EFFECT OF ORIENTATION AND APPLIED STRESS ON GFRP LAMINATE'S COMPLEX MODULUS AND DAMPING

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Over the past few decades, glass fiber reinforced polymer (GFRP) as a new composite building material has been widely used in the field of civil engineering. Although the performance under static loading has been studied wildly, the experimental, and analytical research of its dynamic response is still not enough. As an anisotropic viscoelastic material, the dynamic performance of GFRP is quite different from that of traditional materials. Therefore, both material and member dynamic studies need to be carried out to get more data for FRP bridge design. This study aims to investigate the dynamic characteristics of GFRP laminates using experiments. Impact tests and non-resonance method tests were performed to determine the main dynamic parameters in this research. The GFRP laminate specimens were divided into different groups with variables that may have an impact. The dynamic characteristics of interest are damping ratio, complex modulus, and loss factor, while the possible influencing factors variables include fiber orientation and applied initial stress. Through the comparison of the results obtained from different groups, whether those of the above factors would affect the laminates' dynamic properties, as well as the influence pattern of each factor, was figured out. Also, through the analysis of the data, the method to control or adjust each parameter according to actual design requirements was been shown. In addition, with consideration that a high damping ratio is a desirable property in the structural application for vibration control, some advice was put forward to optimize the factor and improve the GFPR laminate dynamic performance according to experimental results.

Key Words: *damping ratio, natural frequency, GFRP, applied stress, loss factor, complex modulus, the effect of fiber orientation*

1. INTRODUCTION

Compared with traditional construction materials, glass fiber reinforced polymer (GFRP) is gaining more and more popularity in the field of civil infrastructure for its high specific strength, corrosion resistance, and lightweight. In recent years, the number of buildings and bridges manufactured with FRP profiles, especially pedestrian bridges, and small water gates, has increased remarkably. In the application of pedestrian bridges, one of the main design requirements is user comfort, for which the dynamic properties of the material are extremely important.

Generally, in the specific case of pedestrian bridges, the design is often not only governed by vibration frequency standards for vibration control and resonance prevention, but parameters such as dynamic acceleration response and damping ratios are also important parts of the comfort examination in the design process. However, due to inadequate research on the dynamic characteristics of GFRP, the current guidelines for GFRP pedestrian bridges do not provide detailed information on the material damping used in the dynamic analysis and design of the structures. [1-2] Therefore, to be able to design GFRP pedestrian bridges comprehensively, it is necessary to have an in-depth understanding of the dynamic characteristics at the material level.

In terms of past studies, Treviso, et al.[3] concluded that at the micromechanical level, studies addressing the dynamic characteristics of composites can be affected by fiber type, orientation, content; geometry, temperature, and frequency. Regarding the relevant studies of fiber orientation, Adams and Bacon[4] investigated the effect of fiber orientation and laminate geometry on the bending and torsional damping of CFRP composites, and present that the damping maximum will be gained at 35° in flexure and around 45° in torsion in the unidirectional case. The effect of stacking order was analyzed by Ohta et al.[5] who observed the different convergence achieved by different plate theories when changing the layup. They revealed that in addition to being related to the overall fiber orientation, the damping ratio was also related to the order of plate stacking. Abderrahim et al.[6] tried to use FEA to analyze the effect of fiber orientation on the damping ratio of unidirectional GFRP laminates beam with one end fixed in a different frequency. In their case, the maximum damping is observed in 60° unidirectional glass fiber composites, and it was revealed that the damping increased accompanying frequency. However, how the dynamics of GFRP laminates under applied stress will be further influenced by the fiber orientation has not been investigated. Considering that the applied initial stress in the structure affects the stiffness of the structure and thus changes the dynamic properties of the structure[7], the analysis of the initial stresses and damping relationship also needs to be carried out.

In addition, given that as a viscoelastic material, the stiffness behavior of FRP varies with frequency directly affecting the modal characteristics of the structural system, leading to complex vibration modes and differences in relative vibration phases.[1] Compared with traditional construction material, the viscoelasticity of GFRP may impose additional requirements for consideration in the design phase of structural development; and its viscoelasticity may also enable structures to be subjected to dynamic loads without additional structural damping elements, but only material damping[8]. Considering these differences with conventional materials, it is necessary to investigate the viscoelastic characteristics of GFRP laminates as well.

Therefore, to gain a deep understanding of the dynamic characteristics of the material and enrich relevant research data, this study investigated the dynamics parameters such as damping ratio, natural frequency, and loss factor of GFRP laminate beams with two fixed ends experimentally. The effect of two variables of fiber orientation and initially applied stress on the dynamic parameters is discussed.

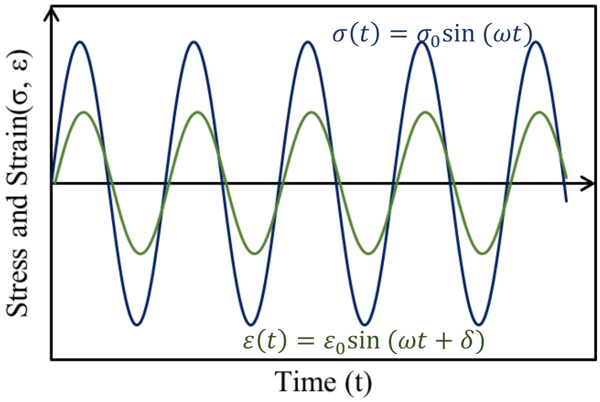

Fig.1 Stress and strain curves in the time domain.

2. THEORETICAL BACKGROUND

(1) Determination of viscoelastic properties

The viscoelastic analysis was performed according to the "Non-resonance Method" of ISO 6721-4[9], where data on loss factor and complex modulus were obtained in the tensile mode.

In this method, two end-fixed specimens will be subjected to sinusoidal cyclic forces to obtain stress and strain curves in the time domain (as shown in **Fig.1**). Due to the viscoelastic property of the GFRP laminates, there will be a phase difference, δ, between the stress and strain curves. Through the stress curve and strain curve, the complex modulus can be expressed as:

$$E^* = E' + iE'' \tag{1}$$

where the real part represents the storage modulus and the imaginary part represents the loss modulus, respectively.

$$E' = \frac{\sigma_0}{\varepsilon_0}\cos(\delta) \tag{2a}$$

$$E'' = \frac{\sigma_0}{\varepsilon_0}\sin(\delta) \tag{2b}$$

And the loss factor is defined as:

$$\tan(\delta) = \frac{E'}{E''} \tag{3}$$

(2) Identification of Modal Properties

Identifying the modal properties of an existing structure is a so-called inverse problem formulated by a non-homogeneous dynamic equilibrium equation represented by the relationship between response and excitation in the time or frequency domain[10]. In a system with separated natural frequencies, modal decoupling transforms the N coupled dynamic equilibrium equations into N decoupled single degree of

Table 1 Static properties of specimens in a different group.

Fiber Orientation	Tensile Strength (MPa)	Elastic Modulus (GPa)
$[0/90]_s$	280.74	22.39
$[15/105]_s$	159.35	17.80
$[\pm 45]_s$	106.23	12.68

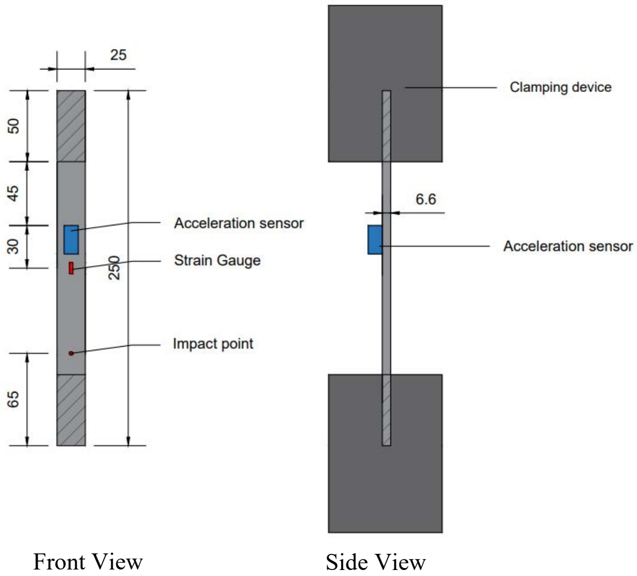

Fig.2 Specimen dimension and experimental setup.

freedom (SDOF) equations, N being the number of vibrational modes to be identified[2].

In order to identify the modal characteristics, this case used a frequency-based approach to determine the frequency response function (FRF) constructed from the ratio between spectral density functions of the applied modal force and the resulting modal response, which is defined as:

$$H(\omega) = \frac{X(\omega)}{F(\omega)} \quad (4)$$

where $X(\omega)$ and $F(\omega)$ are the Fourier transforms of the response and excitation, respectively.

To gain the damping ratio of the GFRP laminate specimens, the half-power bandwidth method was used. In this method, the damping ratio of each mode is derived from the difference between two frequency values with a decrease in amplitude near the resonance point in the frequency response function, namely, from the following equation:

$$\xi_n = \frac{f_b - f_a}{2f_n} \quad (5)$$

where f_n the natural frequency of the nth mode, f_a and f_b the frequencies corresponding to an amplitude of $f_n/\sqrt{2}$.


Fig.3 Impact test.

3. EXPERIMENTAL DETAIL

(1) Characteristics of the Material and Specimens

The GFRP specimens used in the experimental program were extracted from a GFRP laminate sheet made of woven roving with the same amount of fibers in the two orthogonal directions and unsaturated polyester resin. By varying the cutting direction, three groups of specimens with different fiber orientations were fabricated, which are $[0/90]_s$, $[15/105]_s$, and $[\pm 45]_s$, respectively. To ensure the feasibility of the experiments, three specimens were prepared for each group of fiber arrangement directions.

The dimension of specimens was chosen as 250 mm × 25 mm × 6.6 mm. **Table 1** shows the static material properties of the specimens with different fiber orientations.

(2) Test Setup and Procedure

As shown in **Fig.2**, during the experiment, each end of the GFRP laminate specimen had 50 mm fixed at the clamp of an MTS material testing machine. The non-resonant cyclic loading and initial static stresses to the specimens are also realized by this machine. Strain gauges were attached to the center of both sides of the specimen to record the strain changes in the longitudinal direction. In addition, the experiments were performed under room temperature and humidity conditions.

a) Non-resonance method test

Before the experimental procedure of the Non-resonance method, a static tensile force was first applied to the specimen to avoid buckling. Then, from the test beginning, a sine-wave cycle was applied to the two-end fixed laminate specimen at a frequency of 1 Hz.

The stress changes in the specimen were obtained from the load measured by the MTS loading machine, and the strain variations were measured by strain gauges affixed, while the data were recorded

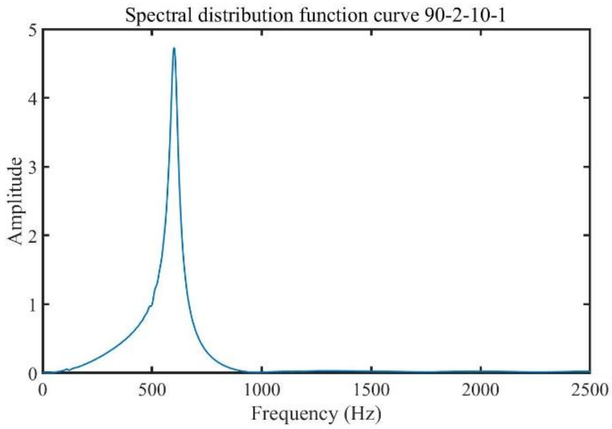

Fig.4 An example of Spectral distribution function curve gain from FFT.

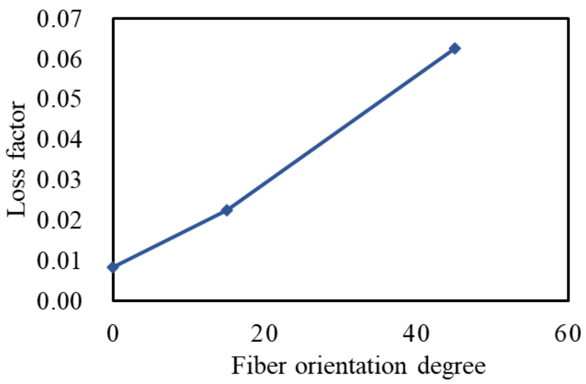

Fig.5 Variation of loss factor with fiber orientation degree

Table 2 Viscoelastic parameters of each group of specimens at room temperature.

Fiber orientations	[0/90]	[15/105]	[±45]
Loss Factor	0.0083	0.0225	0. 0626
Storage Modulus (MPa)	20.24	15.10	9.68
Loss Modulus (MPa)	$0.167i$	$0.241i$	$0.606i$

by a dynamic data logger. To avoid the change of viscoelastic properties due to the increase in specimen temperature caused by cyclic loading, the number of cycles was set to 30 times.

b) Impact test

Aiming to investigate the effect of initial stress on the damping of GFRP laminate specimens with two fixed ends, the impact tests on the specimens were carried out in the state of being applied with uniaxial tension. In the states of no applied tensile force and applied initial stress of 1%, 5%, 10%, 20%, and 40% of tensile strength, the damping ratios of the specimen with different fiber orientations were measured.

As shown in **Fig.3**, an NP-2120 accelerometer sensor was fixed to the surface of the specimen with double-sided tape for response measurement, and a GK-3100 hammer was used to excite the free vibration of the GFRP laminate specimen by hitting. After being hit, the response of the specimen was measured by the accelerometer, and the acceleration signal was recorded by a data logger with a sampling frequency of 5,000 Hz.

Spectral distribution curves of the specimens were obtained by performing Fast Fourier Transformation (FFT) through the Matlab program. **Fig.4** shows an example of the spectral distribution curve obtained by a set of impact tests. Moreover, to ensure the accuracy of the experimental data, the hit was repeated three times in each impact test, and the experimental results were given by the average of the three sets of data.

4. RESULTS AND DISCUSSIONS

Through the analysis of the stress-strain relationship under the non-resonance method test and the free vibration response under the impact test, the dynamic parameters of the three groups of GFRP laminate specimens with different fiber orientations varying a level of initial stress are shown in **Table 2**, and **Figs.5** to **9**.

(1) Loss factor

In the non-resonance method test, the mathematical expressions of specimens' strain and stress time domain curves were acquired from a curve fitting program in Matlab. This program is based on the Bisquare weights method to find a curve that fits the input data using the least-squares approach while minimizing the effect of outliers. After obtaining the mathematical function, the loss factors and complex moduli of the specimens were derived from Equations (1) to (3), and the variation of the values in different fiber directions is shown in **Table 2** and **Fig.5**.

As can be seen from the table, among the three groups of specimens, the $[\pm 45]_s$ set of GFRP laminates has the largest longitudinal loss factor while the $[0/90]_s$ set has the smallest.

(2) Natural frequency

The first-mode transverse free vibration frequencies of three groups of two-end fixed GFRP laminate beams with different fiber orientations were investigated. As shown in **Figs.6** and **7**, for GFRP laminates with the same initial stress condition, those with a fiber orientation of 0/90 exhibit the largest first mode natural frequency. Considering the dimension of the specimens are identical, this can be explained by their

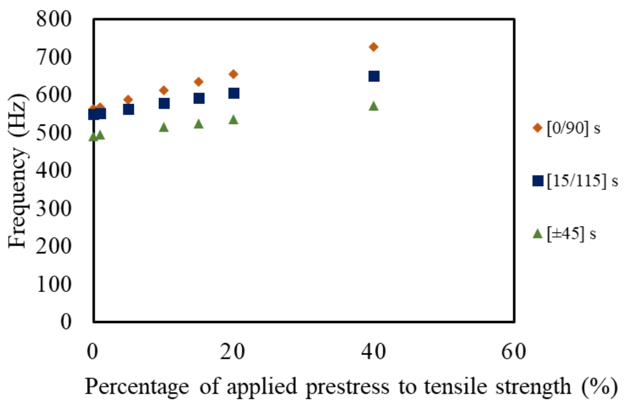

Fig.6 The variation of the first-mode flexural frequency with initially applied stress.

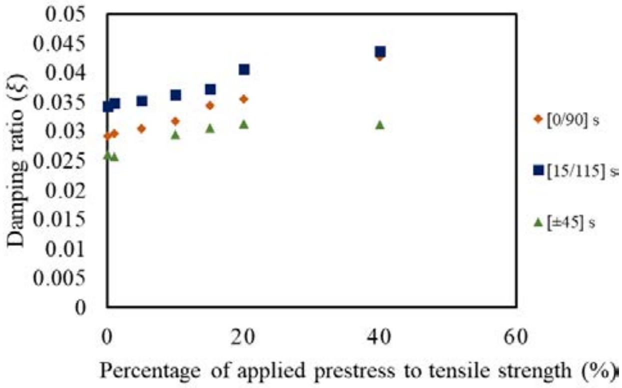

Fig.8 The first-mode flexural damping ratio variation with initially applied stress.

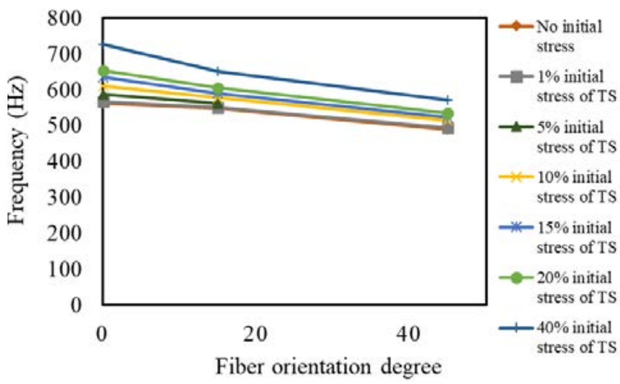

Fig.7 The variation of the first-mode flexural frequency with fiber orientation degree.

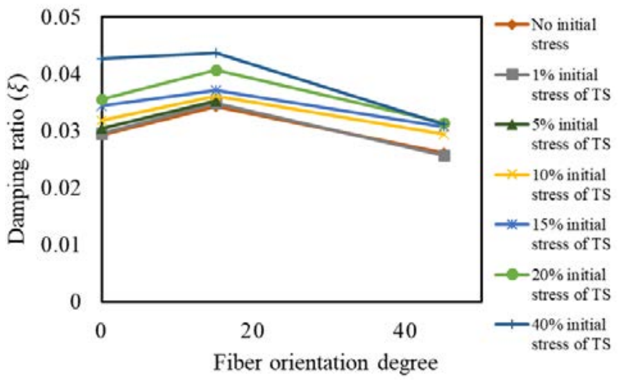

Fig.9 The first-mode flexural damping ratio variation with fiber orientation degree.

maximum tensile elastic modulus.

All three groups of specimens exhibited an increase in natural frequencies with the increase in initially applied stress. It is noteworthy that the three groups of laminates do not have the same increasing rate of flexural vibration frequency with increasing applied stress. The natural frequency of the group with 0/90 fibers changed significantly faster with initial stresses than in the other two groups. In this case, the average growth rate of the natural frequencies in the $[0/90]_s$ group, accompanied by an increase in the initial stress, was roughly 5%, compared to about 3% for both the $[\pm45]_s$ group and $[15/105]_s$ group. But the reason for this difference needs to be further investigated.

(3) Damping ratio

The damping ratios in this study were calculated in the first flexural vibration mode. As shown in **Figs.8** and **9**, the damping ratios of all three groups of GFRP laminate specimens increased with the increase of initially applied stress.

In terms of the rate and proportion of increment, the damping ratio of the GFRP laminates with a fiber orientation of 0/90 increased the fastest with the increase of the initially applied stress, and the proportion of increment was also higher than in the other two groups. Compared to the case without initial stress applied, the damping ratio increased by about 46% when 40% of the tensile strength initial stress was applied, while the damping ratios of the $[15/105]_s$ group and $[\pm45]_s$ group's specimens increased by only 28% and 19%.

Furthermore, by comparing the effects of the two variables on the damping ratios of the specimens, it is found that the effect of the initial stress is greater than the effect of the fiber orientation. Under any initial stress conditions, the increase in the damping ratio of the system that can be achieved when changing only the fiber orientation is ranging from 10% to 30%, while when changing the initially applied stress, the increase in damping ratio can be more than 45%.

5. CONCLUSION

The effect of fiber orientation, as well as applied stress on the dynamic parameters of GFRP materials, was investigated by conducting experimental studies on GFRP laminate beams with two fixed ends.

Firstly, in terms of loss factors, the case of this study demonstrates that fiber orientation affects the loss factor, and the GFRP laminates of the $[\pm45]_s$ group show the largest loss factor in this case.

Secondly, the experimental results show that the fiber orientation has a significant effect on the damping ratio, natural frequency of the flexural free vibration, and loss factor in the longitudinal direction of the GFRP laminate. In this case, the GFRP laminate of the $[0/90]_s$ group has the largest natural frequency of vibration, the $[15/115]_s$ group has the largest damping ratio under the conditions of both no initial stress and initially applied stress, and the GFRP laminate of $[\pm45]_s$ group has the largest longitudinal loss factor.

In addition, by varying the initial stress of the specimen, it was found that the damping ratio of GFRP laminate with the fiber orientation of the 0/90 group has the highest rate of increase and the largest percentage of increase as the initial stress rises in this case.

Finally, according to the experimental results, the damping ratio and vibration frequency of GFRP can be changed by changing the fiber orientation and the initially applied stress. Therefore, on the one hand, during the design process, it should be taken into account that the natural frequency, as well as material damping ratio, will change when the initial stress happens. On the other hand, in the case where the damping ratio of GFRP material needs to be improved, changing the arrangement ratio of fiber orientation can be a good approach. However, although the investigation of the GFRP dynamic parameters in this study exhibited a series of patterns, the specific reasons for the variation trends in the damping ratio and loss factor demonstrated by the experimental results are still difficult to explain due to the complexity of the composite dynamics performance, which requires further investigation.

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(Received August 26, 2022)