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Theoretical Analysis of Temperature and Shrinkage Stresses of Box-girder Section

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Abstract: The objective of this study is to analyze the temperature and shrinkage stresses of the mid-span cross-section of a 20 meters box girder to find the reasons which cause the longitudinal cracks in the web and bottom of box girder. According to the results of damage inspeation, there are many longitudinal cracks in the web and bottom slab of box girders, especially the web of the edger beam, the crack is very clear. Ansys ver.10 software is used to analyze two dimensional finite element model of a typical cross section of a real bridge to calculate the temperature stresses caused by temperature difference between inside and out side of the box and the shrinkage stresses based on moisture diffusion. The results of analysis show that the outer surface of the web and bottom slab of the fabricated box girder will produce tensile stress at the effect of negative temperature difference. If the concrete reaches a certain age, the tensile stress does not cause creaks in the cross-section. The shrinkage stress changes with the moisture gradient in the box section. It will reach the maximum in 15 days and then decreases with the growth of the age. Shrinkage stress may cause cracking of the concrete surface because of the tensile strength is low in the early age.

Introduction

Box girder section has a good structural performance, cross-section torsional stiffness, bending ability, high utilization of section, and good economic returns. Therefore, this type of girder is widely used in the construction of the highway and city prestressed concrete bridge. Author surveyed many fabricated box girder bridge and found that most of the web and bottom slab exist longitudinal cracks, especially the web of the edger beam, the crack is very clear. Fig.1 shows the cracks in the web of box girder. These cracks in were not found in the process of precasting, tensioning,transportation and lifting, but found in the next spring. The author initially judged that these cracks were caused by the transverse stress of temperature difference between inside and outside the box and uneven shrinkage.

Box girder section is closed section and the temperature deformation of the wall was constrained by the framework and then causes large horizontal and vertical temperature stress. This is one of the important reasons which cause creaking of concrete. The temperature effect of box-section is more significantly than other forms of concrete cross-section. Now many designers calculate the temperature effect only limit to the longitudinal force caused by the vertical temperature gradient on the structure and neglect the transverse stress and effect of the horizontal temperature gradient. As a result, many girders appear longitudinal cracks and many of them are larger than specification limits. Shrinkage is an inherent time-varying characteristic of concrete and an important factor which causes long-term deformation and cracking of concrete structure. In the project, people use theoretical thickness of component to describe the drying rate of concrete structure and consider that there is only volume shrinkage when the structure is on the state of no constraint [1]. This is appropriate for the overall analysis of the structure, but for the local analysis, especially for the cracks analysis, it will be incorrect. The development of shrinkage in internal and surface of box girder cross-section is not synchronized. The non-uniform shrinkage of box girder cross-section is significantly which will lead to crack. The objective of this study is to analysis the temperature and shrinkage stresses of the mid-span cross-section of a 20 meters box girder to find the reasons which cause the longitudinal crack in the web and bottom of box girder. Fig.2 shows the cross-section of box girder.

Fig.1 Box longitudinal crack

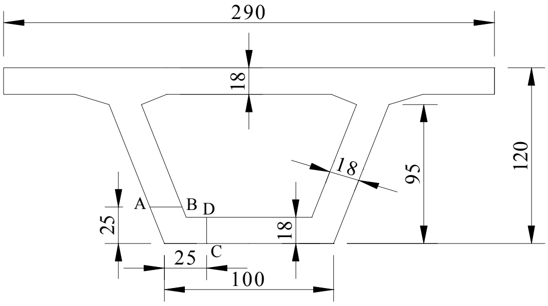

Fig.2 Mid-span cross-section (unit:cm)

Concrete material properties

The girder uses high-strength concrete. Strength grade is C50. The 28-day strength f_c =50MPa; the 28-day Elastic modulus E_c=34500MPa.

Relation between elastic modulus and age. Using the formula of model code CEP-FIP MC90 [2]:

$$E_c(t) = E_c\sqrt{\beta_t} \tag{1}$$

Where: E_c is the elastic modulus of concrete at 28 days; $\beta_t = e^{s\left(1-\sqrt{28/t}\right)}$, t is the age; s depends on the type of cement, Portland cement and rapid hardening cement to takes 0.25, rapid hardening high strength cement take 0.2.

Relation between strength and age. Using the formula of model code CEP-FIP MC90 [2]:

$$f_c(t) = \beta_t f_c = e^{s\left(1-\sqrt{28/t}\right)} f_c \tag{2}$$

Where: f_c is the compressive strength of concrete at 28 days; $\beta_t = e^{s\left(1-\sqrt{28/t}\right)}$, t is the age; s depends on the type of cement, Portland cement and rapid hardening cement to takes 0.25, rapid hardening high strength cement take 0.2.

In this paper, tensile strength of concrete is taken as the following formula:

$$f_t(t) = 0.395 f_c(t)^{0.55} \tag{3}$$

Relation between autogenous shrinkage and age. There are many analysis models of autogenous shrinkage [3,4]. In the present, Eurocode2 (GEN2001) is the only code which clearly states the prediction modal of autogenous shrinkage of high strength concrete. This code divides the shrinkage into drying shrinkage and autogenous shrinkage. The autogenous shrinkage is calculated as [5]:

$$\varepsilon_{acs}(t) = \varepsilon_{acs0}\beta_{as}(t) \tag{4}$$

Where: $\varepsilon_{cs}(t)$ is the autogenously shrinkage of concrete at the age of t; ε_{cs0} is the nominal shrinkage coefficient of concrete; $\beta_s(t)$ is the development function of autogenous shrinkage. As:

$$\varepsilon_{acs0} = -a_{as}\left(\frac{0.1f_c}{6+0.1f_c}\right)^{2.5}\times 10^{-6} \tag{5}$$

$$\beta_{as}(t)=1-e^{-0.2\sqrt{t}} \tag{6}$$

Where: f_c is Compressive strength of concrete; a_{as} is the correction parameter of different types of materials. When the concrete is general slowly hardening material， $a_{as}=800$; When the concrete is general fast hardening material, $a_{as}=700$; When the concrete is high strength fast hardening material, $a_{as}=600$.

Stress analysis of the temperature difference

The wall temperature difference of box girder cross-section is up to -10℃ when the cold air is coming [6]. Chinese Fundamental code for design on Railway Bridge and culvert (TB1002.3-2005) provides consideration should be given for the transverse thermal stress caused by temperature difference of box girder cross section. For the cooling temperature, the negative temperate difference along the thickness can take -10℃ and temperature curve is exponential distribution. Larger number of documents and observational data show that the temperature change along the axis of the beam direction can be ignored. Therefore, the temperature problem of beam can be reduced to two-dimensional heat conduction problem [7]. This paper directly consider the temperature difference between inside and outside the box girder cross-section to calculate the thermal stress using the first boundary condition. We take the 28 days material properties of concrete and consider the temperature difference of -5℃, -10℃, -15℃. The inner temperature is higher than the outside temperature. Ansys Ver. 10 software is used in the analysis of temperature and shrinkage stresses.

Fig.3 and Fig.4 shows the results of analysis. From these Figs it can be seen that the higher negative temperature difference, the greater tensile stress on the outer surface of the web and the bottom slab. The maximum tensile stress of the web is in the heigh of 0.2m. when the negative temperature difference is -15℃, the tensile stress arrives 2.26MPa, The maximum tensile stress of the bottom slab is at the position of 0.3m from the bottom center. when the negative temperature difference is -15℃, the tensile stress arrives 2.68MPa. If the concrete reaches a certain age, the outer surface of the box will not crack in the negative temperature difference which is less than -15℃.

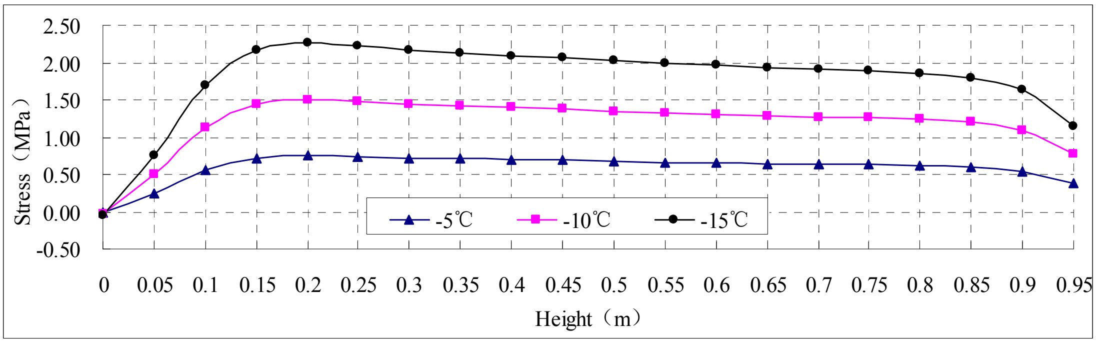

Fig.3 Vertical stress distribution of the web outer surface at negative temperature difference

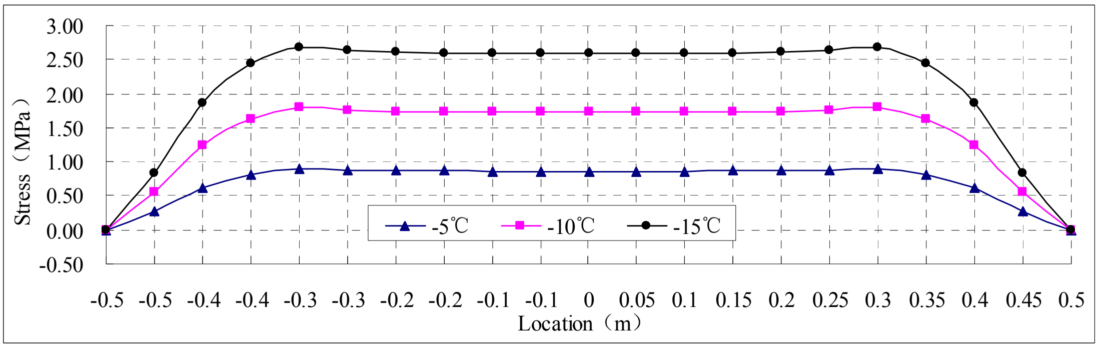

Fig.4 Horizontal stress distribution of the bottom slab outer surface at negative temperature difference

Stress analysis of shrinkage

Cement hydration occurs after concrete pouring. Variety types of shrinkage will occur in the early age because of the various physical and chemical changes, such as shaping shrinkage, chemical shrinkage, autogenous shrinkage and drying shrinkage. After the initial setting of concrete, autogenous shrinkage and drying shrinkage are the main types of shrinkage. This paper will only focus on these types. Autogenous shrinkage of concrete is caused by the volume deformation because of the consumption of pore water within the structure in the concrete hydration process. We can consider there are the same mechanism with the external drying shrinkage. Autogenous shrinkage in the ordinary concrete is negligible because of the small value. But in the case of a large number of high–strength concrete with low water-cement ratio concrete used in the recent years, the value of autogenous shrinkage can not be ignored. When the water-cement ratio is less than 0.4, the autogenous shrinkage is considered the significant impact of the concrete shrinkage cracking in the early age.

Theory of nonlinear moisture diffusion. The analysis method of concrete shrinkage deformation based on the moisture diffusion theory as a refinement of analytical tools can solve the calculation of shrinkage in concrete structures. Kim [8] neglected the interaction between the drying shrinkage and autogenous shrinkage and established the analysis method of shrinkage considering the autogenous shrinkage based on the theory of moisture diffusion. The enperiment results and the calculated results are consistent. Huasheng Xu and Zhengwu Jiang [9] research on the relationship of the relative humidity change and the autogenous shrinkage of high-strength concrete. They obtained the conclusion that the autogenous shrinkage and the relative humidity has a significant linear relationship. Haidong Huang and Zhongfu Xiang [5,10] used the nonlinear moisture diffusion theory considering the autogenous shrinkage and drying shrinkage to analysis the structural deformation caused by shrinkage difference in different parts of the structure.

In the drying process, the internal relative humidity decreasing leads to structural volume changes and shrinkage deformation. Concrete drying shrinkage and autogenous shrinkage process, were shown to decrease the humidity of concrete. Concrete relative humidity changes as:

$$\Delta h = \Delta h_d + \Delta h_a \tag{7}$$

Where, Δh is the total inner variation of relative humidity, Δh_d is the variation of relative humidity due to moisture diffusion of evaporation, and Δh_a is the variation of relatitive humidity due to autogenous shrinkage.

Thus, variations of internal relative humidity in concrete are expressed as the variation of relative humidity due to moisture diffusion and autogenous shrinkage of concrete, as shown in Eq. (8):

$$\frac{\partial h}{\partial t} = \frac{\partial h_d}{\partial t} + \frac{\partial h_a}{\partial t} \tag{8}$$

Using Fick's second law to establish concrete moisture diffusion equation, as shown in Eq. (9):

$$\frac{\partial h}{\partial t} = div\left[D(h)\cdot grad(h))\right] + \frac{\partial h_a}{\partial t} \tag{9}$$

Where, $D(h)$ denotes the moisture diffusion coefficient. In CEB-FIP (1990) model code [2], the moisture diffusion coefficient for isothermal conditions is expressed as function of the pore relative humidity as seen in Eq. (3-4):

$$D(H) = D_1\left[\alpha + \frac{1-\alpha}{1+\left[(1-h)/(1-h_c)\right]^n}\right] \tag{10}$$

Where D_1 is the maximum of $D(H)$ for H=1.0, h_c is the pore relative humidity at $D(H) = 0.5D_1$, α、n are the experimental constant. When lacking of experimental data, $\alpha = 0.05$, $h_c = 0.8$, $n = 15$, $D_1 = \frac{D_{1.0} f_{ck0}}{f_{ck}}$, $D_{1.0} = 3.6\times10^{-6} m^2/h$ are approximately assumed; $f_{ck0} = 10MPa$, f_{ck} is the

Characteristic strength which can be estimated by the average compressive strength, $f_{ck} = f_{cm} - 8.0MPa$.

The nonlinear moisture diffusion equation, as shown in Eq. (9), was formulated by finite element method, considering the boundary condition in previous study [11]. As the boundary condition of moisture, it is necessary to correlate the surface moisture with the humidity of the environmental atmosphere. On the exposed surface S, the boundary condition is shown in Eq. (11):

$$D(h)\cdot grad(h)|_s = f(h_e - h_s) \tag{11}$$

Where: f is the surface humidity convection coefficient, h_e is the environmental humidity, and h_s is the relative humidity on the exposed surface.

The coupling relationship between humidity and shrinkage. When $0.6 < h < 1.0$ [12], Concrete shrinkage and humidity change exist the approximate linear relationship shown in Eq (12):

$$\Delta\varepsilon_{sh} = \beta\Delta h \tag{12}$$

Where: β is the shrinkage coefficient associate with inner relative humidity.

From the Eq.(4), Eq.(5), Eq.(6), Eq.(12), we can obtain the function of the rate change in humidity in the autogenous shrinkage process of concrete. Shown as Eq.(13):

$$\frac{\partial h_a}{\partial t} = \frac{0.1\varepsilon_{cas0}e^{-0.2\sqrt{t}}}{\beta\sqrt{t}} \tag{13}$$

Box girder cross-section shrinkage analysis. In this paper, the ordinary rapid hardening cement is used, f takes 0.0003m/day, h_e takes 0.7, β takes 0.0012, the initial relative moisture of the concrete takes 1.0; Other parameters take as the first section describe.

The results at different age are shown in Fig.5，Fig.6，Fig.7，and Fig.8.

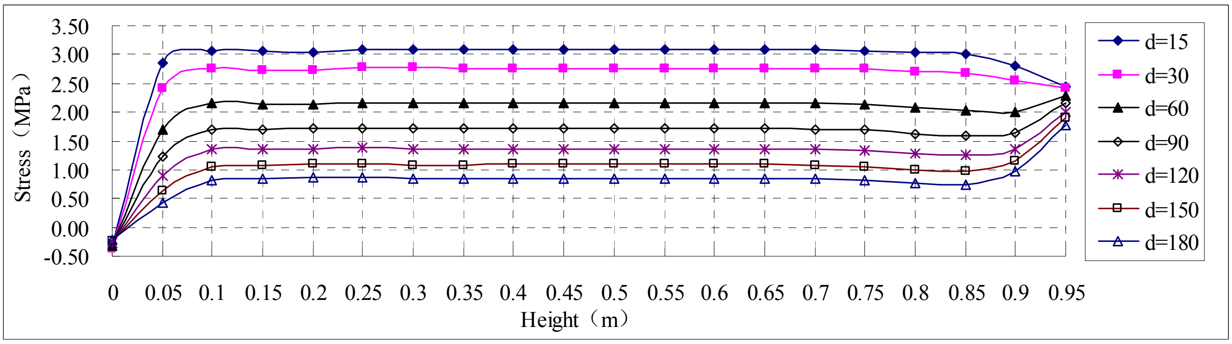

Fig.5 Vertical shrinkage stress distribution of the web outer surface at different age

From Fig.5, it can be noted that the shrinkage stress in the outer surface of the web is uniform between the heights of 0.1m to 0.85m. In 15 days, the tensile stress at the outer surface reach 3.09MPa, but the tensile of the concrete at this time in small, so the surface of the web may be cracking. After 15days, the shrinkage stress reduces gradually as the time increasing.

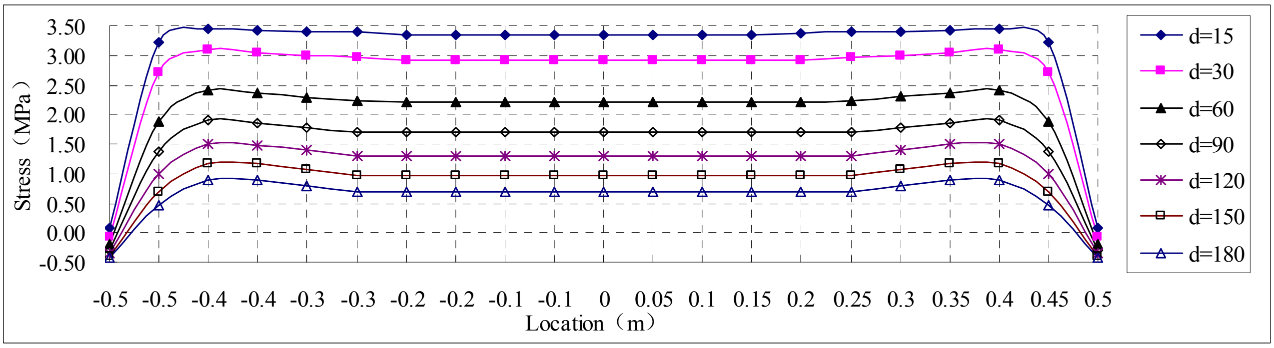

Fig.6 Horizontal shrinkage stress distribution of the bottom slab outer surface at different age

From Fig.6, it can be seen that the shrinkage stress in the outer surface of the bottom slab is uniform between the locations of -0.4m to 0.4m. In 15 days, the tensile stress at the outer surface reach 3.45MPa.But the tensile of the concrete at this time in small, so the surface of the web may be cracking. After 15days, the shrinkage stress reduces gradually as the time increasing.

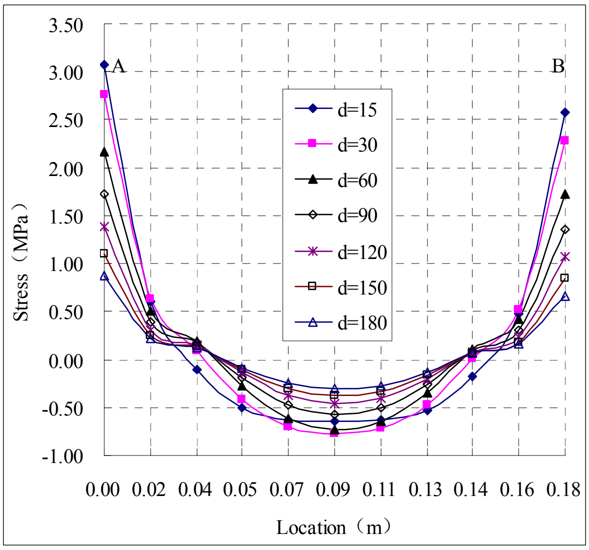

Fig.7 The vertical shrinkage stress distribution curve from point A to point B

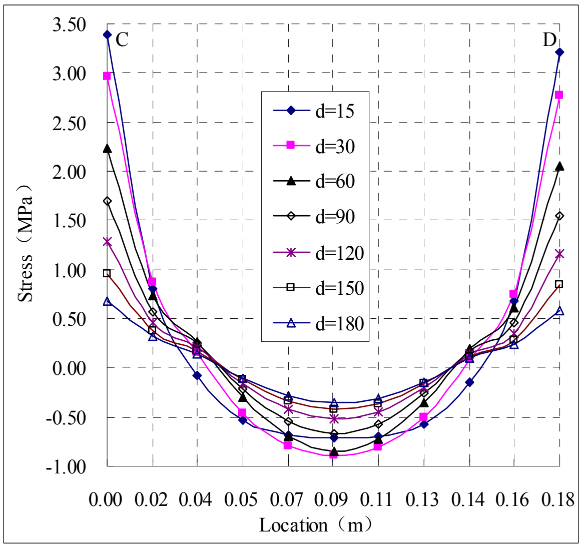

Fig.8 The horizontal shrinkage stress distribution curve from point C to point D

From Fig.7 and Fig.8, it can be shown shrinkage will cause tensile stress in the surface and the compressive stress in the inside of the web end bottom slab. The tensile stress is larger in the surface than other place. The tensile stress reduces drastically along the depth form the surface to the inner. Whether the web or the bottom slab, the tensile stress is less than 1.0MPa at the depth of 0.02m. if the concrete cracking caused by shrinkage, that is limited to the surface.

Temperature difference and shrinkage work together

The box girder will receive the combined effects of shrinkage and temperature difference. In the bridge inspection, the longitudinal crack generally occurs within the scope of height 0.5m in the web and within the scope 0.3m form the edge in the bottom slab. Considering the results of the previous analysis, we select the point A at the height of 0.25m on the web surface and the point B at bottom slab surface 0.25m from the edge as shown in Fig. 2 to analysis the stress of temperature difference and shrinkage work together. The analysis results are shown in Fig.9 and Fig.10.

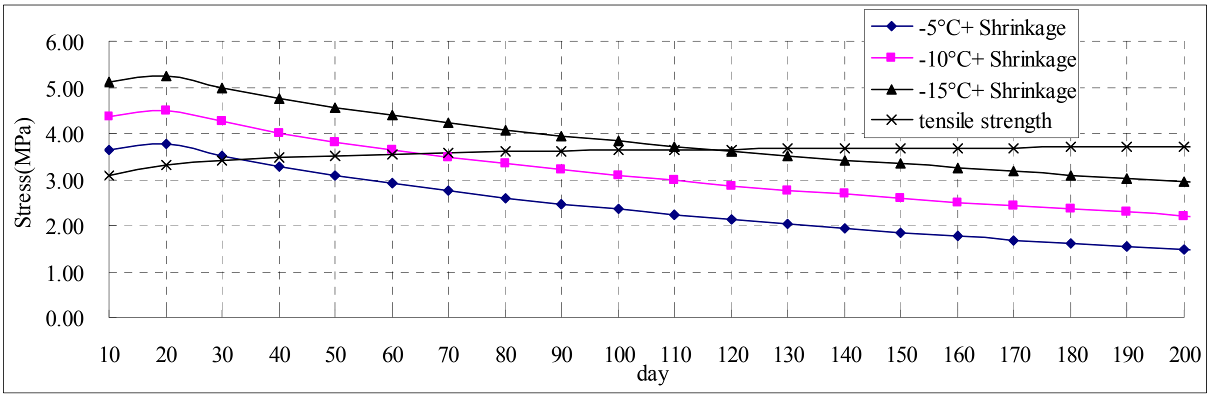

Fig.9 Vertical stress curve of point A

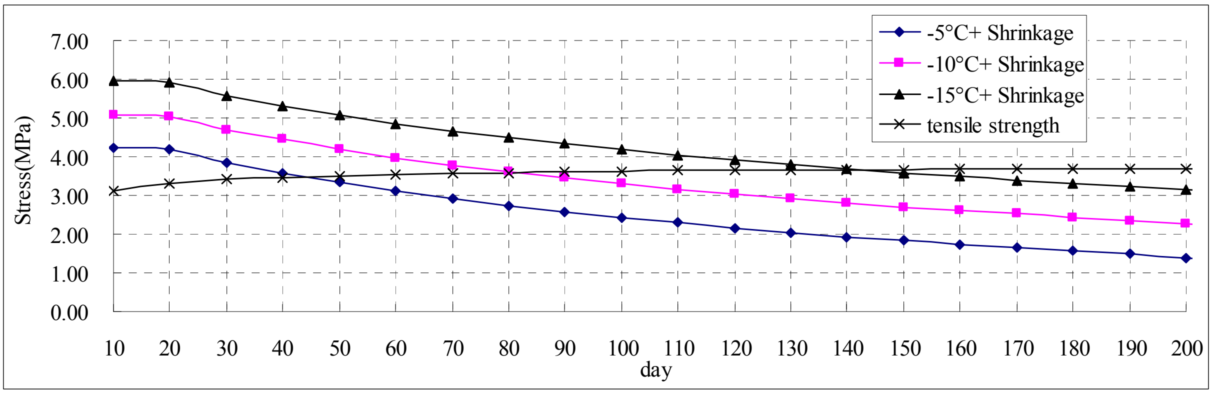

Fig.10 Horizontal stress curve of point C

From Fig. 9, considering the shrinkage stress, the point A of the web can withstand the negative temperature difference -5℃ at the age of 35 days, -10℃ at the age of 65 days, -15℃ at the age of 115 days. In Fig. 10, considering the shrinkage stress, the point C of the bottom slab can withstand the negative temperature difference -5℃ at the age of 45 days, -10℃ at the age of 80 days, -15℃ at the age of 140days. If received the negative temperature difference at the earlier age than them, the concrete may be cracking. In northeast China, especially in Heilongjiang province, if the box girder is casting at September or October, it is likely to encounter the negative temperature greater than -10℃. In the prestressed box girder, we must consider the transverse stress caused by the longitudinal prestressing. Thus the box girder cracking is common in the Heilongjiang province.

Conclusions

The main conclusions of this study are:

(1) The outer surface of the web and bottom slab of the fabricated box girder will produce tensile stress at the effect of negative temperature difference. If the concrete reaches a certain age, the tensile stress does not cause creaks in the cross-section.

(2) The shrinkage stress changes with the moisture gradient in the box section. It will reach the maximum in 15 days and then decreases with the growth of the age. Shrinkage stress may cause cracking of the concrete surface because of the tensile strength is low in the early age.

(3) Considering the temperature difference and shrinkage work together, if the box girder withstand the negative temperature difference too early, the surface of the section will crack. But as the tensile strength increasing and the shrinkage stress decreasing with the age growing, Concrete can withstand a large negative temperature difference without cracking.

(4) In northeast China, especially in Heilongjiang province, if the box girder is casting at September or October, it is likely to encounter the negative temperature greater than -10℃. In the prestressed box girder, we must consider the transverse stress caused by the longitudinal prestressing. Thus the box girder cracking is common in the Heilongjiang province.

In order to avoid the longitudinal cracking of the box-girder, there are some recommendations:

(1) Take the optimization of concrete mix proportion to improve the tensile strength of concrete.

(2) Strengthen the conservation of the concrete to reduce the shrinkage deformation in the early age.

(3) Set vents in the web and the bottom slab to enhance air circulation to reduce the temperature difference between the inside and outside of the box.

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