Hydraulic and Civil Engineering Technology VI
M. Yang et al. (Eds.)

doi:10.3233/ATDE210176

Analysis of Temperature and Humidity Distribution and Corrosion Effect on Suspender of Arch Bridge

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Abstract. With the continuous improvement of bridge span, high-strength steel wire suspenders are more and more widely used in arch bridges. Because metals are thermodynamically unstable, most metals will corrode at a different speed. Especially with the increase of bridge operation time, the suspender steel wire will be corroded under the coupling effect of external environment and internal temperature and humidity. By taking Wanganshi Fuhe Bridge as the engineering example, this study established a numerical finite element model to simulate the variation of temperature in the cross section of the suspender. Then, the distribution of humidity in the cross section in the suspender under the influence of temperature can be obtained. Finally, the corrosion rate of the suspender and the residual diameter after corrosion at different operating years were calculated. Based on the analysis results, the performance of the suspender is divided into different grades which can be used to guide the maintenance and replacement of the suspender of the arch bridge by the bridge maintenance and management department.

Keywords. Suspender of arch bridge, corrosion, steel wire, distribution of temperature and humidity, maintenance strategy

1. Introduction

For half-through arch bridges, the suspender is an important connection and force transmission structure between the main arch ring and the bridge span girder [1]. In addition, the arch bridge suspender system has more components and smaller structural size, which makes the suspender easy to be corroded under the coupling effect of temperature, humidity and other corrosion factors in the operation process. In recent years, there have been many engineering accidents in China, which lead to the overall collapse of the bridge span due to the problems of the suspender system. Most accident investigation reports show that the corrosion of suspender steel wire caused by temperature and humidity coupling and fatigue under vehicle load are the main factors leading to suspender fracture. In order to ensure the safety of arch bridge structure operation, the common practice in China is to replace the suspender regularly, but the damage degree of different suspenders in the same period must be different [2]. If the maintenance and replacement cycle of suspender is determined according to the

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suspender with the fastest corrosion rate, it will obviously cause great waste. In this paper, a half-through arch bridge across Fuhe River is taken as the engineering background, and the Fluent module in ANSYS is used to establish the simulation model of the temperature and humidity distribution of the suspender. The temperature and humidity distribution in the suspender of the bridge and its corrosion effect are analyzed. The residual diameter of the suspender steel wire after different operating years under the action of temperature and humidity is analyzed.

2. Engineering Background and Model Building

The main span arrangement of Wanganshi Fuhe Bridge is 60+168+60 m. The main bridge has 19 pairs of suspenders, and the longitudinal bridge spacing is 6 m. The span arrangement and structural form are shown in figure 1.

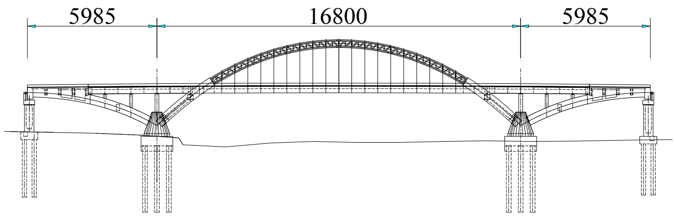


Figure 1. The span arrangement and structural form of Wang Anshi Fuhe Bridge (unit: cm).

During the long-term operation of arch bridge suspenders, water will continuously penetrate into the suspender through the cable clamp position for various reasons, which is called the initial ponding and is liquid water [3]. In the research process of this paper, the steel wire in the suspender is simplified as a porous medium to simulate the temperature and humidity distribution in the suspender section under the action of external temperature, so as to analyze the influence of temperature and humidity coupling on the corrosion of suspender steel wire. In the simulation process, above the initial liquid level is the gas-liquid mixed phase (due to evaporation, diffusion and seepage), and below is the liquid phase (initial water). As is shown in figure 2, it is the indicative model of temperature and humidity simulation of the suspender.

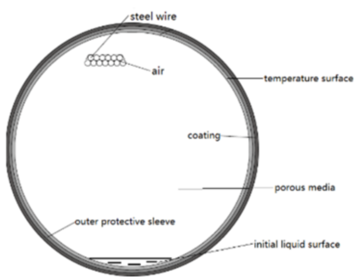


Figure 2. Schematic model for studying the variation mechanism of temperature and humidity inside suspender.

In addition, the physical processes such as gas-liquid water diffusion, flow and infiltration in the suspender are similar to the water transmission in unsaturated soil.

Therefore, in this study, the steel wire of suspender, external protective air, wrapped steel wire, ethylene belt or rubber anticorrosive belt, and external surface coating were treated into solid, liquid and gas three-phase mixture. According to the above theory, the simulation model of temperature and humidity distribution of suspender of Wanganshi Fuhe Bridge is established by utilizing Fluent module in ANSYS.

3. Study on Distribution Law of Temperature and Humidity in Suspender

3.1. Extraction of Physical Model of Temperature and Humidity Change in Suspender

The physical phenomenon simulated in this study is the change and distribution of temperature and humidity inside the suspender under the influence of external environment temperature [4]. The physical processes such as diffusion, flow and infiltration of gaseous liquid water in the suspender are similar to that in unsaturated soil. Therefore, this study intends to analyze the variation law of temperature and humidity inside the suspender through the two-dimensional analysis method shown in figure 3. Considering the random characteristics of gap between steel wires, the temperature change, water flow, capillary effect, water-gas migration and cross-sectional diffusion of humidity are simulated. Heat transfer is generally mainly composed of vaporization latent heat, convection and conduction. According to the model, the finite volume analysis method was used to simulate the temperature and humidity change process and mechanism [5]. Considering the spatial effect of the suspender and the spanwise effect in the height direction, a two-dimensional numerical analysis model is established based on the above theoretical model. Through the simulation analysis, the temperature and humidity variation characteristics of the suspender are verified.

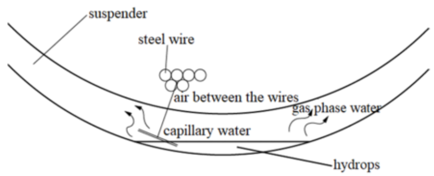
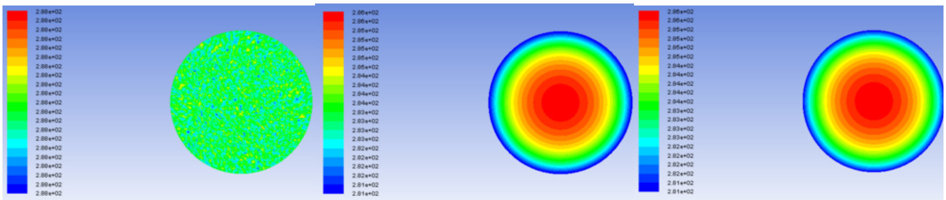


Figure 3. Simulation diagram of water and humidity migration at the bottom of the main cable.

3.2. Simulation of Temperature Distribution Law of Suspender

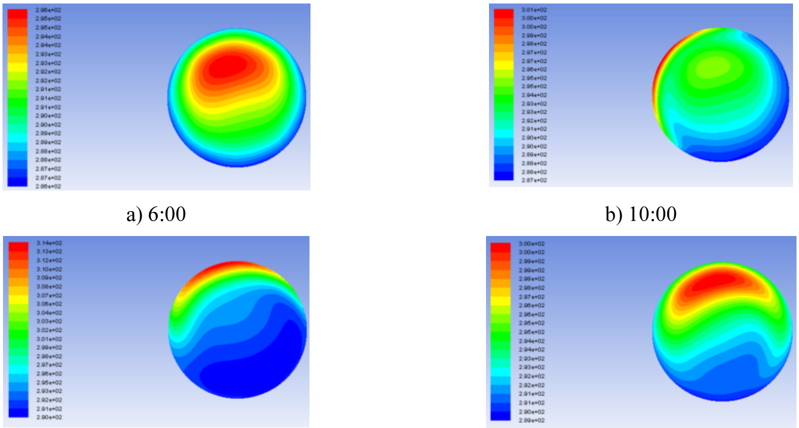
The initial temperature field in the Fluent module of ANSYS is unknown. In this study, the numerical simulation is carried out for three consecutive days (refers to the actual time) by applying environmental parameters such as temperature and light. In this paper, the temperature variation trend of spring equinox, summer solstice, autumn equinox and winter solstice in Wanganshi Fuhe Bridge site in 2020 is queried through meteorological data. After the above conditions are met, the actual time length of one day before and after the spring equinox, summer solstice, autumn equinox and winter solstice is simulated, that is, each time period is 3 days and 72 hours. The light, temperature and humidity of each time period of the whole year are simulated with the temperature of 12 days. Due to space limitations, this study selected Fuzhou City where Wanganshi Fuhe Bridge located from June 20 to June 23, June 21, 2020 as summer solstice. The temperature variation range is 23~33°C. Thus, the temperature in the suspender under different temperature fields can be simulated, and the results are shown in figure 4 and figure 4a) shows the initial temperature field of iteration, and the initial iteration temperature is determined as 28 degrees of average temperature in Fuzhou from June 20 to June 23 figure 4b) shows the calculation results of the first iteration. Taking this temperature field as the initial temperature field of the second iteration, the calculation results are shown in figure 4c). Obviously, the final calculated temperature field shown in figure 4b) is very close to that shown in figure 4c). It can be considered that the iterative calculation converges, that is, the temperature field can be used as the initial temperature field in subsequent studies.



a) First day b) Second day c) Third day

Figure 4. Simulation of initial temperature field in suspender.

Figure 5 shows the temperature field distribution of suspender cross-section every four hours from 6:00 to 18:00. figure 5 a) shows that at 6:00, the temperature in the central area of the suspender is higher than that in the external area. This is because the suspender continues to dissipate heat to the surrounding environment at night, the heat dissipation near the surface area is fast, and the heat dissipation in the central area away from the surface is slow. It can be seen from figure 5 b), the east side of the boom is directly exposed to sunlight, and the west side is the back side. Therefore, on the cross section, it is reflected that the temperature on the upper left side is high and the temperature on the lower side is low. It can be seen from figure 5c) that the upper side of the suspender is directly exposed to the sun, and the lower side is the back-sunlight surface. Therefore, it is reflected in the cross section that the temperature at the upper side is the highest. In addition, during the summer solstice, the strongest light occurs at 13:00, and the highest temperature occurs at 14:00 due to the lag of temperature change in light. Therefore, although the sun has passed the highest position at this time, due to the hysteresis effect of temperature, the highest temperature of the suspender cross section is still at the top of the suspender cross section. As in shown in figure 5 d), the west side of the suspender is directly exposed to the sun, and the east side is the back sunny side at 18:00. Because the intensity of sunshine is very weak, the ability to adjust the temperature field is further reduced, and the solar altitude angle is smaller. The western lower side of the suspender can also be partially illuminated, so the lowest temperature area moves to the left side of the suspender cross section.



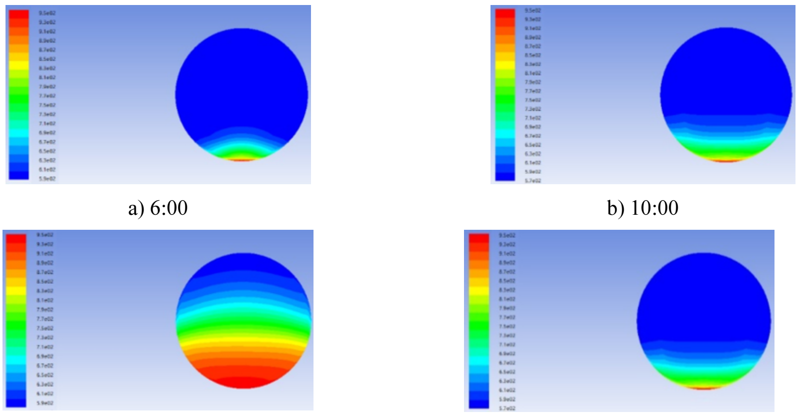
a) 6:00 b) 10:00

c) 14:00 d) 18:00

Figure 5. Temperature distribution of the suspender cross section at different time.

3.3. Simulation of Humidity Distribution Law in Suspender

The time-history data of the temperature field change of the suspender obtained by the simulation calculation in Section 2.1 under the action of solar radiation, environmental radiation and air convection are loaded into the suspender section model as the source term of water evaporation and condensation. Then, the time-history data of the humidity field change inside the suspender are obtained after transient analysis, and the humidity change inside the suspender is shown in figure 6. Among them, the warm part represents high humidity (red is the highest), and the cold part represents low humidity (blue is the lowest).



a) 6:00 b) 10:00

c) 14:00 d) 18:00

Figure 6. Humidity distribution of the suspender cross section at different time.

According to the humidity distribution in the cross section of the boom at different times in figure 6, it can be found that the humidity distribution in the cross section of the suspender is very different due to the different external temperature at different times. During the process of 6:00–10:00, due to the influence of temperature and water vaporized, the area with high humidity in the suspender was very large (more than 60%). The maximum humidity in the cross section was about 95%, and the minimum humidity was about 50%. With the increase of external temperature from 10:00 to 14:00, more water in the suspender is converted into water vapor. Since it is a closed space, water vapor is still retained in the suspender which will result in the increase of humidity in the suspender and the stable state of humidity in the most cross section. That is to say, the internal humidity does not change with the increase of temperature at this time, which is the unique feature of humidity change in the closed space of the suspender. During the time from 14:00–18:00, the ambient temperature gradually decreased, and the water vapor in the hanger gradually condensed into water. Through the simulation results of different temperatures, it can also be found that the higher the external temperature is, the more the converted water is, and the greater the humidity in the closed space of the suspender is.

4. Corrosion of Steel Wire Caused By Coupling Effect of Temperature and Humidity in Suspender

In order to analyze the durability of suspender steel wire under the coupling action of temperature and humidity, according to the temperature data and humidity data obtained by simulation analysis, the residual diameter of suspender steel wire due to external corrosion after different operating years is obtained by combining with relevant research results. In addition, the steel wire grade is divided into different grades according to the residual diameter of steel wire. Betti obtained the dominant relationship between the suspender humidity and the steel wire corrosion rate through the analysis of experimental data [6]. The results show that the corrosion rate of the suspender steel wire increases by 24μm/year with each 25% increase in humidity, and the suspender steel wire does not rust when the internal humidity of the suspender is less than 60%. Therefore, the following calculation formula of the corrosion rate and the internal humidity of the suspender can be obtained:

$$CR = \frac{RH - 60\%}{25\%} \times 24$$

Table 1. Residual diameter of suspender steel wire after different service years under coupling effect of temperature and humidity.

Operating years	1	2	3	4	5	6	7	8	9	10
Diameter after corrosion	5.233	5.226	5.217	5.202	5.196	5.185	5.173	5.162	5.154	5.143
Grade after corrosion	I	I	I	I	I	II	II	II	II	II
Operating years	11	12	13	14	15	16	17	18	19	20
Diameter after corrosion	5.132	5.125	5.116	5.107	5.093	5.086	5.073	5.062	5.054	5.045
Grade after corrosion	II	II	II	II	II	III	III	III	III	III

CR is the corrosion rate of suspender steel wire, and RH is relative humidity of suspender steel wire. The temperature and humidity data at different steel wire positions of the suspender can be calculated and simulated in Section 2. Then, the humidity distribution inside the suspender at different external temperatures can be obtained. Therefore, according to the relationship between temperature and humidity, the numerical value of internal humidity under different external temperatures in a year cycle can be simulated. According to the design data, the diameter of the steel wire in the suspender of Wanganshi Fuhe Bridge is 5.24 mm. Combined with its corrosion rate, the residual diameter of the suspender can be calculated after different operating years, which is shown in table 1. According to the size of the residual diameter after corrosion, the suspender steel wire is divided into three grades, and the minimum diameters corresponding to the three corrosion grades are 5.19 mm, 5.09 mm and 4.85 mm, respectively.

5. Conclusions

By the establishment of a numerical analysis model, the temperature distribution in the cross section of the suspender caused by the influence of light is analyzed. Based on the analysis results, the humidity fraction in the suspender is analyzed. Finally, the durability of the suspender steel wire under the coupling effect of temperature and humidity can be obtained. The main conclusions of the paper are as follows:

1) The temperature distribution in the suspender is mainly affected by the side sunlight, and the maximum temperature of the suspender in one day appears at about 13:00. In addition, the temperature difference between day and night on the surface of suspender is large.

2) Under the influence of temperature load, the humidity distribution in the cross section of the suspender varies greatly in different time periods. As the temperature rises, the water in the boom transforms from liquid to steam and distributes throughout the boom.

3) With the increase of bridge service time, the corrosion degree and corrosion rate of suspender steel wire are getting higher and higher. The monitoring and testing of different suspender steel wires should be strengthened after 11 years of operation of Wanganshi Fuhe Bridge.

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