Influence of cold wave on temperature and stress fields of cylindrical concrete hollow pier

Liang Zhao
School of architectural engineering, Wuhan Polytechnic, Wuhan 430074, China
Corresponding author e-mail: Zhaolianghj16@163.com

Abstract. Piers attacked by a cold wave, often exhibit uneven temperature distributions, which are direct causes of temperature effects in concrete structures. In order to investigate the influence of cold waves, a three-dimensional transient thermal-structural coupled field method was implemented in a finite element software ANSYS to analyze the temperature field of concrete hollow pier under a cold wave first. The validity of the finite element (FE) model was verified by the experimental results. After that, the FE model was extended and used to simulate the temperature field and thermal stress of a cylindrical hollow pier under the cold wave. The results show that the circumferential stress under the cold wave is large, and therefore it needs to be considered in the cylindrical concrete hollow pier design.

1. Introduction
Concrete hollow pier, one of the main pier forms used in bridges, has advantages of saving materials, light self-weight, low requirements for the strength of foundations. Therefore, the concrete hollow pier is widely used. With the development of bridge construction technology and a sharp increase in number of high-piers and long-span bridges, the adverse effects of temperature on concrete hollow piers are significantly observed. The cold snap is an extreme environmental temperature change situation, and it causes damages to concrete whose thermal conductivity is poor [1]. When the air temperature drops abruptly, the temperature of concrete structure exhibits a non-uniform distribution, which inevitably leads to large temperature stresses. The safety and durability of the concrete hollow piers, consequently, decreased by the temperature effects [2-3]. Therefore, it is necessary to investigate the temperature effects of concrete hollow piers under the cold wave.

Experimental investigation and numerical simulation to calculate the temperature effects on the bridge under the sunshine have been widely studied [4-6], but barely about the cold wave. Based on an actual project, Zeng et al. [7] carried out an experiment to study the temperature and stress fields of railway hollow piers under a cold wave. The temperature field obtained from the experiments was used to analyze the temperature stress of piers using ANSYS. Lin & Ou [8] first analyzed the meteorological data of Harbin (China, 1963-2002) and Guangzhou (China, 1997-2006) and established a finite element model to investigate the temperature gradient parameters of large bridge hollow members during cold wave cooling. The influence of the thickness of the pier wall on the extreme value of the temperature difference is qualitatively analyzed, and the formula for predicting the extreme value of the temperature difference is proposed. On the basis of considering the effect of ages on the concrete elastic modulus and the intensity, Shen et al. [9] had investigated the early age cast-in-place floor, and got the corresponding conclusions and proposals to reduce the influence of cold wave by simulating the temperature stress of cast-in-place floors in different sizes at the disparate ages with ANSYS. Further, Chen et al. [10] obtained the temperature distribution of the hollow pier...
under the cold wave through experiment and on-sit measurement, and proposed the temperature gradient mode under the cold wave. Gu et al. [11] proposed a model that can accurately predict temperatures over the cross-section of the concrete box girder under the effect of cold wave. A parametric study that considered meteorological factors was performed, which shows that the cold wave may cause more unfavorable effect on the concrete box girder bridge, especially on the large concrete box girder bridge. Shi et al. [12] simulated the temperature field and temperature stress of the four-wire hollow pier of Da shaping bridge of Lanzhou junction in Lanzhou-Chongqing railway under the action of cold wave using the software ANSYS.

However, most of the researches above are mainly on the analysis of temperature gradient model of pier under cold wave, mostly simplified as two-dimensional model for rectangular hollow high pier, but barely about cylindrical concrete hollow pier. Therefore, this paper takes ANSYS as a platform to carry out numerical simulations on the temperature field as well as the thermal stress of cylindrical concrete hollow pier under the cold wave, which establishes the foundation for subsequent studies.

2. Finite element analysis method

2.1 Boundary simulation of cold wave

It is difficult to simulate the temperature changes during the cold wave. The cold wave intensity is an important factor affecting the cold wave stress of concrete structures. Zhang & Garga [13] adopted the polygonal function to approximate the time-dependent change of temperatures during the cold wave, and it is considered that the rise of temperature is the same rate of change as the drop of temperature. Further, a sine function is also proposed to simulate the temperature change between cold waves in this literature. Based on the variation characteristics of single station temperature, a multi-order continuous derivable function curve is used to simulate the cooling and heating process of cold wave in [14]. In this paper, the finite element simulation was carried out with the sine function formula (1) for the air temperature during the cold wave.

\[ T_s(t) = T_{s0} - \Delta T_s \sin \frac{\pi}{2\Delta t} t \]  

where: \( T_s(t) \) is the atmospheric temperature at time \( t \), °C; \( t \) takes the time of the temperature decline as the starting point, h; \( T_{s0} \) is the initial temperature when the temperature starts to drop, °C; \( \Delta t \) is the time of the cold wave, hours, \( \Delta T_s \) is the decline of temperature during the cold wave, °C.

2.2 Establishment of finite element model

The experimental model is a hollow cylinder with an inner diameter of 2.4 m, a wall thickness of 30 cm, and a height 2.0 m (as shown in Figure 1). The digital temperature sensors were used to measure the temperature on the outer surface and inner surface of the cylinder. There were 8 measurement points inside and outside the surface respectively. The cold wave occurred on November 30, 2014. The lowest temperature dropped by 9 ~ 10 °C within 48 hours, and the daily minimum temperature dropped to -2 °C. The wind was 5 ~ 6 level.

The numerical simulation is implemented by using ANSYS software. The Solid 90 thermal element is used to establish the solid model. In the heat transfer analysis, the external boundary is given in the form of a second boundary. The essence of the thermal stress analysis of the structure is the analysis of structures under temperature load. The solid 90 element is automatically converted into solid 95 element to come true the temperature loading of each node, thus completing the structural analysis.

In the analysis, the initial temperature of cooling was 8.5 °C, which was the same as reference temperature. The average wind speed during the cold wave was 4.5 m/s. What is more, the internal and external temperature difference refers to the difference between the inner wall temperature and the outer wall temperature. When the inner wall temperature is higher than the outer wall temperature, the temperature difference is positive. The FE model is shown in Figure 2.
2.3 Model verification

Figure 3 shows the FE results and test results of four measurement points in the directions of the east and the north. It can be seen that the FE results is consistent with the test results. Within 24 hours after cooling, the FE results are slightly larger than the test results because the cooling rate of the simulated temperatures is slightly lower than that of the measured ones. During the period of 25 ~ 48 hours, the measured temperatures remain basically the same during the daytime, while the simulated curves still show a cooling trend, so the simulated temperatures reduce slightly at 13:00 on the second day. The measured value at this stage is slightly larger than the calculated value, but the difference between the points on the outer wall is less than 2 °C. It is feasible to use sine function to simulate the cold wave temperature change process, and the model is effective.

3. Temperature distribution

Taking a reinforced concrete cylindrical hollow pier as an example, numerical analysis is carried out using the finite element model verified above. The hollow pier is of 30 m in height, the inner diameter of pier is 4.4 m at the bottom, with the wall thickness 0.7 m. It is assumed that it is equal cross section to simplify calculation. C30 concrete is adopted. The intensity of cold wave is the same as that of the experimental hollow cylinder.

Figure 4 shows the variation of the temperature of the inner and the outer surface against time. Figure 5 and Figure 6 show the temperature distribution along the wall thickness and the temperature nephogram at the typical moment of the pier, respectively. As it can be seen clearly from Figure 4, since the wall of the hollow pier is thick, the temperature of the inner surface changes slowly. The temperature of the outer surface is mainly affected by the cold wave, which changes greatly. The maximum temperature difference between the inner and the outer surface occurs at the 42th hour of cooling, while the lowest temperature of the outer surface occurs at the 48th hour. Figure 5 and Figure
6 show that the maximum temperature difference between the inner and outer wall is 9.43 °C at the 42th hour, while the temperature difference is 9.26 °C at the 48th hour, and the distribution along the pier wall is basically the same, showing significance nonlinearity. Although the temperature difference at the 42th hour is only 0.17 °C higher than that of the 48th hour, the nonlinearity of temperature distribution along the pier wall thickness is more significant.

![Figure 4. Temperature of inner and outer surface change with time.](image1)

![Figure 5. Distribution of temperature along pier wall thickness on the east at different times.](image2)

![Figure 6. Temperature distribution of hollow pier at typical time.](image3)

**4. Thermal stress of hollow pier**

Figures 7 ~ 9 show the circumferential stress $\sigma_y$ and vertical stress $\sigma_z$ at different heights of the hollow pier. It can be seen that the inner surface of the hollow pier is compressed and the outer surface is in tensile. The stress is different at different heights, and the maximum stress occurs at the bottom of the pier.

![Figure 7. The moment of maximum temperature difference $t_{\Delta\text{max}}$ (the 42th hour) / °C](image4)

![Figure 8. The moment of minimum temperature of outer surface $t_{\text{min}}$ (the 48th hour) / °C](image5)
Figure 7. Thermal stress at the bottom of pier at the moment of the maximum temperature difference. (z=0 m)

Figure 8. Thermal stress in middle part of pier at the moment of the maximum temperature difference. (z=15 m)

Figure 9. Thermal stress near the top of pier at the moment of the maximum temperature difference. (z=28 m)

Figure 10 shows the distribution of thermal stress along the pier wall thickness at the bottom of the pier. The distributions of the circumferential stress and the vertical stress along the wall thickness in the four directions are basically the same, showing obvious non-linear. The maximum $\sigma_y$ and $\sigma_z$ are 4.02 MPa and 3.29 MPa, respectively. Because the vertical tensile stress value of the outer surface will be reduced under the action of external load and its own gravity, it could be ignored in design. However, circumferential stress and external load do not produce stress superposition, so circumferential stress should be mainly considered in the horizontal direction of the pier shaft. The design of circumferential reinforcement needs to be arranged through calculation to make sure that the concrete structure will not crack, thus ensuring the durability and safety of the structure.
5. Conclusion

(1) The temperature field and thermal stresses of the pier are distributed symmetrically along the wall thickness under the cold wave. Which show a significant nonlinearity. Further, the temperature difference reached 9.43 °C, and the outer surface as a whole showed tension, with the maximum circumferential tensile stress reaching 4.02 MPa at the moment of maximum temperature difference.

(2) The thermal stress analysis of bridge piers under cold wave shows that the circumferential stress and vertical stress are larger. It is found that the vertical stress under cold wave could be neglected, while the circumferential stress needs to be considered in the design.

(3) In the design of concrete cylindrical hollow piers, enough attention should be paid to thermal stress under the cold wave, and sufficient circumferential reinforcement should be arranged on the outer surface of the pier to prevent the pier surface cracking caused by the cold wave.

References

[1] Kaewunruen S, Wu L, Goto K, and Najih Y M 2018 Vulnerability of structural concrete to extreme climate variances Climate vol 6 pp 1–13
[2] Zhu Z H, Davidson M T, Harik E I and Sun L C 2015 Effect of superstructure temperature changes on intermediate pier foundation stresses in integral abutment bridges Journal of bridge engineering vol 20 04014058
[3] Zhu J S and Meng Q L 2017 Effective and fine analysis for temperature effect of bridges in natural environments Journal of Bridge Engineering vol 22 04017017
[4] Zhang J, Prader J, Grimmelsman K, Moon F, Aktan A and Shama A 2013 Experimental vibration analysis for structural identification of a long-Span suspension Bridge Journal of Engineering Mechanics-ASCE vol 139 pp 748–759
[5] Zhou G D, Yi T H, Chen B and Zhang H 2015 Analysis of three-dimensional thermal gradients for arch bridge girders using long-term monitoring data Smart Structures and Systems vol 15 pp 469–488
[6] Xia Q, Zhang J, Tian Y D and Zhang Y F 2017 Experimental Study of Thermal Effects on a Long-Span Suspension Bridge Journal of Bridge Engineering vol 22 04017034
[7] Zeng Y P, Chen S X, Chen K J, Chen T D and Zhang L L 2011 Test study of temperature and stress fields of railway bridge hollow piers under action of cold wave Bridge Construction pp 48–51
[8] Lin C and Ou J P 2011 Study on temperature gradient parameters of hollow members of bridge structure Journal of the China Railway Society vol 33 pp 94–100
[9] Shen C M, Yang H F and Hang Z Y 2012 Effect of cold wave sudden attack on temperature stress of concretes thin plates Sichuan Building Science vol 38 pp 62–65
[10] Chen T D, Yan Y and Zhang L L 2013 Study on stress of cold wave and temperature fields of high pier structure on high speed railway High Speed Railway Technology vol 6 pp 24–28
[11] Gu B, Chen Z J and Chen X D 2014 Temperature gradients in concrete box girder bridge under effect of cold wave Journal of Central South University vol 21 pp 1227–1241
[12] Shi J, Li L and Lu W D 2014 Temperature stress analysis of superwide hollow pier under cold Journal of Lanzhou Institute of Technology vol 21 pp 35–40
[13] Zhang Z M and Garga V K 1994 Temperature stress of massive concrete under cold wave Journal of Hohai University vol 22 pp 94–97
[14] Xu H F 2009 Study on the key factors of temperature effect of concrete box-girder bridges. Huazhong University of Science & technology