Measurement of Cell Body and the Whole Surfaces of Long Fiber Reinforced Woven Composites

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Abstract. 3D measurements at cell body and the whole surface scales are researched as one of the series of long fiber reinforced woven composites (LFRWCs) multi-scale measurement and evaluation. This paper proposes a method to determine the maximum sampling step (MaxSS) at cell body surface scale and the minimum cell body number (MinCBN) at the whole surface to solve the problem that the measurement results are inaccurate owing to the improper sampling parameters. Three LFRWC surfaces are tested as demonstrations to state the method concretely. The results show that as long as the woven style and the processing angle are confirmed for an LFRWC, the shape and the size of the cell body is constant. At cell body scale, the sampling area is equal to the cell body size, and the MaxSS is about fiber diameter. At the whole surface scale, the proper sampling step should not go beyond the MaxSS at cell body scale, and the MinCBN the sampling area should contain is different for various materials which should be determined based on the practical situation. This research provides a fundament for the precise evaluation of the relation between an LFRWC property and the whole surface topography.

1. Introduction
Long fiber reinforced woven composites (LFRWCs) not only have excellent properties such as high specific strength and modulus, good chemical and thermal stability, low density and high strength retention\cite{1-3}, but also possess the characteristics of being insensitive to micro cracks, and are not prone to large-area fracture\cite{4,5}. Therefore, they have broad application prospects as thermal protection components and structure materials in defense, aerospace and other high-tech engineering\cite{6}. Whereas owing to their obvious anisotropy, traditional measurement method and evaluation approach for isotropic materials are no longer suitable for them. In order to reveal the relation between their surfaces and the properties thus making them used more widely, a multi-scale evaluation system based on the complex surface structure of an LFRWC including fiber bundle, cell body and the whole surface scales is proposed\cite{7}. The measurement and evaluation at fiber bundle scale has been researched in\cite{7,8}.

This paper is mainly focused on the measurement of cell body and the whole surface scales as one of the series of the surface evaluation papers of an LFRWC. Cell body contains different fiber bundle orientations, and the whole surface is composed of cell bodies, thus standard procedures designated to 2D profile sampling at fiber bundle scale is in general not applicable for 3D topographies measurement at cell body and the whole surface scales\cite{9} because 2D measurement is of
directionality which mainly reflects the damage between fibers, the fiber and the matrix. Whereas at cell body and the whole surface scales, the scales are bigger, thus the measurement and evaluation mainly reflect the damage between fiber bundles and the matrix, which cannot consider the integrate effect of the fiber orientation and the processing direction simultaneously. Therefore, a 3D surface measurement and evaluation method should be adopted at these two scales. The sampling parameters for a 3D measurement is sampling area and sampling step. The sampling area of a cell body with a processing angle and a woven style of an LFRWC is constant which can be obtained through a macro measurement. Therefore, the only parameter needs to be determined at cell body scale is the MaxSS. Proper sampling step can make the surface information of a cell body extracted accurately thus reflecting the surface topography exactly and in further researching the using performance such as the surface friction property. The MaxSS at cell body scale can be used on the whole surface measurement, therefore, the only parameter needs to be determined at the whole surface scale is MinCBN that the sampling area should include. The situation is simply suitable when an LFRWC surface is so large that measuring the whole surface is time-wasting and unnecessary.

Therefore, this paper solves the problem that the surface measurement results are inaccurate owing to the improper sampling parameters, and gives a method to determine the MaxSS at cell body scale and the MinCBN at the whole surface. Three surfaces with different processing angles of an LFRWC are used to state the method concretely, meanwhile the relation between the MaxSS and the fiber diameter is revealed to obtain a general sampling law. This research provides a fundament for the precise evaluation of the relation between the property of an LFRWC and the whole surface topography.

2. Determination of sampling parameters

2.1. Selection of assessment indexes

Four indexes according to the international standard ISO 25178[10], namely surface arithmetic mean deviation $S_a$, surface square root deviation $S_q$, surface skewness $S_{sk}$ and surface kurtosis $S_{ku}$, are picked out to determine the appropriate sampling parameters, because they are obtained easily, accepted commonly, and of statistical significances of the measured surface. Meanwhile, their corresponding 2D assessment indexes are proved effective to evaluate the fiber bundle surface situation [8].

$S_a$ is the average offset of the points within the sampling area and the reference surface. It is on behalf of the roughness degree of a surface. $S_q$ is the reaction of deviation degree of a surface to the reference plane. It is equivalent to $S_a$ in statistics, but more sensitive to surface roughness. $S_{sk}$ reflects the asymmetry of the measured surface compared with a Gaussian surface, which describes the surface amplitude characteristic. $S_{ku}$ usually describes the discrete degree of the height distribution of a surface. While $S_{sk}$ and $S_{ku}$ are more sensitive than $S_a$ and $S_q$ because they are higher moments of the surface data. The four indexes can depict the roughness and height distribution of a surface clearly.

2.2. Determination of MaxSS at cell body scale

A surface has the constant surface topography parameters which simply fluctuate a little when the proper sampling parameters are selected. Therefore, a method is proposed to confirm the confidence intervals of all values of the four indexes, in further determine the MaxSS on the cell body surface of an LFRWC. First use a smaller sampling step of the measurement device which is at least 1/3 of the LFRWC fiber diameter to sample the surface and obtain the values of the four indexes. Then take the values of the four indexes at this sampling step as the surface true values $\hat{\theta}$. Suppose the measured values of the four indexes at larger sampling steps are $\hat{\theta}$, then the residual error (RE) $e$ is as formula (1) shows

$$e = \hat{\theta} - \theta$$

(1)
Some assumptions should be made to simplify the method. The first one is the RE obeys the normal distribution $X \sim N(0, \sigma^2)$, that is, the average value $\mu$ of RE is 0 and its standard error is $\sigma$. Because each measured value is random, and the sampling method is the same. Therefore, the values are independent and identically distributed. Based on the central limit theorem, the sampling distribution of the overall values tends to be normally distributed when the sample quantity is large. The second one is the credible percent of RE is $\pm 15\%$, that is, not all REs are credible, only the values within 15% of the mean are credible. This is to improve the confidence degree of the sampling. According to the relation between a normal distribution and a standard normal distribution

$$x = \frac{X_s - \mu}{\sigma}$$

Here $X_s$ is the value from the overall sample of the RE $N(0, \sigma^2)$, and $x$ is the value after the distribution of the RE has become a standard normal distribution. Based on the standard normal distribution table, when the credible percent is $\pm 15\%$, the probability density $\Phi(x) = 0.65$, and the corresponding value of $x$ is 0.39, then $X_s = \pm 0.39\sigma$. Then the confidence interval of the truth value $\theta$ on cell body surface can be obtain as follow,

$$\left[\theta - 0.39\sigma, \theta + 0.39\sigma\right]$$

Therefore, once the measured value $\hat{\theta}$ firstly exceeds its confidence interval at one certain step, this step and steps bigger than it can no longer extract the accurate surface information. Thus, the maximum permitted sampling step can be confirmed under one evaluating index. Combining the four indexes, the MaxSS on cell body surface can be determined.

2.3. Determination of MinCBN at the whole surface scale

The same principle is used to confirm the confidence interval for all values of the four indexes to determine the MinCBN on the whole surface of an LFRWC. On the whole surface, the proper sampling step is not more than the MaxSS on cell body surface to guarantee the measurement result. The concrete implementation course to determine the MinCBN is that firstly make a balance between the sampling area and the sampling efficiency, and select the cell body numbers (CBNs) as many as possible to obtain the whole surface information. Then take the four indexes at this sampling area as the surface truth value $\theta$. Because larger components of the topography are sensitive to the process, the whole surface has much more unpredictable damage and a higher degree of irregularity, which is more complex than the cell body[11]. Therefore, the credible percent herein is improved and supposed to be $\pm 34.13\%$. The value of the credible percent selected is to easily look up the standard normal distribution table. Thus, the probability density $\Phi(x) = 0.8413$, and the corresponding value of $x$ is 1, then $X_s = \pm \sigma$. Therefore, the confidence interval of the truth value $\theta$ on the whole surface is

$$\left[\theta - \sigma, \theta + \sigma\right]$$

Decrease the sampling area, once the measured value $\hat{\theta}$ firstly exceeds the confidence interval at one certain CBNs, it means that this CBN and CBNs smaller than it can no longer depict the complete surface information. The minimum permitted CBN can be confirmed under one evaluating index. Combining the four indexes, the MinCBN on the whole surface can be determined. What should be noted that the credible percent of RE on the whole surface can be changed. It is just supposed that if the surface is smoother, the credible percent can be lowered and reversely if the surface is rougher, the credible percent can be improved to obtain the proper MinCBN for an LFRWC.

3. Equipment and materials

A commercial optical non-contact measurement system, NANOVEA® ST400, is employed to obtained the surface topographies. It has been testified[7] that this system is capable of composite surface
measurement and has an advantage over traditional contact systems in protecting the tested samples. Three processing angles (the angle between z-pin fiber bundle and the cutting surface) are used to process 3D C/SiC surface. The details are shown in table 1. Each surface has its corresponding serial number to simplify the name. All surfaces are ground by a grinding wheel with a wheel speed of 10 m/s, grinding depth of 0.1 mm, feed rate of 1 m/min and grain mesh size of 120#. Then three surfaces are obtained which are all cleaned by absolute ethyl alcohol to remove any debris, and guarantee the planeness after machined and before scanning. Figure 1 clearly shows the macro surface, the cell body and the whole surface topographies of the LFRWC. It reflects that the cell body surface topography is different owing to the integrated effect of the woven style and the processing angle, but its size is constant when both are fixed.

![Image](image1.png)

**Figure 1.** Macro surface, the whole surface topography and the cell body surface topography of three surfaces of LFRWC: (a1) ~ (a3) 1# (b1) ~ (b3) 2# (c1) ~ (3) 3#

**Table 1.** The details of three kinds of LFRWC surfaces.

| Material Number | 1# Material Name                        | 2# Material Name                        | 3# Material Name                        |
|-----------------|----------------------------------------|----------------------------------------|----------------------------------------|
|                 | 3D C/ SiC with processing angle 30deg  | 3D C/ SiC with processing angle 45deg  | 3D C/ SiC with processing angle 90deg  |
| Cell Body Size (mm×mm) | 3×1.6                             | 1.8×1.5                             | 1.6×1.6                             |

4. Application of the determination method of sampling parameters

4.1. MaxSS determination of the concrete LFRWC cell body surfaces

According to the MaxSS method described in Section 2.2, three cell body surfaces are measured with the constant sampling area equal to their corresponding size, and the sampling step gradually increasing. Figure 2, Figure 3 and Figure 4 are the changing trends of four assessment indexes with
sampling steps on cell body surface of 1#, 2# and 3# respectively. In conclusion, the MaxSSs are all smaller than 10μm, and mainly concentrate on 6 to 8μm.

Figure 2. The changing trends of (a) Sa (b) Sq (c) Ssk and (d) Sku with sampling steps on cell body surface of 1#.

Figure 3. The changing trends of (a) Sa (b) Sq (c) Ssk and (d) Sku with sampling steps on cell body surface of 2#.
To obtain a general sampling law about MaxSS of LFRWC cell body surface, the surfaces of material 3# are observed by the PHENOM scanning electron microscope (SEM) (Figure 5). It can be seen that fiber is the minimum constitutional unit of a composite surface, and the diameter of carbon fiber is about 7μm. There is an obvious change in surface characteristics every 6-8μm, and the change mainly depends on fiber diameter. Therefore, it can be inferred probably that the MaxSS is equal to fiber diameter of the measured fiber reinforced composite. As long as the fiber diameter is known, the MaxSS is determined, and accurate surface information can be obtained in further, which proves from another aspect that the credible percent ±15% selected is appropriate.

Figure 4. The changing trends of (a) $S_a$ (b) $S_q$ (c) $S_{sk}$ and (d) $S_{ku}$ with sampling steps on cell body surface of 3#. 

Figure 5. SEM images (a)(b) Fiber bundle surfaces of 3#.
Figure 6. The changing trends of (a) $Sa$ (b) $Sq$ (c) $Ssk$ and (d) $Sku$ with sampling steps on the whole surface of 1#.

Figure 7. The changing trends of (a) $Sa$ (b) $Sq$ (c) $Ssk$ and (d) $Sku$ with sampling steps on the whole surface of 2#.
4.2. MinCBN determination of the concrete LFRWC surfaces
The sampling step is 6μm based on the results in Section 4.1. The changing trends of the four indexes with sampling steps on the whole surface of 1#, 2# and 3# are shown in Figure 6 to Figure 8. It reflects that the MinCBN is different for each material and there is no obvious law. A conclusion is made that if the measured surfaces are larger enough for an LFRWC, as long as the sampling area is equal to the MinCBN and the selected sampling step is smaller than their fiber diameter, the measurement result can reflect the surface statistical characteristics clearly, and the sampling process is time-saving. But if the surface area is smaller than the MinCBN, the entire surface should be measured to obtain the accurate topography.

5. Conclusions
In this paper, a method for determining the appropriate sampling parameters on the cell body and the whole surfaces of an LFRWC is proposed and three LFRWC surfaces are tested as demonstrations. The conclusions are as follows:

(1) 3D measurement should be adopted on cell body and the whole surface scales because the integrate effect of the fiber orientation and the processing direction cannot be divided during sampling. The sampling parameters need to determine are sampling area and sampling step.

(2) The woven style is fixed for an LFRWC, and once the processing angle is confirmed, the shape and size of the cell body is constant at cell body scale, the sampling area is equal to the cell body size which can be obtained through a macro measurement, and the MaxSS is approximately fiber diameter.

(3) At the whole surface scale, the proper sampling step should not exceed the MaxSS at cell body scale and the MinCBN the sampling area should contain is different for various materials which should be determined based on the practical situation.
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