Fatigue Damage of Stayed Cables Due to Buffeting Induced by Eastern-Zhejiang Typhoon

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Abstract. In this paper, a 450 km simulation circle method is used to extract all meteorological records from 1949 to 2018, and to obtain random samples. The Yanneng typhoon wind field model is compiled by MATLAB, the optimal typhoon wind profile index $\alpha$ is calculated. The harmonic superposition method is used to simulate the typhoon wind field at the construction site. Stress time-history of cables under buffeting is analyzed using ANSYS and MATLAB. Palmgren-miner linear cumulative fatigue damage method is used for fatigue damage analysis, combined with rain flow counting method and S-N curve. It is shown that the damage value of cable increases with the growth of wind speed. The damage of cable has a similar trend with the variance of axial stress. The cable of middle span, about an eighth of the way to bridge tower, is extremely sensitive to the wind. The low stress region is the main circulating region of the cable. The region of low stress expands with the increase of wind speed. The amplitude of cable stress mainly circulates from low amplitude to high amplitude with the increase of wind speed.

Keywords. Stayed cables; fatigue damage; typhoon; buffeting; rain-flow counting method; characteristics of typhoon wind field.

1. Introduction
Studies have been carried out to estimate the wind-induced fatigue damage and long-term condition assessment of cable-stayed bridges and suspension bridges, such as the fatigue life estimation for Yangpu Bridge in Shanghai [1] and evaluation of typhoon induced fatigue damage for Tsing Ma Bridge in Hong Kong [2, 3]. The efficiency of hysteretic dampers in suppressing wind-induced vibrations is evaluated by Ali et al. [4]. These papers are focus on the evaluation of wind-induced fatigue damage of steel decks of long span bridges. Nevertheless, research on the typhoon induced fatigue damage of cables is rather limited. This paper presents the method to evaluate typhoon induced fatigue damage of stayed cables based on Eastern Zhejiang meteorological information, in which the climatic and tropical cyclone data of all typhoons in Zhoushan, Zhejiang Province from 1949 to 2018 are collected and analyzed. The harmonic superposition method is used to simulate the time history of wind speed in the direction of cross wind flow at the stay cables. The increment of fatigue damage due to typhoon is afterwards evaluated by applying the fatigue models based on the Miner’s law.

2. Characteristics and Numerical Simulation of Typhoon Wind Field

2.1. Analysis of Typhoon Wind Field Data
A field measurement system for wind load based on a wireless sensor network was developed for large-span roofs recently [5]. In this paper, the Dinghai station (Observation altitude is 35.7 m) in Zhoushan,
Zhejiang Province, China, is analyzed, the longitude and latitude of which are 30.02 N and 122.06 E, respectively. Data are taken from China Meteorological Science Data Sharing Service Network—China ground climate data international exchange station data set station information. The typhoon meteorological data are obtained from the “best tropical cyclone path data set for CMA-STI” [6]. With the Dinghai weather station served as the central position, using a simulated circle with a radius of 450 km, all meteorological records within this circle from 1949 to 2018 are adopted. Invalid data such as tropical storm, tropical depression, etc. are filtered out, and a total of 280 sets of typhoon records are extracted. Each group of files records the longitude position of the typhoon center, the latitude position of the typhoon center, the pressure of the typhoon center, the typhoon radius, the speed of the typhoon moving as a whole and the direction of the typhoon moving as a whole.

In this paper, wind speeds are calculated into two intervals. The first interval is from 1949 to 2012. The second interval is from 1949 to 2018. The first interval contains 242 data sets in the simulation circle and the second interval contains 280 data sets in the simulation circle. Adding eight years, the number of typhoons in the circle increases to 38 groups, which means that the number of typhoon impacts increases from an average of 3.78 to 4 per year, showing that the annual average number of extreme weather events is still in a process of increasing.

The latitude and longitude of typhoon center change periodically every ten years, and the latitude and longitude keep the same trend. The years are divided into a 10-year cycle of 70 years from 1949 to 2018, with the longitude distribution of each 10-year cycle showed in figure 1 and the latitude distribution of each 10-year cycle showed in figure 2. The probability density distribution of the typhoon center longitude and latitude between 1949 and 2018 are showed in figures 3-4. Latitude and longitude maintained the same trend in each decade, with the mean value rising and falling. In the next 10-year cycle, the average longitude probability will fall in the range below 123.2E, and the average latitude probability will fall in the range below 29.48N. The region within this range will be focused in the next decade.

Figure 1. Longitude distribution of typhoon center.

Figure 2. Latitude distribution of typhoon center.

The distribution maps of typhoon center pressure difference, typhoon radius of maximum wind, typhoon moving speed, and typhoon moving direction are obtained by probability and statistical analysis, which are showed in figures 5-8 respectively.
Figure 3. Longitude probability density of typhoon.

Figure 4. Latitude probability density of typhoon.

Figure 5. Probability density of pressure difference.

Figure 6. Probability density of typhoon radius.

Figure 7. Probability density of typhoon moving speed.

Figure 8. Probability density of moving direction.
The calculation of the probability parameters of each variable is showed in table 1. In general, the typhoon’s central longitude, central latitude, central air pressure, overall moving speed, radius of maximum wind and overall moving direction are chosen by the same distribution probability model. The mean square deviation of the parameters decreases with the increase of samples. The longitude probability of typhoon center is a normal distribution. The latitude of typhoon center is a log-normal distribution. The pressure difference of typhoon center is a log-normal distribution. The whole moving speed of typhoon is a normal distribution. The radius of maximum wind of typhoon is a log-normal distribution. The overall moving velocity of typhoon fits a bi-normal distribution.

Table 1. Typhoon probability distribution parameters.

| Probability distribution | Parameters               |
|--------------------------|--------------------------|
| Longitude position of Typhoon Center | Normal distribution  |
|                          | $\mu=123.2571$; $\sigma=1.5313$ |
|                          | Log-normal distribution  |
|                          | $\mu=4.8135$; $\sigma=0.1020$ |
| Latitude position of Typhoon Center | Normal distribution  |
|                          | $\mu=28.9632$; $\sigma=1.6903$ |
| Air Pressure in the center of Typhoon | Normal distribution  |
|                          | $\mu=47.2857$; $\sigma=12.6674$ |
|                          | Log-normal distribution  |
|                          | $\mu=3.8057$; $\sigma=0.2557$ |
| Overall moving speed of typhoon | Normal distribution  |
|                          | $\mu=5.3852$; $\sigma=2.3623$ |
|                          | Log-normal distribution  |
|                          | $\mu=1.5312$; $\sigma=0.4826$ |
| Typhoon Radius of maximum wind | Normal distribution  |
|                          | $\mu=48.3513$; $\sigma=9.3084$ |
|                          | Log-normal distribution  |
|                          | $\mu=3.8478$; $\sigma=0.1906$ |
| Overall moving direction of typhoon | Normal distribution  |
|                          | $\mu=-26.3965$; $\sigma=32.7674$ |
|                          | Bi-normal distribution  |
|                          | $\mu_1=48.3841$; $\sigma=4.6549$ |
|                          | $\sigma_2=16.6879$; $\sigma=0.5854$ |

Notes. In the table, $\mu$ is the mean and $\sigma$ denoting the variance. $\mu_1$ and $\sigma_1$ are the mean and variance of negative data; $\mu_2$ and $\sigma_2$ are the mean and variance of positive data, respectively.

2.2. Calculation of Wind Profile in Typhoon Wind Field

In this paper, the basic wind speed of 10 meters in 100 years is 43.5 m/s, taking from Wind-resistant Design Specification for Highway Bridges (JTG/T 3360-01-2018) [7]. The probability density distributions of the six typhoon parameters mentioned above are used for random sampling. Ten thousand random samples of each parameter are obtained by the Monte Carlo method. Yanmeng typhoon wind field model is compiled by Matlab for calculation [8]. The maximum value of the wind speed series at the height of 35.7 m at the Dinghai Meteorological station is obtained.

The power exponent of typhoon profile in this area is shown in equation (1) by equivalent roughness length $Z_0$ [8]

$$\alpha=0.27+0.09\log_{10} Z_0 + 0.018(\log_{10} Z_0)^2 + 0.0016(\log_{10} Z_0)^3 = 0.109241$$

where $Z_0$ is equal to 0.0004m, the relative error of maximum wind speed is minimum. The optimized values are substituted into the equation (1) to obtain the typhoon profile index in this area: $\alpha=0.109$. The calculation is shown in table 2.
Table 2. Simulation results of maximum wind speed corresponding to different $Z_0$ values.

| $Z_0$ | $V_{35.7m}$ (m/s) | Deviation (%) | $a$ |
|-------|--------------------|----------------|-----|
| 0.004 | 44.8681            | -11.4623       | 0.135626 |
| 0.003 | 47.21              | -6.84106       | 0.131817 |
| 0.002 | 46.9513            | -7.35155       | 0.126756 |
| 0.001 | 49.782             | -1.76576       | 0.1188 |
| 0.0008| 50.01              | -1.31585       | 0.11639 |
| 0.0005| 50.49              | -0.36867       | 0.111497 |
| 0.0004| 50.7022            | 0.050062       | 0.109241 |

2.3. Three-Dimensional Simulation of Fluctuating Wind Velocity in Typhoon Wind Field at Bridge Site

The bridge selected for analysis is a cable-stayed bridge with Twin Towers and double cable planes in Zhoushan, Zhejiang Province. The main girder is an orthotropic deck steel box girder with a height of 3m and a width of 30.1m. The main bridge is 1210m long, and the span layout is 77m+218m+620m+218m+77m. There are 182 simulation points, among which 84 simulation points are arranged on the stay cables. The simulation point is located at the center point of the stay cable as shown in figure 9.

The basic wind speed at an altitude of 10 meters in the 100-year recurrence period is 43.5 m/s. The mean wind profile index is 0.109 as calculated above. Up to now, there is no single wind spectrum with a fixed norm for typhoon spectrum due to the variable typhoon with a variety of environmental conditions and changes. In coastal area, the measured power spectrum of typhoon is much different from the theoretical spectrum, and the fitting spectrum at high frequency is larger than that at low frequency. The power spectral function of fluctuating wind speed in reference [9] is adopted here.

![Figure 9. Wind field simulation point of cable-stayed bridge.](image)

![Figure 10. Wind speed time history of cable No.141.](image)

![Figure 11. Wind speed time history of cable No.159.](image)
Wind speed time history of some stay cables presented in figures 10-11, wind speed normalized power spectral density (PSD) is showed in figures 12-13, in which most of the simulated results are similar to those in reference [10].

![Figure 12. Normalization PSD of cable No.141.](image1)

![Figure 13. Normalization PSD of cable No.159.](image2)

The time history of wind speed is different for various cable positions, and the maximum value of wind speed time history of middle span cable position is larger than that located in other positions. The power spectral density function of the cable in the middle of the span is relatively weak during the low frequency band, and almost all the theoretical spectrum during the high frequency band is in the middle of the simulated spectrum, which is relatively well simulated.

### 3. Cable Stress Time-History Analysis under Typhoon

#### 3.1. Finite Element Model of the Cable-Stayed Bridge

The three-girder cable-stayed bridge model is established by ANSYS, which is shown in figure 14. The main beam is composed of two side beams and one middle beam, which are rigidly connected. Thus the shear effect is taken into account [11]. In the finite element model, the column and beam are simulated by beam section element Beam44. The main beam is simulated by Beam4, and the stay cable is simulated by 3D link element. The sag effect of cable is simulated by equivalent elastic modulus [12], and the cable tension is simulated by initial strain. The first 6 modal frequencies of and corresponding mode shapes of the cable-stayed bridge are showed in figure 15.

![Figure 14. The finite element model of cable-stayed bridge.](image3)
3.2. Cable Stress Time-History Calculation of Stay Cables under Typhoon

The transverse wind load has the greatest influence on buffeting of stay cables [13], and the axial stress of the stay cable oscillates with the change of holding time. Therefore, in this paper, the harmonic superposition method is used to simulate the time history of the cross wind direction at the cable of the cable-stayed bridge [14]. In this paper, the basic wind speed at an altitude of 10 meters in 100 years is 43.5 m/s, according to the Wind-resistant Design Specification for Highway Bridges (JTG/T 3360-01-2018) [7], is adopted. The typhoon parameters are obtained by Monte Carlo method, and the average wind profile index of typhoon field is optimized by Yan Meng Typhoon Model. The buffeting wind spectrum is obtained from the wind tunnel analysis of Xihoumen Bridge, Dinghai, Zhoushan, by Liu Ming [9]

\[
\frac{n s_v(n)}{\sigma_v^2} = \frac{2.41f}{(1+3.93f)^{5/3}}
\]  

(2)

The turbulent integral scale is obtained by empirical formula proposed by Fu [15]

\[
L_u = 100 \times \left( \frac{z}{30} \right)^{0.5}
\]  

(3)

The Architectural Institute of Japan Empirical Formula [16] is used to obtain the crosswind

Figure 15. Mode shapes of the cable-stayed bridge.
turbulence intensity.

$$I_u = 0.1 \times \left( \frac{z}{z_G} \right)^{-0.05}$$  \hspace{1cm} (4)

The ratio of turbulent intensity in three directions are adopted in accordance with Liu [6]

$$I_u : I_v : I_w = 1 : 0.67 : 0.24$$  \hspace{1cm} (5)

Turbulence integration scale is adopted as follow:

$$L_u : L_v : L_w = 1 : 0.58 : 0.18$$  \hspace{1cm} (6)

Based on the wind angle of attack 0 degrees, the stress time-history analysis of stay cables under typhoon is carried out using ANSYS and Matlab joint calculations. The calculation steps are as follows: (1) whole bridge coordinates are inbound in Matlab. (2) the turbulence intensity, the turbulence integral scale and the coherence of the vertical and horizontal bridges are considered. (3) the average wind velocity matrix and the fluctuating wind velocity matrix are obtained by the orthogonal decomposition method combining with the power density matrix. (4) each point resistance of the tower and cables is calculated, and export as txt data text. (5) three-dimensional whole bridge model is established. (6) write the document which is finally imported into ANSYS, set the resistance coefficient in the document, define the initial motion state considering the effect of fluid-solid coupling, read the data group generated by Matlab and define the parameters of transient analysis solution. According to the steps above, the axial stress time-history of 82 cables under the action of transverse typhoon is calculated, and the response interval is set to 0.17s. The axial stress time history of 18 cables in figure 16 is analyzed, which are illustrated in figures 17-20.

**Figure 16.** Calculated cables layout.

**Figure 17.** Axial stress time history of cable No. 1.

**Figure 18.** Axial stress time history of cable No. 2.
The average axial stress of stay cables under different typhoon wind speeds is showed in figure 21. The transition of cable forces is not uniform. The relative average axial stresses of stay cables No. 7, No. 9 and No. 13 are smaller than that of stay cable No. 1. The average axial stresses of No. 1, No. 2 and No. 3 stay cables in the middle part of the pylon are larger than that of No. 11, No. 12 stay cables and No. 18 stay cables near the pylon. When the wind speed increases, the average axial stress of stay cables increase, and the maximum increase is approximate 8%.

The mean square deviation of the cables stress time-history in the typhoon wind field is shown in figure 22. The axial stress variance of middle span cable is larger than that of side span cable. With the increase of wind speed, the amplitude of the cable vibration increases, and the mean square deviation at the side span location oscillates seriously.

The cable No. 9 is located in a position of high average axial stress and low variance, which indicates that the cable is continuously subjected to relatively higher axial stresses (about 500 MPa). The stay cable is vibrating in a small amplitude with higher axial stresses.

4. Fatigue Damage Analysis of Stay Cables
Firstly, the stress time-history of stay cables is transformed into several stress cycles by rain-flow counting method. Secondly, the S-N curve of fatigue analysis is derived from the fatigue test of low relaxation prestressed steel strand made in China by Malin in 2000 [17]. The formula showed in the equations (7) is close to the S-N curve of the 270 grade steel strand proposed by Paulson et al. in the intercept and slope [18].
Finally, combining the rain-flow counting method and the S-N curve, the famous Palmgren-Miner linear cumulative fatigue damage rule is used to analyze the fatigue cumulative damage [19]. The total number of cycles before failure is calculated as N, and the total damage is defined as the ratio of the total number of times of superposition:

\[
D = \sum_{i=1}^{l} \frac{n_i}{N_i}
\]

(8)

Where D is the damage value, \(n_i\) is the cycle number under a certain stress, and \(N_i\) is the fatigue life number under that stress. When D is equal to 1, the cycle number of the simulated object reaches the maximum and the absorbed energy reaches the limit. The fatigue failure of the simulated object occurs subsequently.

In this section, under the typhoon parameters calculated above, the 18 characteristic cables set above are taken as the analysis object, and the damage values of the cables at five different wind speeds of 43.6 m/s, 50 m/s, 60 m/s, 70 m/s and 80 m/s are extracted as shown in figure 23. Relationship between fatigue damage index and wind speeds is shown in figure 24.

The number of stress amplitude cycles of cable No. 9 under different wind speeds in the typhoon environment is shown in figures 25-28. With the increase of wind speed, the range of the total stress amplitude becomes wider and the maximum stress amplitude also increases. The cycle times of stay cables are mainly concentrated in the relatively low stress amplitude region, and the range of the lower stress amplitude region increases with the growth of wind speed. The amplitude of the main stress cycle region of stay cables changes from low amplitude to high amplitude with the increase of wind speed.
5. Conclusions

(1) In this paper, the typhoon wind field data at Dinghai station, Zhoushan City, Zhejiang Province, are analyzed through the simulation circle method. The mean wind profile index of the optimal typhoon field is calculated as 0.109, based on the YanMeng typhoon model.

(2) The harmonic superposition method is adopted to simulate the wind field at the calculated position. The turbulence intensity along the wind direction follows the Japanese code. The turbulence integral scale and the wind spectrum refer to wind velocity time history and normalized spectral density from numerical simulations based on the measured wind spectrum at the Xihoumen Bridge site. The simulation results are satisfactory. The wind speed time-history is different for various cable positions, and the wind speed time-history reaches the maximum value at the mid-span position. The spectral density function of the cable in the middle of the span is relatively weak in the low frequency band and well simulated in the high frequency band.

(3) In this paper, ANSYS and Matlab are used to build the geometric shape and physical properties of the cable-stayed bridge, and to calculate the stress time-history of the cables under the typhoon wind load. The stress transition of stay cables is not uniform. The average axial stress of stay cables increases with wind speed, and the variance of axial stress increases significantly.

(4) The damage value of stay cables increases with the wind speed. When the wind speed is 43.6 m/s, the maximum damage value of stay cables is 8.77 e-6, and when the wind speed is 80 m/s, the maximum damage value is 1.0822 e-4. The damage diagram of stay cables is similar to the axial stress variance diagram of stay cables. When the wind speed is 43.6 m/s, 50 m/s and 60m/s, the maximum damage position is cable No.13. When the wind speed is 60 m/s, 70 m/s and 80m/s, the maximum damage position is cable No. 9.

(5) With the increase of wind speed, the damage of stay cables increases rapidly. The damage curve slope between 43.6 m/s and 50 m/s is nearly 60 times different from that between 70 m/s and 80 m/s.

(6) The fatigue damage of stay cables is rather sensitive to the wind speed. The wind sensitivity of the stay cable located in 1/8 mid span is more stronger.

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