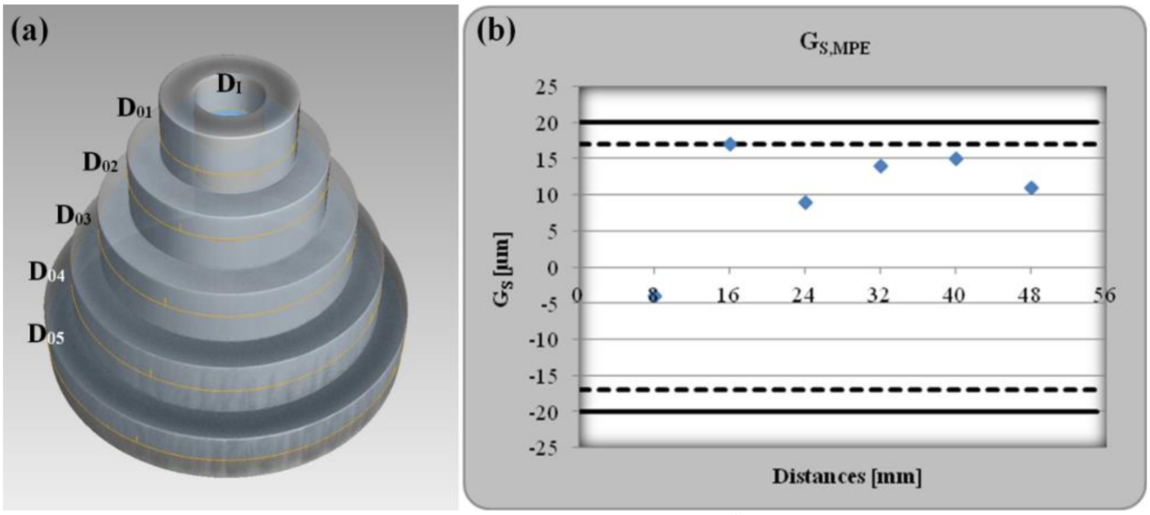

Figure 6. (a) 3D XCT representation indicating diameters for geometrical size error; (b) Max. GS,MPE after voxel size correction. Each measure represents the error for a specific diameter.

3.4. Metrologic investigation in CFRP specimen

After calibration procedure, the CFRP sandwich component has been inspected through different cross sectional views (Figure 7). Different dimensions have been investigated: (i) thickness measures along top CFRP laminate; (ii) characteristic length of honey comb deformed cells; and (iii) other dimensions between internal features. Indication of measures are presented in Figure 7 and reported in Table 2. The accumulated error is presented as well and calculated from $E_{L,MPE}$ expression (see section 3.2). For the largest recorded dimension, the error has been estimated in ± 0.087 mm.

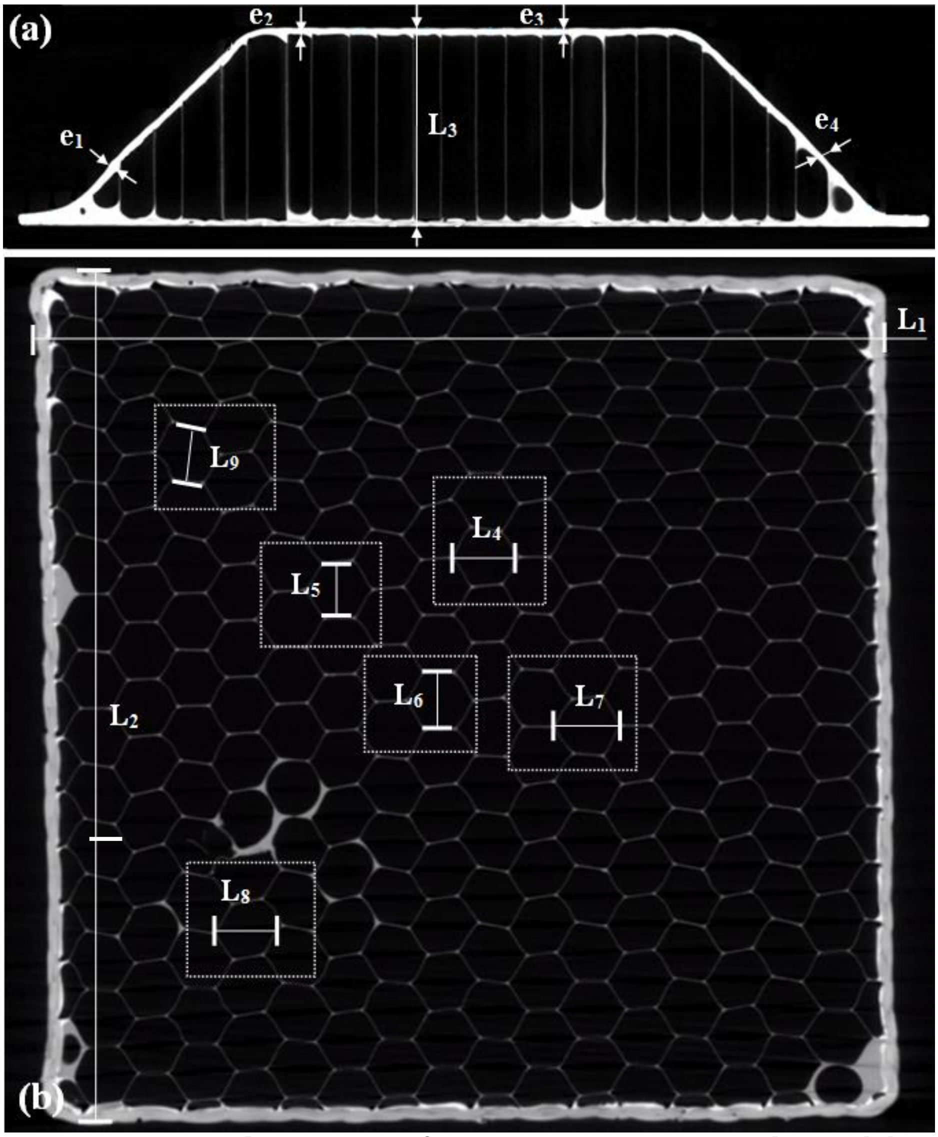

Figure 7. XCT reconstructed cross section for CFRP specimen; (a) XZ plane and (b) XY plane.

Feature ID	Length (mm)	$E_{L,MPE}$ (mm)
e_1	0.901	±0.040
e_2	0.978	±0.040
e_3	0.734	±0.039
e_4	0.913	±0.040
L1	73.701	±0.087
L2	72.990	±0.086
L3	19.036	±0.051
L4	5.253	±0.042
L5	4.846	±0.042
L6	4.500	±0.042
L7	5.419	±0.043
L8	5.039	±0.042
L9	5.714	±0.043

Table 3. CFRP honey comb sandwich measurements results.

4. Conclusions

X-ray computed tomography has demonstrated its potential for metrologic characterization. The calibration of commercial XCT system has been performed according to [7]. Through the use of a reference object, calibration of the voxel size is achieved leading to a great improvement in the precision of measurements. Uncertainty of measurements is calculated based on the previous calibration and on the surface determination task. This process allows the dimensioning of outer, and more relevant, and inner geometrical features, even more common in aerospace composite parts. Furthermore, metrological investigations, microstructural characterization and non-destructive inspections can be performed using the same data set.

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