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Effect of gaps/overlaps induced waviness on the mechanical properties of automated fiber placement (AFP)-manufactured composite laminate

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Abstract
Automated Fiber Placement (AFP) process is widely used to produce lightweight composite components owing to its excellent flexibility and efficiency. However, the out-of-plane fiber waviness induced by gaps and overlaps inevitably formed in the AFP process lack experimental studies. Therefore, an experimental research is proposed to study the influence mechanism of out-of-plane fiber waviness. Herein, based on the description of the shape of the fiber waviness, the relationship between the magnitude factor and the axial elastic modulus of laminate with fiber waviness is established. By embedding gaps and overlaps in the layup, a new approach to manufacturing composite laminate with fiber waviness of sine wave and sine-like wave is proposed, and the rationality of the theoretical analysis on the elastic properties of laminate with fiber waviness is verified. Finally, the effect of the magnitude factor on the mechanical properties of composite laminate is obtained by tensile and compression test. Experimental results show that the tensile and compression properties of laminate decrease significantly with the increase of magnitude factor. The effect of sine-like wave on mechanical properties is similar to that of sine wave, and it is feasible to splice sine-like wave into sine wave for mechanical property analysis.

1. Introduction
Carbon fiber reinforced polymer (CFRP) composite are composed of matrix resin and high-performance carbon fibers, which have become the standard materials for aerospace structural components owing to its advantages of high specific strength and high specific modulus [1–3]. However, in the manufacturing process of composite components, various artificial defects such as gaps, overlaps and inaccurate angles will occur and have a negative impact on the mechanical properties of composite components. For these reasons, the automated fiber placement (AFP) technology of composite materials has gradually become main research direction due to its efficiency and flexibility [4–6]. In the AFP process, the uneven width caused by tow slitting process of composite prepreg inevitably leads to emergence of transverse gaps and overlaps in the interior of composite components (figure 1).

In the curing process, the prepreg tow laid upon the gap position is pressed into the gap under pressure, and the overlap defect will cause the swelling of the subsequent prepreg tow [7]. The uneven thickness will cause a large number of out-of-plane fiber waviness in the AFP-manufactured components. Usually, the waviness induced by gaps and overlaps contain two kinds of wave patterns: sine wave and sine-like wave. The out-of-plane waviness is a common defect in the composite material, which significantly affects the mechanical properties, such as tensile strength, compression strength, and fatigue strength [5]. Therefore, it is necessary to study the influence mechanism of the waviness induced by gaps and overlaps in AFP process.

The earlier studies on out-of-plane fiber waviness were mostly mechanism research. Karami et al [8] studied the effects of periodic waviness and local waviness on the modulus and strength of composite laminates by finite
element method. Elhajjar et al\cite{9} researched the effect of fiber waviness on the compression strength of composites through open hole compression test, and the results showed that the matrix cracking and failure mode were closely related to fiber waviness, and the resin rich zone played a decisive role in crack initiation and propagation. Hsiao et al\cite{10–12} described the uniform fiber waviness as a sine wave defined by amplitude and wavelength through mathematical method, and established the elastic model of three wave patterns of fiber waviness, which was verified by compression test. Chun et al\cite{13} studied the nonlinear behavior of out-of-plane fiber waviness on unidirectional composites through theoretical and experimental method, and established an analytical model for predicting the influence of magnitude of fiber waviness on tensile and compression properties. Sutcliffe et al\cite{14} studied the compression properties of random waviness through finite element analysis. At the same time, in order to get controlled defects, some scholars prepared specimens with waviness by different prefabrication methods. Wu et al\cite{15} made the specimens with in-plane waviness through a glass rod, while the specimens with out-of-plane waviness were prepared with a prepreg strip. The results showed that both out-of-plane waviness and in-plane waviness have little effect on the tensile properties and will significantly reduce the compression properties. Khattab et al\cite{16} manufactured the tensile specimens with graded wavy strips and found that all failures occurred in the waviness area. Davidson et al\cite{17} introduced the waviness by insetting the pre-cured resin blocks in the specimens, and the failure modes were studied.

However, there were few studies on the out-of-plane fiber waviness induced by gap and overlap defects in the AFP process. Nimbal et al\cite{18} studied the effect of various triangular gaps embedded in laminates on the compression strength of composites through experiments and numerical analysis, and analyzed the magnitude of fiber waviness through metallographic microscope. The results showed that the increase of the total number of gaps in the thickness direction raised the severity of out-of-plane waviness, leading to the increase of the maximum waviness angle, and finally reduced the compression strength. Wang J et al\cite{19} manufactured specimens with different magnitudes of out-of-plane waviness by inserting discontinuous 0° and 90° layers in the laminate, but the waviness was only half of the full wave. The study showed that when the waviness angle of the specimen was 8°, it failed under similar stress and strain as the non-defective specimen, while when the waviness angle was 30°, the load of the out-of-plane waviness was redistributed, causing the overall stress of the specimen reduced. In addition, some scholars have carried out finite element simulation research on the out-of-plane fiber waviness caused by gaps and overlaps\cite{20–22}. However, the triangular gap and the incomplete waviness cannot reflect the actual superposition of the gap and overlap in the thickness direction of the laminate. The above studies have not established the theoretical model of the out-of-plane waviness induced by gaps and overlaps in AFP process. Thus, the objectives of the work described herein are as follows.

![Figure 1. Out-of-plane waviness induced by transverse gaps and overlaps in the AFP process.](image-url)
Explore the relationship between the common wave-patterns (sine, sine-like wave) induced by gaps/overlaps in the AFP process and the elastic properties of composite laminate, and obtain the analysis method of sine-like wave.

(2) Establish appropriate experimental methods to obtain gaps/overlaps with different magnitudes and wave-patterns, and obtain the evolution law of wave-patterns. Through the tensile and compression test, the relationship between the magnitudes of fiber waviness and mechanical strength is studied.

2. Theory analysis of mechanical performance of laminates with out-of-plane fiber waviness in AFP process

2.1. Definition of fiber waviness induced by gaps and overlaps

In order to establish a mathematical model to describe the mechanical behavior of laminate with out-of-plane waviness, the model needs to contain three sets of data: material properties, laminate geometry and out-of-plane waviness geometry. The material properties are determined by engineering constants. The geometric structure of laminate is determined by the number of plies, ply thickness, the layup sequence, the number of waviness plies and the position of waviness plies. Firstly, it is necessary to locate the amplitude and wavelength of the waviness. These two factors are the most important parameters of the waviness, which can measure the sharpness and flatness of the fiber. For convenience, it will be combined into a dimensionless parameter and defined as magnitude factor. Its value is the ratio between the amplitude and the wavelength, which can also be understood as the aspect ratio of the sine wave. The definition of magnitude factor of waviness is as follows:

\( \tau = \frac{\delta}{\lambda} \)  \hspace{1cm} (1)

For fiber usually only includes the waviness in one side direction in AFP process, the model is simplified. The fiber waviness caused by gaps and overlaps are generally approximated as sine with amplitude \( \delta \) and wavelength \( \lambda \), as shown in figure 2(a).

\( w = \delta \sin\left(\frac{\pi x}{\lambda}\right) \)  \hspace{1cm} (2)

The angle between the fiber direction and the axis at any position along the \( x \)-axis curve can be calculated by the following formula:

\( \gamma = \arctan\left(\frac{dw}{dx}\right) = \arctan\left(\frac{\pi \delta}{\lambda} \cos\left(\frac{\pi x}{\lambda}\right)\right) \)  \hspace{1cm} (3)

When gap and overlap defects reach a certain size, the induced waviness tends to be a sine-like wave. The middle section of the fiber in this wave is a straight line, while the two sides of the wave are still curved. It is proposed to splice the curves on both sides, and define the new spliced curve as sine wave. Therefore,
Fiber orientation angle of any point on the spliced curve is:

\[
\gamma = \arctan\left(\frac{\frac{d\psi}{dx}}{\lambda_{d} + \lambda_{s}}\right) = \arctan\left(\frac{\pi \delta_{t}}{\lambda_{d} + \lambda_{s}} \cos \frac{\pi x}{\lambda_{d} + \lambda_{s}}\right)
\]

2.2. Prediction of elastic properties of laminate with out-of-plane fiber waviness

For anisotropic composites, the stress-strain relationship in the main axis direction of the material is as follows:

\[
[\varepsilon] = [S][\sigma]
\]

According to the classical lamination theory \[23\], the orthotropic unidirectional laminate is subjected to in-plane stress \((\sigma_{1}, \sigma_{2}, \tau_{12})\), and the stress-strain relationship is as follows:

\[
\begin{bmatrix}
\varepsilon_{1} \\
\varepsilon_{2} \\
\varepsilon_{3} \\
\gamma_{32} \\
\gamma_{13} \\
\gamma_{12}
\end{bmatrix}
= 
\begin{bmatrix}
S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\
S_{21} & S_{22} & S_{23} & 0 & 0 & 0 \\
S_{31} & S_{32} & S_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & S_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & S_{55} & 0 \\
0 & 0 & 0 & 0 & 0 & S_{66}
\end{bmatrix}
\begin{bmatrix}
\sigma_{1} \\
\sigma_{2} \\
\sigma_{3} \\
\tau_{32} \\
\tau_{13} \\
\tau_{12}
\end{bmatrix}
\]

(7)

In traditional laminates with uniform stiffness, the fiber angle is fixed, so \(S_{ij}\) is also a fixed value. However, the angle of curved fiber changes continuously in the plane, making \(S_{ij}\) no longer fixed and change continuously with different coordinates. On the XOZ plane, the stress-strain relationship can be obtained by the transformation of the following formula, where \([S]\) is the compliance matrix and \([S^*]\) is the off-axis compliance matrix of the XOZ plane:

\[
[S] = [R][T]^{-1}[R]^{-1}[S][T^*][\sigma] = [S^*][\sigma]
\]

(8)

Where \(R\) is the Reuter matrix \[24\], and \([T^*]\) is the transformation matrix:

\[
[R] = 
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 2 & 0 & 0 \\
0 & 0 & 0 & 0 & 2 & 0 \\
0 & 0 & 0 & 0 & 0 & 2
\end{bmatrix}
\]

(9)

\[
[T^*] = 
\begin{bmatrix}
\cos^2\gamma & 0 & \sin^2\gamma & 0 & 2 \sin \gamma \cos \gamma & 0 \\
0 & 1 & 0 & 0 & 0 & 0 \\
\sin^2\gamma & 0 & \cos^2\gamma & 0 & -2 \sin \gamma \cos \gamma & 0 \\
0 & 0 & 0 & \cos \gamma & 0 & -\sin \gamma \\
-\sin \gamma \cos \gamma & 0 & \sin \gamma \cos \gamma & 0 & \cos^2\gamma - \sin^2\gamma & 0 \\
0 & 0 & 0 & \sin \gamma & 0 & \cos \gamma
\end{bmatrix}
\]

(10)

Since the angle of the sine wave \((\gamma)\) of the fiber is constantly changing, the calculation can be obtained according to the out-of-plane description model of the fiber. The average transformation compliance \(\langle S_{ij}\rangle\) of the fiber waviness can be calculated by the following formula:

\[
\langle S_{ij}\rangle = \frac{1}{2\lambda} \int_{0}^{2\lambda} S_{ij} dx (i, j = x, y, z, q, r, s)
\]

(11)

The elastic properties can be obtained by applying uniaxial loads in the X direction respectively. The calculation results of the axial elastic modulus of the laminate are as follows:

\[
E_{x} = \frac{\sigma_{x}}{\varepsilon_{x}} = \frac{2\lambda}{\langle S_{y}\rangle} S_{y} dx
\]

(12)

Since the waviness of the fiber in the 90° layer has little effect on the elastic properties, the transverse gaps and overlaps in the 90° layer were used to manufacture the fiber waviness. It is proposed that the curved fiber is equivalent to a straight fiber with elastic modulus modified by the magnitude factor. The test specimens were manufactured by AFP machine, so the fiber matrix is firmly bonded, that is, the strains between composite layers are equal, and the calculation model of equivalent modulus of orthogonal layers is established:
\[ E_m = \frac{n_{fw}}{n_t} E_x + \left(1 - \frac{n_{fw}}{n_t}\right) E_y \]

\[ T_1 = \frac{1 + \pi^2 r^2/2(1 + \pi^2 r^2)^2}{1 + \pi^2 r^2/2} \]

\[ T_2 = \frac{\pi^2 r^2/2(1 + \pi^2 r^2)^2}{1 + \pi^2 r^2/2} \]

\[ T_3 = 1 - \frac{1 + 3\pi^2 r^2/2(1 + \pi^2 r^2)^2}{1 + \pi^2 r^2/2} \]

\[ S_{11} = 1/E_t, \quad S_{22} = 1/E_t, \quad S_{12} = -\nu_{21}/E_t, \quad S_{66} = 1/G_{12} \]

In the formula, \( n_{fw} \) is the number of layers with fiber waviness, \( n_t \) is the total number of layers, \( S_{11}, S_{22}, S_{12} \) and \( S_{66} \) are the elastic compliance components of the unidirectional laminate, and \( E_t, E_2, G_{12} \) and \( \nu_{21} \) are the longitudinal Young’s modulus, transverse Young’s modulus, in-plane shear modulus and longitudinal Poisson’s ratio of the unidirectional laminate.

In this method, the fiber is equivalent to a straight line, and the out-of-plane waviness in 90° layer is ignored. At the same time, the accuracy of the method of predicting the elastic properties can be obtained by the error coefficient (\( \mu \)).

\[ \mu = \frac{E_m - E_x}{E_x} \]

Where, \( E_m \) is the theoretical modulus obtained by the method mentioned above, and \( E_x \) is the actual modulus.

### 3. Experimental studies of the influence of out-of-plane fiber waviness on composite laminate

#### 3.1. Design of experimental set-up

On the basis of theoretical analysis, the typical single fiber with waviness was selected as the main research object. In order to introduce different magnitudes of out-of-plane fiber waviness, the deformation of fibers in the stacking direction was realized by embedding different gap and overlap defects in the specimen (figure 3(a) and (b)). The schematic diagram of the designed layers is shown in figure 3, in which the dimensions of embedded gap and overlap are 6.35 mm and 12.7 mm. The layup of test specimen includes 90° layer, 0° layer and 90° supplementary layer, in which the 0° layer plays the main bearing role, the 90° layer is the foundation layer to manufacture the fiber waviness, and the role of the 90° supplementary layer is to ensure that the laminate is of equal thickness. At the same time, the experimental scheme of multiple fibers with waviness is shown in figure 3(c). The specific layup configurations are shown in table 1. Tensile and compression tests were carried out on the prepared specimens with fiber waviness, and the actual magnitude of the specimens was observed by metallographic microscope. In order to ensure the bonding quality between layers, all the test specimens were manufactured by the AFP machine (figure 3(d)).

#### 3.2. Materials and experiments details

The thermoset prepreg used in the experiment was EM118/A10 prepreg supplied by Hengshen Co. Ltd, with a width of 6.35 mm and a single-layer thickness of 0.15 mm. The prepreg is composed of the epoxy toughened by unidirectional T300 fibers, and the fiber volume fraction is 63%. The detailed information of prepreg is shown in table 2. According to the theoretical analysis, the interlayer bonding quality has a great effect on the accuracy of the analysis. In order to ensure the bonding quality between layers, autoclave was used for curing.

The tensile test was carried out according to ASTM D 3039/D 3039M-08[25] with the loading rate of 1 mm min\(^{-1}\) (figure 4(a)). The defect was embedded in the middle of the specimen, and the defect area is perpendicular to the direction of the tensile load. Use an extensometer to measure the deformation of the specimen within the gauge distance, so as to obtain its axial tensile modulus, and the specimen size is shown in figure 4(b). In order to avoid premature failure due to possible stress concentration caused by the clamping system of the tensile testing machine, 50 mm × 25 mm × 2 mm aluminum sheet was bonded to the end of the specimen with epoxy adhesive, and 5 specimens were tested for each defect type. After the tensile test is completed. The tensile strength can be calculated by the following formula:
Figure 3. Manufacturing scheme of test specimens with embedded waviness: (a) Prepared by overlaps, (b) Prepared by gaps, (c) Multi-waviness prepared by overlaps, (d) AFP device.
is the ultimate tensile strength

Table 1. Layup configurations of specimens with gaps and overlaps.

| No. | Specimen Name | Layup sequence | Defects |
|-----|---------------|----------------|---------|
| 1   | FWB$^a$       | $[90^\circ]_y/0^\circ/[90^\circ]_x$ | none    |
| 2   | FWO-6.35-2    | $[90^\circ]_y/[90^\circ]_y/0^\circ/[90^\circ]_y$ | 6.35 mm overlap |
| 3   | FWO-6.35-3    | $[90^\circ]_y/[90^\circ]_y/0^\circ/[90^\circ]_y$ | 6.35 mm overlap |
| 4   | FWO-6.35-4    | $[90^\circ]_y/[90^\circ]_y/0^\circ/[90^\circ]_y$ | 6.35 mm overlap |
| 5   | FWO-6.35-5    | $[90^\circ]_y/[90^\circ]_y/0^\circ/[90^\circ]_y$ | 6.35 mm overlap |
| 6   | FWO-12.7-2    | $[90^\circ]_y/[90^\circ]_y/0^\circ/[90^\circ]_y$ | 12.7 mm overlap |
| 7   | FWO-12.7-3    | $[90^\circ]_y/[90^\circ]_y/0^\circ/[90^\circ]_y$ | 12.7 mm overlap |
| 8   | FWO-12.7-4    | $[90^\circ]_y/[90^\circ]_y/0^\circ/[90^\circ]_y$ | 12.7 mm overlap |
| 9   | FWO-12.7-5    | $[90^\circ]_y/[90^\circ]_y/0^\circ/[90^\circ]_y$ | 12.7 mm overlap |
| 10  | FWO-6.35-2    | $[90^\circ]_y/[90^\circ]_y/0^\circ/[90^\circ]_y$ | 6.35 mm gap |
| 11  | FWO-6.35-3    | $[90^\circ]_y/[90^\circ]_y/0^\circ/[90^\circ]_y$ | 6.35 mm gap |
| 12  | FWO-6.35-4    | $[90^\circ]_y/[90^\circ]_y/0^\circ/[90^\circ]_y$ | 6.35 mm gap |
| 13  | FWO-6.35-5    | $[90^\circ]_y/[90^\circ]_y/0^\circ/[90^\circ]_y$ | 6.35 mm gap |
| 14  | FWO-12.7-2    | $[90^\circ]_y/[90^\circ]_y/0^\circ/[90^\circ]_y$ | 12.7 mm gap |
| 15  | FWO-12.7-3    | $[90^\circ]_y/[90^\circ]_y/0^\circ/[90^\circ]_y$ | 12.7 mm gap |
| 16  | FWO-12.7-4    | $[90^\circ]_y/[90^\circ]_y/0^\circ/[90^\circ]_y$ | 12.7 mm gap |
| 17  | FWO-12.7-5    | $[90^\circ]_y/[90^\circ]_y/0^\circ/[90^\circ]_y$ | 12.7 mm gap |
| 18  | MWO           | $[90^\circ]_y/[0^\circ]_y/[0^\circ]_y$ | none    |
| 19  | MWO-12.7-5    | $[90^\circ]_y/[0^\circ]_y/[0^\circ]_y$ | 12.7 mm overlap

The notations for specimen name, AWX-M-N, are as follows: AW contains FW and MW. FW is short for Fiber Waviness. MW stands for multi-waviness. X contains B, G, O, representing Baseline, Gap, and Overlap respectively. M represents the size of defects in all plies, N refers to numbers of defects.

$^b$ 90° is the incomplete ply which fabricates fiber waviness, and 0° is the supplementary layer of 90° direction.

Table 2. Material properties of prepreg EM118/A10.

| Nominal Thickness | 0.15 mm | Resin content | 35% |
|-------------------|---------|---------------|-----|
| $E_1$/GPa         | 140     | $E_2 = E_3$/GPa | 7.5 |
| $\nu_{12} = \nu_{13}$ | 0.3     | $\nu_{23}$ | 0.4 |
| $G_{12} = G_{13}$/GPa | 5.69    | $G_{23}$/GPa | 4   |
| $X_1$/MPa         | 2156    | $X_C$/MPa | 1157 |
| $Y_1$/MPa         | 36.3    | $Y_C$/MPa | 145  |
| $S_{12}$/MPa       | 110     | $S_{23}$/MPa | 55     |

$$\sigma_t = \frac{P_t}{s}$$  \hspace{1cm} (14a)

Where, $\sigma_t$ is the ultimate tensile strength (MPa), $P_t$ is the maximum load before failure (N), and $s$ is the average cross-sectional area of the tensile specimen (mm$^2$).
The compression test of composite materials was carried out according to ASTM D6641/D6641m-09\cite{26} with the loading rate of 1.5 mm min$^{-1}$ (figure 5(a)), and the specimen size is shown in figure 5(b). The ultimate compression strength of the specimen can be obtained by using the maximum load value when the specimen is broken:

$$\sigma_c = \frac{P_c}{A}$$  \hspace{1cm} (15)

Where, $\sigma_c$ is the ultimate compression strength (MPa), $P_c$ is the maximum load before failure (N), and $A$ is the average cross-sectional area of the specimen (mm$^2$).

4. Results and discussion

4.1. Actual magnitude of out-of-plane fiber waviness fabricated by the experiment scheme

The actual magnitude factor of the specimen is shown in table 3, and the wavelength $\lambda$ of the sine wave in the table is the sum of the value of $\lambda_d$ and $\lambda_w$ defined above. The value of $\lambda$, $\delta$, $\gamma_{\text{max}}$ of all defect types are the average value measured by 5 specimens. According to the magnitude factor and fiber orientation angle, the designed specimens with gaps and overlaps have basically similar magnitude factor. This is because the number of gaps causing waviness is consistent with the number of overlaps, resulting in the only difference is the opposite

Table 3. Shape parameters of fiber waviness in specimens.

| No. | Name         | Fiber characteristic | $\lambda$ (mm) | $\delta$ (mm) | $\tau$ | $\gamma_{\text{max}}$ ($\degree$) |
|-----|--------------|----------------------|----------------|--------------|--------|----------------------------------|
| 1   | FWB          | Straight line         | 0              | 0            | 0      | 0                                |
| 2   | FWO-6.35–2  | Sine wave            | 13.79          | 0.43         | 0.031  | 3.57                             |
| 3   | FWO-6.35–3  | Sine wave            | 14.66          | 0.69         | 0.047  | 5.38                             |
| 4   | FWO-6.35–4  | Sine wave            | 15.52          | 0.86         | 0.055  | 6.32                             |
| 5   | FWO-6.35–5  | Sine wave            | 17.24          | 1.03         | 0.060  | 6.81                             |
| 6   | FWO-12.7–2  | Sine-like wave       | 19.82          | 0.60         | 0.030  | 3.47                             |
| 7   | FWO-12.7–3  | Sine-like wave       | 20.69          | 0.86         | 0.042  | 4.75                             |
| 8   | FWO-12.7–4  | Sine-like wave       | 21.55          | 1.05         | 0.049  | 5.57                             |
| 9   | FWO-12.7–5  | Sine-like wave       | 22.41          | 1.20         | 0.054  | 6.11                             |
| 10  | FWG-6.35–2  | Sine wave            | 13.17          | 0.42         | 0.032  | 3.65                             |
| 11  | FWG-6.35–3  | Sine wave            | 13.96          | 0.63         | 0.045  | 5.16                             |
| 12  | FWG-6.35–4  | Sine wave            | 15.68          | 0.86         | 0.055  | 6.26                             |
| 13  | FWG-6.35–5  | Sine wave            | 18.11          | 1.15         | 0.064  | 7.24                             |
| 14  | FWG-12.7–2  | Sine-like wave       | 19.22          | 0.63         | 0.033  | 3.75                             |
| 15  | FWG-12.7–3  | Sine-like wave       | 20.25          | 0.84         | 0.041  | 4.74                             |
| 16  | FWG-12.7–4  | Sine-like wave       | 21.92          | 1.03         | 0.047  | 5.37                             |
| 17  | FWG-12.7–5  | Sine-like wave       | 21.17          | 1.26         | 0.060  | 6.79                             |
| 18  | MWB          | Straight line         | 0              | 0            | 0      | 0                                |
| 19  | MWO-12.7–5  | Sine-like wave       | 19.58          | 1.12         | 0.057  | 6.21                             |

Figure 5. Compression test of specimens with fiber waviness: (a) Compression test device, (b) Size of compression specimen.
direction. Therefore, the subsequent mechanical analysis is transformed into using the magnitude factor as the scale parameter to focus on the influence of fiber waviness on the laminate.

When there is no gap and overlap defect, the morphology of the single fiber is a straight line (figure 6). When the defect width is 6.35 mm, the morphology of the fiber is a sine wave (figure 7). While the defect width is 12.7 mm, the fiber is flat in the middle and curved at both ends (figure 8), which shows that the out-of-plane waviness of fiber gradually transits to the sine like wave with the increase of defect width. As can be seen from figure 9(b), the multi-waviness manufactured by 12.7 mm overlaps also presents a sine-like waveform. At the same time, due to the different influence of the pressure distribution on the surface with different sizes of defects in the curing process, the magnitude factor of sine-like wave in the specimen is less than that of sine wave.

4.2. Influence of magnitude factor of fiber waviness on tensile properties
According to [19, 27, 28], out-of-plane fiber waviness leads to the reduction of composite strength owing to the redistribution of load in the waviness area. At the same time, the waviness area is also a stress concentration area.
where the initial defects are easy to occur. Therefore, the influence of magnitude factor and failure mode are analyzed through the experimental results.

The comparison between the theoretical and actual values of the tensile modulus of the specimens with different magnitude factors is shown in figure 10. It can be seen from the figure that the in-plane longitudinal tensile modulus of specimens decreases with the increase of magnitude factor of fiber waviness. However, the actual axial modulus is slightly smaller than the predicted modulus. The error coefficient of multi-waviness is 3.77%, which proves the effectiveness of the theoretical model for multiple fibers. As can be seen from table 4, the error coefficient increases with magnitude factor, which shows that the accuracy of the calculation method decreases. The main reason is that the method proposed in this paper ignores the out-of-plane waviness in 90° layer. However, the influence of out-of-plane waviness in 90° layer is less than 13%, so the proposed calculation method of elastic modulus can be regarded as an effective method. When the magnitude factor reaches 0.6, the

Figure 9. Fiber distribution of multi-waviness: (a) Baseline, (b) Sine-like wave ($\tau = 0.057$).

Figure 10. Theoretical and actual values of longitudinal tensile modulus of specimens with different magnitudes of single fiber waviness.

Table 4. Theoretical and actual values of longitudinal tensile modulus of different fiber waviness.

| Wave pattern     | Magnitude factor | Theoretical value | Actual value | $\mu$ (%) |
|------------------|------------------|-------------------|--------------|-----------|
| Single waviness  | Sine wave        | 0                 | 16.35        | 16.68     | -1.96     |
|                  | 0.031            | 15.50             | 15.28        | 1.44      |
|                  | 0.047            | 14.61             | 14.01        | 4.28      |
|                  | 0.055            | 14.14             | 13.35        | 5.92      |
|                  | 0.060            | 13.84             | 12.25        | 12.98     |
| Sine-like wave   | 0                | 16.35             | 16.68        | -1.98     |
|                  | 0.030            | 15.55             | 15.18        | 2.44      |
|                  | 0.042            | 14.90             | 14.2         | 4.93      |
|                  | 0.049            | 14.49             | 13.48        | 7.49      |
|                  | 0.054            | 14.20             | 13.15        | 7.98      |
| Multi-waviness   | Sine-like wave   | 0                 | 38.71        | 39.22     | -1.30     |
|                  | 0.057            | 29.71             | 28.63        | 3.77      |
axial modulus of sine wave decreases by 26.56%. When the magnitude factor reaches 0.54, the axial modulus of sine-like wave decreases by 21.16%. The effect of sine-like wave is close to that of sine wave, which indicates the correctness of analysis on spliced curve of sine-like wave.

Through the analysis of the tensile test results of the specimens, it is found that magnitude factor has an impact on the tensile properties of the specimens. Figure 11(a) is the load-displacement curve of the tensile test of the specimens. It can be seen that the load-displacement curves of specimens with different waviness have a sudden drop in load at a certain position with a small stepped shape appears, indicating that the crack is expanding and stress relief happens. Then the laminate with fiber waviness continues to bear the load with the load curve rising, and finally breaks with the fiber fracture. At the same time, with the increase of the out-of-plane magnitude factor and the off-axis angle, the tensile performance tends to decrease gradually. During the tensile process, there is a process of fiber straightening in the waviness area of the fiber. The larger magnitude of the waviness, the greater the off-axis angle of the fiber is. As the load continues to increase, the fiber with the largest out-of-plane waviness will break first owing to the largest off-axis angle, and the corresponding tensile load will be smaller when failure occurs.

The influence of magnitude factor of fiber waviness on the tensile strength of the laminate is shown in figure 11(b), in which the tensile strength of the defect-free specimen is 196.15 MPa. With the increase of the magnitude factor of the waviness, the tensile strength of specimens with both sine wave and sine-like wave gradually decreases. The tensile strength of the specimens with sine wave and sine-like wave at their maximum magnitude decreased by 23.86% and 29.50%, respectively. The detailed tensile strength of specimens with different magnitude factor is shown in table 5.

![Figure 11. Tensile test results: (a) Load displacement curves, (b) Tensile strength.](image_url)

| Table 5. Tensile strength of single fiber waviness. |
|---------------------------------|--------|--------|
| Magnitude factor | Tensile strength (MPa) | Reduction rate(%) |
|------------------|---------------------|------------------|
| Sine wave | 0.000 | 196.15 | 0.00 |
| | 0.031 | 183.23 | 6.59 |
| | 0.047 | 168.87 | 13.91 |
| | 0.055 | 155.51 | 20.72 |
| | 0.060 | 149.35 | 23.86 |
| Sine-like wave | 0.000 | 196.00 | 0.00 |
| | 0.030 | 178.61 | 8.87 |
| | 0.042 | 165.59 | 15.52 |
| | 0.049 | 152.11 | 22.39 |
| | 0.054 | 138.18 | 29.50 |
The failure mode of tensile specimens containing fiber waviness can be divided into four stages: initial loading, crack appears at the apex of waviness, crack propagation, entirety breakage (figure 12). It can be seen from figure that the position of initial crack is the contact area between the 90° ply and the apex of the waviness, and then the crack gradually propagates in each layer. Finally, the specimen fails as a whole with fiber fracture.

4.3. Influence of magnitude factor of fiber waviness on compression properties
The load displacement curve of the compression specimens is shown in figure 13(a). It can be seen from the figure that the compression curve has obvious curvature change with a curvature inflection point, which is caused by the stress relief during compression. The inflection point corresponds to the position where the delamination appears and the stress relief happens. The influence of out-of-plane fiber waviness on the compression strength of laminate is shown in figure 13(b). The compression strength of defect-free specimen is 211.28 MPa. With the increase of magnitude factor of the waviness, the compression strength of specimens with sine wave and sine-like wave shows a gradual decrease trend. When the magnitude factor of sine wave is 0.06, the compression strength of specimen is 154.56 MPa and the strength ratio decreases to 73.15%. When the magnitude factor of the sine-like wave is 0.054, the compression strength of the specimen is 142.31 MPa and the strength ratio is reduced to 67.36%. The influence trend of sine-like specimens obtained in tensile test and compression test is similar to specimens with sine wave, but the mechanical properties are less than sine wave.
Obviously, the effect of magnitude factor on the compression properties is greater than that on the tensile properties. The detailed compression strength of specimens with different magnitude factor is shown in Table 6.

The actual compression failure mode corresponds to the load displacement curve. The compression test of specimens with out-of-plane waviness can be divided into three stages from initial loading to final fracture failure: fiber compression in fiber waviness, delamination initiation at the apex of out-of-plane waviness, and entirety breakage (Figure 14). In the initial stage of loading, the specimen does not first produce cracks in the $90^\circ$ ply, but first produces cracks in the apex area of waviness. With the gradual increase of compression load, the delamination continues to expand and laminate eventually fail with kink band and fiber fracture.

Through the influence analysis of magnitude factor on the mechanical properties of laminate, it can be seen that when magnitude factor of the fiber is lower than 0.03, the reduction rate of tensile and compression strength of the laminate is less than 10%, and the number of corresponding gaps/overlaps is no more than 2. Therefore, with the purpose of realizing the high quality and efficient laying of complex composite components, based on the results presented above, the actual magnitude factor should be controlled under 0.03 for good performance of composites, via trajectory adjustment in AFP process, such as ply-staggering method and cutting strategy of fiber tows.

### 5. Conclusion

Through theoretical and experimental methods, the influence mechanism of fiber out-of-plane fiber waviness induced by the gaps and overlaps on the mechanical properties of laminates is studied, and the following conclusions are obtained:

1. For different layups, the proposed longitudinal elastic modulus prediction model is basically consistent with the experimental data. The out-of-plane fiber waviness induced by gaps and overlaps will reduce the
axial modulus of composites, which will affect the tensile and compression properties of composite laminates.

(2) Observation of the fiber morphology shows that when the defect width is 6.35 mm, the fiber waviness presents a sinusoidal distribution. When the defect width increases, the fiber morphology tends to have a half-sine curve distribution at both ends of the fiber, and a flat area in the middle. The influence mechanism of mechanical properties of sine wave is similar to that of sine-like wave, mainly because the linear section of sine-like wave can still play a bearing role, while curve area at both ends of sine-like wave caused by wider defect width (12.7 mm) can be spliced into a sine wave. The magnitude of sine-like wave is close to that of sine wave, so it has a close influence on the mechanical properties of composite laminates. It is a feasible method to analyze the spliced curve of sine-like wave.

(3) The apex area of the waviness is a stress concentration area, where initial cracks are likely to occur. According to the failure analysis of the tensile test and the compression test, the laminate first cracks at apex of the fiber waviness, and then the crack gradually expands. Finally, the specimen fails as a whole with fiber fracture and delamination.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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