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Variation of Temperature Stress for Concrete in Industrial Intelligent Steam Curing Environment

Wu Mengshan[1, a], Yang Xiaoyan[2, 3, b, *], Qiu Songli[3, c]

[1]*School of Civil Engineering, Chongqing Jiaotong University, Chongqing, 315000, China*
[2] *School of Civil Engineering & Architecture, Ningbo Tech University, Ningbo, Zhejiang, 315000, China,*
[3]*Ningbo Communication Engineering Construction Group Co., Ltd., Ningbo, Zhejiang, 315000, China,*
[a]*wmengshan@163.com,* [b]*yangxiaoyan0024@126.com,* [c]*328624661@qq.com*
[*]*Corresponding author*

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Abstract: There is a large temperature difference between inside and surface of concrete components for its own hydration degree in the environment of industrial intelligent steam curing. It has a certain negative impact on the quality of concrete. In this paper, the temperature variation and hydration degree of 30m prefabricated T-beams in the whole process are analyzed by field tests. On this basis, industrial production process parameters such as temperature, humidity and curing time are optimized. Theoretical temperature field and stress distribution law which conform to industrial intelligent steam curing production process are proposed by temperature-structure coupling method. The results show that the industrial intelligent steam curing production process includes three stages of heating, constant temperature and cooling. The first curing chamber of concrete is heated to 50℃ with 10℃/h, and then enters the next curing chamber after 5h. The second curing chamber keeps temperature of 50℃ and 0.5h, then cools to 30℃ with 10℃/h, and stops steam input, 2.5h natural cools to end steam. The local stresses concentration for the T-beam and diaphragm are generated with steam curing 10h. The maximum principal tensile stress of diaphragm reaches maximum by sharp drop of ambient temperature with curing 10h.

1. Introduction

With the transformation and upgrading of industrial construction mode, the traditional construction industry is gradually upgraded to the advanced manufacturing industry with design standardization, production industrialization, construction assembly, and management informationization. Nation transport development strategies with Resource-economical and Environment-friendly have been established. In 2020, Ningbo was selected as the first batch of pilot cities of Made in China 2025. Ningbo Communication Engineering Construction Grop and Yintong Group rely on the demonstration project of *Civil Construction TJ-3 Bidding Section of Ningbo Xiangshan Bay Shugang Expressway Kunting to Tangxi Section* to build an intelligent manufacturing research and innovation base for bridge concrete components industrial assembly line to realize the core goal of building industrialization. Key technologies of industrial production such as digital steel processing, combined intelligent integration of mould machine, concrete mixing, feeding, pouring and vibration, intelligent steam curing, prestressed initial tension and girder transportation are proposed. It makes the concrete to reach the specified strength and elasticity modulus in period of time, realize the rapid tension and transportation of prefabricated components, improve the capacity of production line. Compared with the traditional production process, the increase of intelligent steam curing temperature in industrial production accelerates the hydration reaction of concrete. It makes the hydration reaction more complete and improves the early strength. At the same time, it also causes the new hydration products to less evenly spread before hardening. After hardening, they gather around the unhydrated cement particles and form a dense wrapping layer to hinder the further hydration of the wrapped cement particles. Ultimately, it affects strength development of steam cured concrete in later stage [1, 2]. A large number of hydration products precipitate and overlap disorderly in a short period of time, forming thick and connected pores. Porosity and average pore size show an increasing trend, resulting in certain negative effects. In view of the above problems, domestic and foreign scholars improved the production quality of prefabricated components by adding mineral admixtures [3], controlling specific parameters of steam curing [4], carrying out subsequent water curing after steam curing or surface moisturizing covering treatment during steam curing and adding appropriate amount of phosphate [5].

In this paper, the field test and digital simulation method were used to analyze the internal temperature field and temperature stress of 30m prefabricated T-beam produced by industrial assembly line in four different steam curing environments. The temperature and humidity parameters of intelligent steam curing were optimized to determine the optimal intelligent steam curing production process.

2. Optimization of Industrial Intelligent Steam Curing Parameters

The Standard for *Test Methods of Mechanical Properties of Ordinary Concrete* [6] stipulates that standard curing conditions of concrete are (20±2) ℃ of temperature, more than 95% of humidity, and mold release curing. Molds and components of prefabricated T-beam in industrial production are loaded through mobile trolleys which needs to be circulated in each station according to fixed design beat. The concrete before intelligent steam curing has short resting time and incomplete solidification hardening. Due to the limitations of these production processes, the side and bottom surface of prefabricated T-beam are provided with steel formwork, and the top surface is open. Therefore, the temperature field and hydration for each section of prefabricated T-beam were analyzed under different steam curing environments.

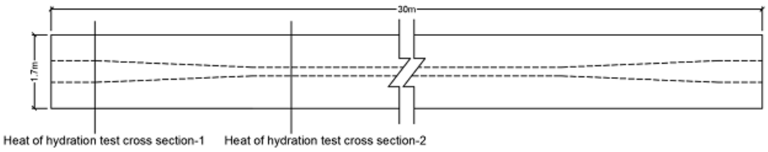
2.1 Design of Experiment

The temperature differences of spatial positions, hydration and temperature change of concrete under different temperature and humidity control conditions in intelligent steam curing environments are analyzed by field test of 30m prefabricated T-beam. A total of 48 conditions are considered in this test, including intelligent steam curing environment, longitudinal and vertical of cross section position. The control parameters of temperature and humidity in intelligent steam curing are shown in Table 1.

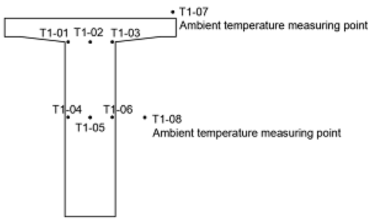
Table 1: Temperature and Humidity Control Parameters of Intelligent Steam Curing Environment

Number of conditions	Intelligent steam curing condition and time
Condition 1-T01	First step: from natural environment temperature to 60℃ for 2h; Second step: duration 60℃ for 6h; Third step: shut off the steam input, natural cool 2h in steam curing chamber. The total time of prefabricated T-beam in steam curing chamber is 10h.
Condition 2-T02	First step: from natural environment temperature to 60℃ for 2h; Second step: duration 60℃ for 6h; Third step: shut off the steam input and open the door of curing chamber, natural cool 19h in steam curing chamber. The total time of prefabricated T-beam in steam curing chamber is 27h.
Condition 3-T03	First step: from natural environment temperature to 50℃ for 2h; Second step: duration 50℃ until the internal average temperature reaches 50℃, shut off the steam input. Third step: natural cool. The total time of prefabricated T-beam in steam curing chamber is 10h.
Condition 4-T04	Change curing chamber. First curing chamber: from natural environment temperature to 50℃ for 2h, and duration 50℃ for 3h; Second curing chamber: duration 50℃ for 4h, shut off the steam input and natural cool. The total time of prefabricated T-beam in steam curing chamber is 10h.

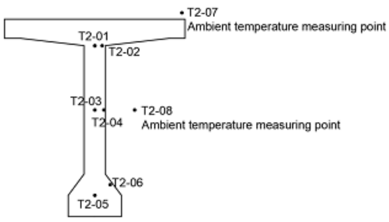
The arrangement of early heat of hydration test cross section and temperature field measuring points of prefabricated T-beam are shown in Figure 1(b) and Figure 1(c). Wherein, 01 to 06 points are arranged on cross section, 07 and 08 points are arranged in prefabricated T-beam ambient.



(a) Early heat of hydration test cross section



(b) Measuring points of end section



(c) Measuring points near mid-span section

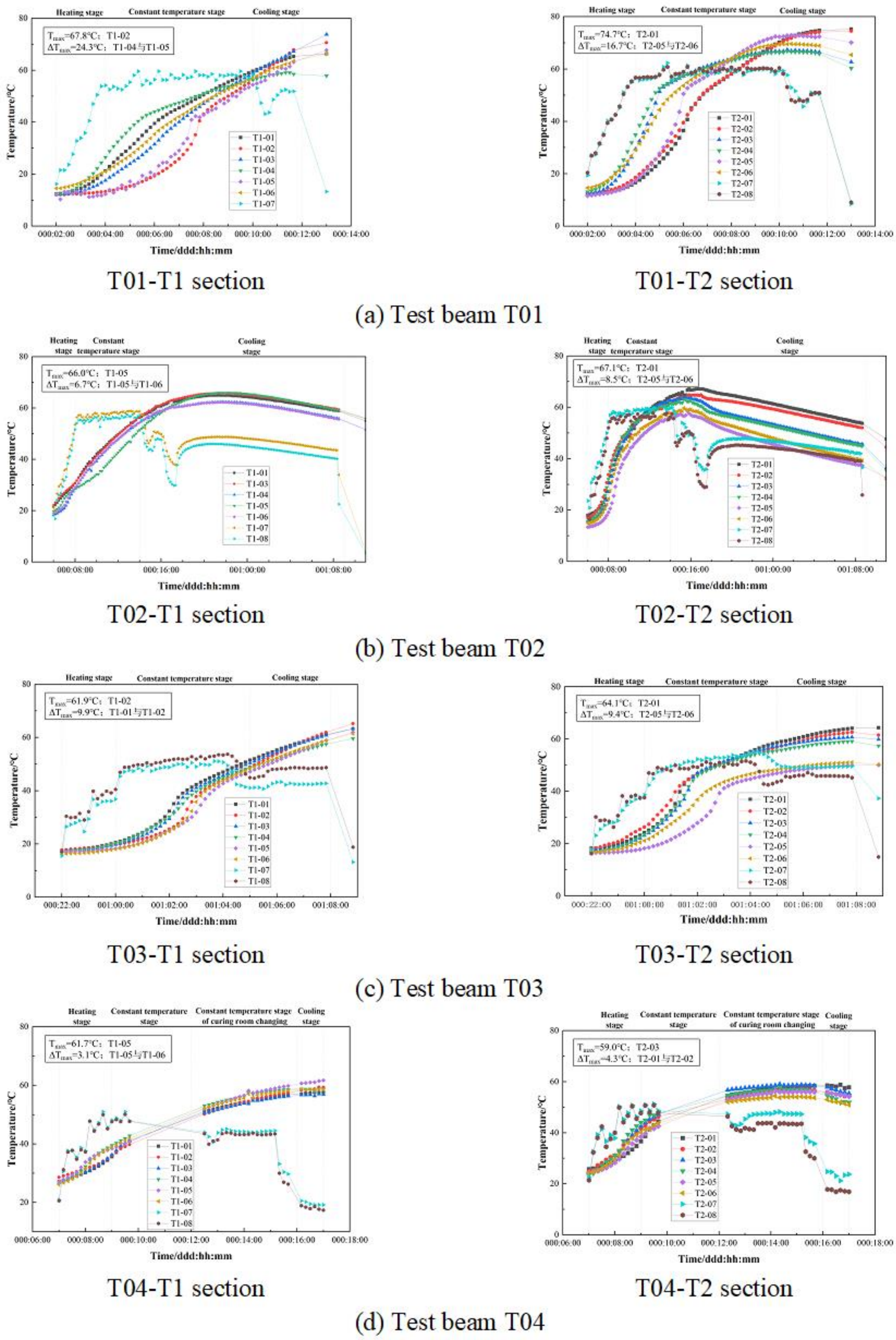
Figure 1: Layout Diagram of Test Section and Measuring Points for Early Hydration Heat

Four test beams are designed by the environment parameters of steam curing in Table 1 and construction requirements. The intelligent steam curing parameters are adjusted in real time according to the test results. Early hydration heat data was collected at an interval of 10min per time.

2.2 Analysis of Result

Temperature curves of test beams T01 to T04 in the intelligent steam curing process are shown in

Figure 2.



T01-T1 section T01-T2 section

(a) Test beam T01

T02-T1 section T02-T2 section

(b) Test beam T02

T03-T1 section T03-T2 section

(c) Test beam T03

T04-T1 section T04-T2 section

(d) Test beam T04

Figure 2: Temperature Variation Curve of Prefabricated t-Beam Section in Whole Process

It can be seen from Figure 2, the maximum temperature and temperature gradient of T01 beam are relatively large, while the T02 to T04 beams are relatively low. Environmental temperature of different heights are also different in the steam curing chamber. The top temperature is higher than the middle position. The maximum temperature in the prefabricated T-beams appeared in the web site, where the hydration degree is more sufficient. In the early stage, the steam curing temperature has a significant effect on the temperature of concrete. Therefore, process parameters for the intelligent steam curing production are preliminarily set: First curing chamber: from natural environment temperature to 50℃ with 10℃/h for 3h, and duration 50℃ for 2h; Second curing chamber: duration 50℃ for 0.5h, cool to 30℃ with 10℃/h for 2h, then shut off the steam input, natural cool for 2.5h.

3. Finite Element Analysis of Temperature Effect under Intelligent Steam Environment

Based on the temperature-time curves of prefabricated T-beams by field tests, the key temperature of production process for heat-constant temperature-cool in steam curing are determined. The temperature-structure coupling analysis of 30m prefabricated T-beam under intelligent steam curing environment is analyzed by ABAQUS. The theoretical temperature field and stress distribution of concrete are obtained.

3.1 Simulation of Temperature Field

The concrete temperature field is simulated by heat transfer element with DC3D8, the stress field is simulated by solid element with C3D8R, and the steel is simulated by truss element with T3D2. The finite element model is shown in Figure 3.

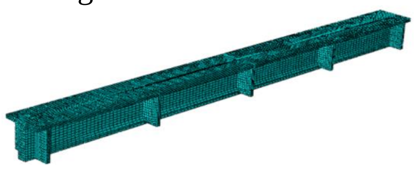


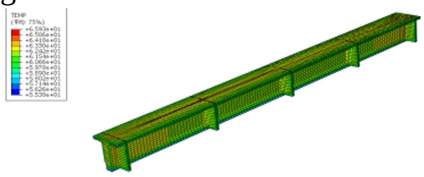
Figure 3: Mesh Generation of 30m Segmental Prefabricated t-Beam

The simulation of temperature field is divided into two stages according to the environment temperature: (1) rising stage in steam curing chamber for 10h; (2) decreasing stage in natural environment for 6h to demould and stretch initial stress. That is to say, the environmental temperature happens suddenly in the whole process. According to the above experimental results, the initial mold temperature is 20℃. Leaving steam curing chamber, the environment temperature is 10℃. In the temperature field analysis, the heat conduction and heat exchange inside concrete are defined by the thermal conductivity and specific heat capacity. The thermal conductivity of concrete is 2.70 W/m·K, and the specific heat capacity is 928J/kg·K. Considering that concrete is inside the steel formwork, the heat exchange coefficient between concrete and air is treated without wind speed [7], it takes as 21.06kJ/(m^2 ·h ·℃). In addition, the thermal load from hydration heat of cement is considered in temperature field of concrete. The exothermic process is consistent with the adiabatic temperature rise process, which can be determined by Equation (1) [7, 8].

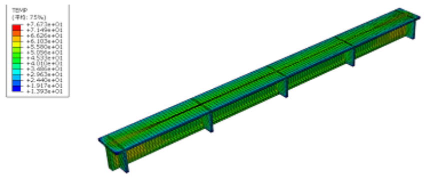
$$q_v = \frac{Q_0}{90}\left(\frac{t}{24}\right)^{-0.26} e^{-0.36\left(\frac{t}{24}\right)^{0.74}} \qquad (1)$$

Where, qv is the heat release rate of concrete hydration, J/m^3/hr; Q0 is the final heat of hydration, which is 364000J/kg.

It can be seen from Figure 2 that environmental temperature of different heights are also different in steam curing chamber, and the temperature at the top surface is slightly higher than side surface and bottom surface. Temperature boundary conditions are applied to top surface, side surface and bottom surface, respectively. Figure 4 shows the temperature field distribution during steam curing chamber.



Temperature field of T-beam at 10h

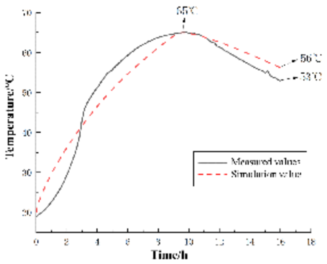


Temperature field of T-beam at 16h

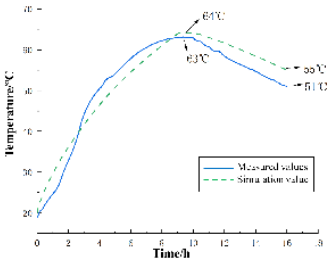
Figure 4: Temperature field distribution diagram of prefabricated T-beam during curing process

As shown in Figure 4, the maximum temperature of T-beam at 10h is 65.9℃, which appears at the joint of roof and web. At 16h, the maximum temperature reaches 76.7℃, which appears at the joint of roof and web.

In order to ensure the accuracy of finite element model, two measuring points on the mid-span section are selected to compare the theoretical value with actual value. The comparison between the measured temperature and the simulated temperature on the mid-span section is shown in Figure 5.



(a) Temperature comparison of T2-02



(b) Temperature comparison of T2-04

Figure 5: Comparison of measured temperature and simulated temperature in midspan section

As shown in Figure 5 that the theoretical highest temperatures of 02 and 04 points on T2 section are respectively 65℃ and 64℃, and close to the measured temperatures. Theoretical temperature of 02 and 04 points are respectively 56℃ and 55℃ for 16h, and close to the measured temperatures. Therefore, the temperature field model established can reflect the actual steaming environment of prefabricated T-beams.

3.2 Temperature Stress of Concrete

3.2.1 Temperature Stress of Main Beam

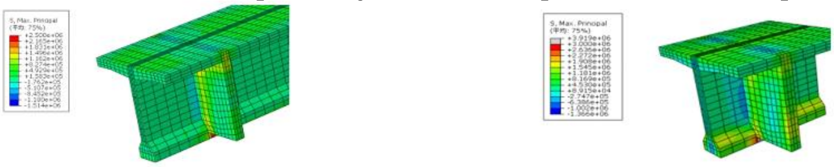
The maximum stress distribution of prefabricated T-beam in steam curing chamber for 10h and nature curing chamber before demould for 16h are shown in Figure 6. The results show that the maximum stress distribution of mid-span section in steam curing chamber is relatively uniform, it takes as 0.2MPa. There is a small amount of compressive stress at the bottom core and top middle surface, that is -0.2MPa. At second stage, the maximum tensile stress at lower part is 1.5MPa. At the bottom edge and top core, the maximum compressive stress reaches -0.7MPa.

(a) At 10 hour (b) At 16 hour

Figure 6: Maximum Principal Stress of t-Beam

3.2.2 Temperature Stress of Diaphragm

The maximum principal stress clouds of diaphragm for intelligent steam curing at the 10h and before prestressed tension at the 16h are shown in Figure 7. It can be seen from Figure 7 that the maximum principal tensile stress of diaphragm is 2.5MPa at its lower part due to the constraints and section mutation. At the end of the second stage, the maximum principal tensile stresses of diaphragm are 3MPa and 1.5MPa respectively at the lower part and the lower part of the outer part.



(a) At 10 hour (b) At 16 hour

Figure 7: Maximum Principal Stress of Diaphragm

4. Conclusion

(1) The parameters such as temperature and time are optimized by field test. The parameters for the intelligent steam curing are preliminarily set: First curing chamber: from natural environment temperature to 50℃ with 10℃/h for 3h, and duration 50℃ for 2h; Second curing chamber: duration 50℃ for 0.5h, cool to 30℃ with 10℃/h for 2h, then shut off the steam input, natural cool for 2.5h.

(2) Theoretical temperature field of 30m prefabricated T-beams is analyzed by temperature-structure coupling method. The results show that the maximum temperature, occurrence time and location of curing environment in simulation are consistent with the test results.

(3) At the end of the first stage of steam curing chamber, stress concentrations are occurred in beam and the diaphragm. The maximum principal tensile stress of the beam and diaphragm are respectively 1.5MPa and 1.2MPa, which theoretically would not cause beam cracking. In the second stage, the sudden drop of external temperature increases the maximum principal tensile stress of diaphragm. Therefore, it is necessary to pay attention to the adverse impact of the sudden drop of external temperature on T-beam in actual construction.

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