Study on hysteretic behavior of concrete CFRP specimen

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Abstract

In order to study the hysteretic behavior of concrete CFRP specimen under different influence factors, 12 specimens were designed. By consulting related literature, the research progress and main results of concrete-wrapped CFRP at home and abroad in recent years are summarized, and the accurate solution calculated by the multi-scale method and the error of the experimental value are verified by MATLAB. The non-linear vibration generated by the hysteretic performance under the action of wind excitation is introduced, which provides a certain reference for the later research.

Introduction And Research Significance

Non-linear motion is widespread in nature. This is an extremely complex form of motion. Since humans discovered the existence of these vibrations, on the one hand, they began to limit and prevent the harm caused by them, and on the other hand, they must try to use useful vibrations [1 -2]. In recent years, my country has made great progress in infrastructure construction. Various beautiful and durable bridges abound. As a key node of the transportation network, the safety, durability and applicability of bridges are of concern to everyone. Therefore, the prediction of the response of the bridge under random moving loads is of great significance to engineering practice. However, large-span bridges are also prone to damage under the excitation of wind loads. The collapse of the Tacoma Bridge occurred in the United States in 1940, and the Humen Bridge was abnormally moved in my country in 2019. Through later investigation, it is found that these engineering problems are caused by the nonlinear flutter of the bridge under the action of wind load [3]. In response to such problems, only corresponding studies were carried out in the 1970s. In 1971, Tomko [4] through the wind tunnel test, for the first time proposed that flutter has a direct relationship with the material, which is the flutter coefficient, and established a nonlinear dynamic expression with 6 different flutter derivatives on the basis of the experiment. Matsumoto [5] studied the flutter problem in more detail in the 1990s, and classified flutter into coupled flutter, low-speed flutter, high-speed flutter, and speed-limited flutter. For the problem of nonlinear flutter, domestic research has also been carried out, especially in the past 20 years. In 2006, Dai Yuzhong [6] studied Lyapunov's nonlinear research on long-span bridges. Zhao Yan [7] studied the chaos phenomenon of long-span bridges in 2003, and explained the importance of studying chaos to long-span bridges. At the same time, he also put forward the limitation of long-span bridge research, that is, it is impossible to achieve large-amplitude test conditions. The calculation of the wind speed, and the more accurate displacement.

At this stage, with the progress of research, my country's non-linear flutter research on long-span bridges has become more in-depth. The current research is mainly divided into two aspects, one is the research of chaotic motion. Zhang Mingjie [8] conducted a wind tunnel test to study the chaotic motion of a long-span bridge under wind loads, and established a corresponding model to study its wind-induced effects in detail. Liu Kaixuan [9] studied the study of wind excitation on the cross-section of long-span bridges, and studied the influence of chaotic motion from the inside of the structure. Zhang Haoqing [10] studied the performance of large-span steel box girder under the action of chaos. On the other hand, some scholars have studied the influence of different wind angles on bridges. In addition to chaotic motion, the

flutter of long-span bridges under different wind angles can also be calculated by other classical nonlinear methods. Wang Huafeng [11] used a multi-scale method to study the impact of turbulent wind on long-span bridges.

From the research of bridge flutter in recent years, it can be seen that with the continuous development of bridge engineering construction, the bridge structure has gradually developed in the direction of flexible and light long-span. Although this design method has improved the aesthetics of the bridge structure, it has And construction puts forward higher requirements. The wind-resistant design of these bridges is more challenging, and the wind-resistant stability problems caused by their nonlinear effects will be more prominent. Therefore, the development of nonlinear flutter calculation theory and method suitable for super long-span bridges is an urgent need for the development of current bridge engineering.

The study found that when the span continues to increase, the increase in bridge deck length gradually transforms into a flexible structure, and the stiffness is significantly reduced, resulting in a decrease in damping. This makes it easier for long-span bridges to produce nonlinear vibrations, especially when subjected to some external excitations, including wind. If these factors are not taken into account during excitation, rain excitation, earthquake excitation, car passing and support changes, it is very easy to cause the structure to collapse and fail. In 1940, the Tacoma Bridge in the United States collapsed only under the action of a level 8 wind. The accident report showed that this was due to the non-linear flutter generated by the bridge during the design process of the Tacoma Bridge. The 35° torsion eventually caused the suspension cables on the bridge to be broken, causing the overall collapse. At this stage, some scholars have studied the nonlinear performance of long-span bridges through wind tunnel tests and adopting traditional nonlinear theories. By consulting relevant information, most of the main causes of engineering accidents for long-span bridges are largely related to wind excitation, and the impact of wind excitation mainly needs to consider the impact of turbulent wind. In addition, the nonlinear flutter of the bridge has a direct relationship with chaotic motion. As a relatively new concept, chaotic motion was first proposed in a paper by Ruelle and Takens [12] in 1971. . At present, the main methods used to deal with the chaotic phenomenon are: qualitative analysis and quantitative analysis. The former analysis methods mainly include the Poincare section method and the power spectrum method, while the latter mainly include the saturated associative dimension method and the Lyapunov exponent method.

This paper is based on the engineering problem of long-span bridge nonlinear vibration, by consulting related materials, referring to related literature, and briefly analyzing it on the basis of the calculation results of the multi-scale method, and using the chaotic analysis method to briefly analyze the chaotic motion of the long-span bridge analyze.

Analysis Of Chaotic Motion Of Long-span Bridges

1.1 Brief description of chaotic motion

Chaotic motion is a mathematical concept that is difficult to define precisely. Chaos studies deterministic motion. Earlier research only focused on linear models and special integrable nonlinear models. With the

popularization of computers, more precise studies have been conducted on complex nonlinear motions including chaotic motions. Compared with other complex phenomena, chaotic motion has its own unique characteristics: the nonlinear dynamic characteristics of chaos determine that chaos is unpredictable, and the sensitivity of chaos to the initial value shows that it is difficult to predict it. For a chaotic dynamic system, the initial conditions can cause significant differences between the numerical trajectories after a long period of simulation. In addition, Lorenz research shows that the Lyapunov exponent changes between negative and positive values even if the time step is small. In the chaotic process of a long-span bridge, when monitoring its sensitivity, it will be found that part of the information will be lost every time it is predicted. As the number of predictions increases, its accuracy is significantly reduced, so chaos is not suitable for long-term prediction. Therefore, Teixeira et al. [12] further studied the time step sensitivity of three nonlinear models using traditional double-precision atmospheric models. Their conclusion shows that "for chaotic systems, numerical convergence cannot be guaranteed forever."

Through some documents, it can be found that the large-span bridge is prone to chaotic motion under the action of wind load. In this paper, the Poincare cross-section method and power spectrum method are used to briefly qualitatively analyze the chaotic motion of long-span bridges.

1.2 Analyze the chaotic motion of the bridge

1.2.1 Poincare section method

The Poincare section method mainly selects a cross-section appropriately in the multi-dimensional phase space. After the system is continuously mapped, different forms of phase points or phase gauge lines can be observed on the Poincare section. According to the topological properties, the periodic motion, quasi-periodic motion or Chaotic movement.

The main idea and analysis method of this kind of method is basically qualitative analysis. It is given by the following state equation. We know that this system has an unstable limit cycle with a radius of 1, as shown in Figure 1.

$$\begin{aligned}\dot{x}_1 &= -ax_1 + x_2 + ax_1(x_1^2 + x_2^2), \\ \dot{x}_2 &= -x_1 - ax_2 + ax_2(x_1^2 + x_2^2).\end{aligned}\tag{1}$$

Consider the nonlinear system. Fig. 1a shows a trajectory of $a=1$, and Fig. 1b shows the case of $a=0.2$. In drawing these figures, two sets of initial conditions were used. The first group of conditions is outside the system limit cycle, and the second group of conditions is inside the system limit cycle. In both cases, the trajectory tends to escape the limit loop. The constant a in the equation cannot change the nature of the phase, but its value is valid for the speed at which the flow escapes the limit cycle.

It can be seen that the graph drawn by the phase plan has a complicated form, and the Poincare mapping shows a strangely attractive form. The analysis shows that when $a=1$, the system has stronger divergence, on the contrary, when $a=2$, the system has stronger cohesion.

In the same way, the nonlinear flutter problem of long-span bridges is analyzed according to this type of method. Yan Cong [14] used wind tunnel tests to build a scaled-down suspension bridge to study the changes in the flutter of the bridge under different wind conditions. The phase diagrams of the bridge when the wind speed is 98m/s and 94.4m/s are tested respectively. And compare this result with the mid-span displacement under the action of two wind speeds. Under the action of two wind speeds, the phase diagram of the bridge is shown in Figure 2.

According to the judgment method of Poincare section method, it can be seen that when the wind speed is 98m/s, the bridge has obvious divergence characteristics. It shows that when the wind speed reaches 98m/s, the long-span bridge is more prone to damage.

1.2.2 Power spectrum method

Spectrum analysis is generally used together with Poincare section method, but the analysis objects of the two are different. The spectrum analysis object is a discrete point sequence generated by point mapping, using Fourier analysis. In addition, when Poincare analyzes chaotic motion, it is distributed as infinite points in a certain area, and the point sequence of the spectrum is continuous. For the analysis of the spectrogram, it mainly analyzes the duration of the sample process and the change of the total number of points. When the extension time of the sample process is longer and the interval is smaller, the spectral lines will be encrypted, and the correctness of the real physical process is better. This is because the interval between the spectra is $2\pi/T$, and as T increases, the spectrum is encrypted.

Sun Qian [14] took Changde Baima Lake Hongqiao as a research project. The site map is shown in Figure 3. An acceleration sensor is set at the fifth span, and the field dynamic experiment is carried out using the frequency spectrum method. The measured frequency spectrum is shown in Figure 4.

According to the spectrum analysis method, it can be seen that the flutter of the bridge is a chaotic motion. In addition, the frequency in the early stage of the test is relatively dense, indicating that the bridge's early stability is better, but as the test progresses, the frequency gradually stabilizes, indicating that the structure is relatively stable during the test period.

Partial Nonlinear Vibration Method

2.1 Multi-scale method and harmonic balance method

The multi-scale method was first proposed in 1957. The difference from other methods is that it introduces "slower" time variables, treats these variables as independent, and introduces a small parameter ϵ , and expands according to the Taylor series. The approximate solution is solved according to the value of the input. The more series that are expanded, the more accurate the solution, instead of

setting it as a variable according to the other methods. According to the multi-scale method, the values in each time state are solved separately, and then the equations of each order of ε can be established according to the perturbation method.

The harmonic balance method assumes that the solution of the nonlinear equation is the superposition of harmonics, and then substitutes the solution of the equation to cancel the sine and cosine in the equation, simplifying the difficulty of the equation, and making it easier to obtain the solution of the equation.

Wang Huafeng used wind tunnel tests to study the nonlinear vibration of long-span bridges under turbulent wind. It simplified the main span of the long-span bridge into a rectangular plate structure, established the dynamic equation after dimensionless, and then used the multi-scale method to obtain the nonlinear vibration equation, and studied the effect of turbulent wind on the structure. The nonlinear differential equation established by it is shown in equation (2) [11]:

$$\begin{aligned}
 & a_{1,i} f_1 \ddot{q}_i + \frac{1}{4} \pi \bar{\rho} \lambda_1 \{ 1.8 k_{1,j} f_3 q_i \ddot{q}_j + [2 p_{1,jm} + g_{1,jm} - r_{1,jm} - 2 s_{1,jm} + 2(a_{1,jm} \\
 & + b_{1,jm} + c_{1,jm})] f_3 q_i q_j \ddot{q}_m \} + a_{1,i} f_1 \zeta_1 \dot{q}_i - \pi R_2 P \lambda_1^2 \left(-\frac{3}{2} d_{1,jm} - \frac{1}{2} g_{1,jm} + A_{1,jm} \right. \\
 & + B_{1,jm} + \frac{1}{2} C_{1,jm} - D_{1,jm} - E_{1,jm} - \frac{1}{2} F_{1,jm} \left. \right) f_3 q_i q_j \dot{q}_m + \frac{1}{2} \pi \bar{\rho} \lambda_1 [0.45 k_{1,j} f_2 \dot{q}_i \zeta_1 \\
 & + (3 G_{1,jm} + h_{1,jm} + \frac{1}{2} H_{1,jm} + 3 K_{1,jm}) f_3 q_i \dot{q}_j \dot{q}_m + (L_{1,jm} - 2 s_{1,jm}) f_3 \dot{q}_i q_j \dot{q}_m \\
 & + O_{1,jm} f_3 q_i q_j \dot{q}_m] + \pi R_2 P [0.9 \lambda_1 (a_{1,j} + b_{1,j}) f_2 q_i \dot{q}_j - b_{1,i} f_1 \dot{q}_i] - [\frac{3}{2} \lambda_1^4 P_{1,jm} f_3 \\
 & + \frac{3}{2} \lambda_2^4 Q_{1,jm} f_4 + \frac{1}{2} \lambda_1^2 \lambda_2^2 (g_{1,jm} f_5 + p_{1,jm} f_6 + 4 p_{1,jm} f_5)] q_i q_j q_m + \frac{1}{12} (\lambda_1^4 c_{1,i} \\
 & + \lambda_2^4 a_{1,i} f_7 + 2 \lambda_1^2 \lambda_2^2 d_{1,i} f_8) q_i - \frac{1}{2} \pi R_1 P^2 \lambda_1 [d_{1,i} f_1 q_i + 0.9 \lambda_1 (c_{1,j} + \frac{1}{2} d_{1,j}) \cdot \\
 & f_3 q_i q_j] + \frac{1}{4} \pi R_1 P^2 \lambda_1^3 (2 P_{1,jm} + 2 R_{1,jm} + 2 S_{1,jm} + T_{1,jm}) f_3 q_i q_j q_m = 0
 \end{aligned} \tag{2}$$

Solve according to the multi-scale method, introduce a small parameter ε , because its value $\varepsilon \ll 1$, it can be transformed as equation (2) [11]:

$$\left\{ \begin{array}{l}
\beta_1 = \varepsilon\beta_1; \beta_2 = \varepsilon\beta_2; \beta_3 = \varepsilon\beta_3; \beta_4 = \varepsilon\beta_4; \beta_5 = \varepsilon\beta_5; \beta_6 = \varepsilon\beta_6; \beta_7 = \varepsilon_1 \\
\beta_8 = \varepsilon\beta_8; \beta_9 = \varepsilon\beta_9; \beta_{10} = \varepsilon\beta_{10}; \beta_{11} = \varepsilon\beta_{11}; \beta_{12} = \varepsilon\beta_{12}; \beta_{13} = \varepsilon\beta_{13}; \\
\beta_{14} = \varepsilon\beta_{14}; \beta_{15} = \varepsilon\beta_{15}; \beta_{16} = \varepsilon\beta_{16}; \beta_{17} = \varepsilon\beta_{17}; \beta_{18} = \varepsilon\beta_{18}; \\
\beta_{19} = \varepsilon\beta_{19}; \beta_{20} = \varepsilon\beta_{20}; \beta_{21} = \varepsilon\beta_{21}; \beta_{22} = \varepsilon\beta_{22}; \beta_{23} = \varepsilon\beta_{23}; \\
\beta_{24} = \varepsilon\beta_{24}; \beta_{25} = \varepsilon\beta_{25}; \beta_{26} = \varepsilon\beta_{26}; \beta_{27} = \varepsilon\beta_{27}; \beta_{28} = \varepsilon\beta_{28}; \\
\beta_{29} = \varepsilon\beta_{29}; \beta_{30} = \varepsilon\beta_{30}; \beta_{31} = \varepsilon\beta_{31}; \beta_{32} = \varepsilon\beta_{32}; \\
\gamma_1 = \varepsilon\gamma_1; \gamma_2 = \varepsilon\gamma_2; \gamma_3 = \varepsilon\gamma_3; \gamma_4 = \varepsilon\gamma_4; \gamma_5 = \varepsilon\gamma_5; \gamma_6 = \varepsilon\gamma_6; \gamma_7 = \varepsilon\gamma_7; \\
\gamma_8 = \varepsilon\gamma_8; \gamma_9 = \varepsilon\gamma_9; \gamma_{10} = \varepsilon\gamma_{10}; \gamma_{11} = \varepsilon\gamma_{11}; \gamma_{12} = \varepsilon\gamma_{12}; \gamma_{13} = \varepsilon\gamma_{13}; \\
\gamma_{14} = \varepsilon\gamma_{14}; \gamma_{15} = \varepsilon\gamma_{15}; \gamma_{16} = \varepsilon\gamma_{16}; \gamma_{17} = \varepsilon\gamma_{17}; \gamma_{18} = \varepsilon\gamma_{18}; \\
\gamma_{19} = \varepsilon\gamma_{19}; \gamma_{20} = \varepsilon\gamma_{20}; \gamma_{21} = \varepsilon\gamma_{21}; \gamma_{22} = \varepsilon\gamma_{22}; \gamma_{23} = \varepsilon\gamma_{23}; \\
\gamma_{24} = \varepsilon\gamma_{24}; \gamma_{25} = \varepsilon\gamma_{25}; \gamma_{26} = \varepsilon\gamma_{26}; \gamma_{27} = \varepsilon\gamma_{27}; \\
\gamma_{28} = \varepsilon\gamma_{28}; \gamma_{29} = \varepsilon\gamma_{29}; \gamma_{30} = \varepsilon\gamma_{30};
\end{array} \right. \quad (3)$$

In the final solution, the values of a_1 and a_2 in the differential equation can be obtained to obtain the displacement value of the long-span bridge under the action of turbulent wind. In the calculation process, a nonlinear term is added to the initial differential equation, and the second-order approximate solution is obtained step by step through the multi-scale method. This type of approximate value is more accurate. For long-span bridges under the action of turbulent wind, the lateral displacement of the bridge can be obtained more accurately through the calculation of the multi-scale method. This is because the bridge has a large span and can be tested at different spans. The detected value is added to the nonlinear term in the function as much as possible. According to the core idea of the multi-scale method, the existence form: $\ddot{q} + f(q) = 0$, the solution of the equation is: $q = q_0 + x = q_0 + \varepsilon x_1 + \varepsilon x_2 + \dots$, move the origin to the center position $q = q_0$. So you can move all the monitored data of the long-span bridge to the center position to solve the maximum lateral displacement point.

Based on the research of literature [11], in order to verify the accuracy of the calculation results, it can be verified according to the more convenient harmonic balance method. According to the differential equation of equation (2), considering the simplest case for easy calculation, only the first harmonic can be retained, and the excitation vibration solution is set as shown in equation (4):

$$q = A \cos \omega t \quad (4)$$

Substitute equation (3) into equation (1), ignore the high-order harmonic term of the last term on the left side of the equation, and find the solutions of the two equations. Because this solution is still difficult to solve in the process of using the harmonic balance method, this paper has not solved it completely, and only proposes a verification idea for this solution.

Set up the MATLAB program and compare the results from the test with the results calculated by the multi-scale method. It can be seen that the error of the multi-scale method is small, and the deviation from the test value is not large.

Summary

This paper introduces chaos theory and some classical nonlinear theoretical methods. Based on the research results of reference, a brief analysis of the nonlinear flutter of long-span bridges is carried out. The analysis results are summarized as follows:

From the research in recent years, it can be found that the research on the nonlinear flutter of long-span bridges has made greater progress than before. Two qualitative and quantitative methods have been proposed for chaotic motion. And it can conduct field test on the bridge and compare it with theoretical test. For long-span bridges, because the multi-scale method moves the origin to the center position, all the monitored data of the long-span bridge can be moved to the center position to solve the maximum point of lateral displacement, so the multi-scale method can be used. Calculate the displacement change more accurately. In addition, this paper compares the data measured by its experiment with its calculation results, and finds that the calculation results of the multi-scale method are more accurate and have smaller errors. And it is proposed that a simpler harmonic balance method can be used for verification. By consulting the literature, it is found that the literature at this stage has less research on bridges with large torsional amplitude, and the development level of bridge nonlinear flutter analysis theory has certain limitations. With the construction of long-span bridges, bridge flutter will need to be dealt with in the future. Non-linear vibration theory such as vibration should be further studied.

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Figures

Figure 1

Phase diagram of the system [13]

Figure 2

Phase trajectory diagram (a) $v=94.4\text{m/s}$ (b) $v=98\text{m/s}$ [13]

Figure 3

The scene of Baima Lake Hongqiao [14]

Figure 4

The frequency spectrum [14]

Figure 5

Comparison of multi-scale method and experimental value