Coupled Thermo-mechanical Analysis of Concrete Pavements under Heavy Traffic

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ABSTRACT The tensile stresses of concrete pavements corners, edge centers, and surface centers under heavy traffic are analyzed as the pavements already deflected under temperature stresses. First, a transient temperature field of the pavements in summer and winter extreme weather is solved on ABAQUS. Then, the temperature field is imported into the mechanical model for coupled thermo-mechanical analysis, to obtain the temperature stresses and deflection of the pavements. Then, a vehicle load is located at different positions of pavements in different time; the tensile stresses of pavements are analyzed and received the most unfavorable combination of vehicle load and temperature stresses. The concrete pavements with thermal deflection may appear fracture at the corner and the edge center at 14:00PM in summer under once over-axle-load, so the linear combined fatigue failure theory of vehicle load and temperature stresses is not applied to concrete pavement under the over-axle-load.

INTRODUCTION

The joints are set up several meters in concrete pavements (CP) to reduce the temperature stresses. But, the joints easily lead to slab crack, dislocation, failures and freeze-thaw damage as water infiltrating. CP temperature field has been studied by many scholars (Jin-Hoon Jeong 2006, Xu Hong 2009, Dong Wang 2009, 2012, Matthew R. Hall, 2012). And temperature stresses, gradient stresses and slab warp are analyzed (Rania E. Asbahan 2011, Zhou Lan 2012). Fatigue of CP under heavy traffic is (Hsiang-Wei Ker 2008, Lu Gao 2012). On coupled thermal-mechanical analysis, the CP in cold region under heavy traffic is studied in this paper.

CP TEMPERATURE FIELD FUNCTION

Heat Transfer Equation of CP Temperature Field

The CP has three layers: the first is concrete slab with length of 5m, width of 6m, thickness of 0.24m, the second is base with thickness of 0.4m, the third is subgrade with thickness of 1.5m. The heat transfer equation of CP temperature field as follow: A cross section is vertical to the line. The vertical down direction is ‘x’ axis. Assuming the 1 layer
The conductive coefficient of temperature is $a_i$, the conductive coefficient of thermal is $\lambda_i$, the thickness is $h_i(h_i=\infty)$, the temperature function is $T_i(x,t)$, then, $T_i(x,t)$ should meet the heat transfer equation, as follow:

$$\frac{\partial T_i}{\partial t} = a_i \left( \frac{\partial^2 T_i}{\partial x^2} \right) \quad i = 1, 2, \ldots, n$$

$t=$time variable.

Between the pavement and base transfer boundary as follows:

$$\lambda_1 \frac{\partial T_1}{\partial x} = \lambda_2 \frac{\partial T_2}{\partial x}$$

$$|T_i(x,t)| \leq M \quad (x \to \infty)$$

$M$ is a finite constant.

**Boundary Conditions of Temperature Field**

**Solar Radiation**

Periodic of CP temperature field is influenced by solar radiation, and can be approximately described as the cosine functions:

$$q(t) = \begin{cases} 
0 & 0 \leq t < 12 - \frac{c}{2} \\
q_0 \cos m\omega(t - 12) & 12 - \frac{c}{2} \leq t \leq 12 + \frac{c}{2} \\
0 & 12 + \frac{c}{2} < t \leq 24 
\end{cases}$$

$q_0=$maximum radiation;
$q_0=0.131\,m\,Q$;
$m=12/c$;
$Q=$total solar radiation in a day ( $J/m^2$);
$c=$effective time of sunshine (h);
$\omega=\text{the earth's rotation frequency}$, $\omega=2\pi/24$, rad.

**Air Temperature**

A linear combination of the double sine function issued to simulate the temperature’s diurnal variation function:

$$T_a = \overline{T_a} + T_a \left[ 0.96\sin \omega(t - t_0) + 0.14\sin 2\omega(t - t_0) \right]$$

$\overline{T_a}=$daily average temperature;
$T_a=$daily temperature variant amplitude;
$t_0 =$initial time, usually, taking $t_0=9\,h$. 

1006
Air Convection

The heat exchange of the atmosphere on CP surface is influenced by wind:

\[ h_v = 3.7v_\omega + 9.4 \]  \hspace{1cm} (6)

\( h_v \) = heat exchange coefficient, W/(m\(^2\)·℃);
\( v_\omega \) = the speed of wind, m/s.

Effective Radiation of the CP

The effective radiation of the CP is calculated by Stefan-Boltzmann's law:

\[ q_r = \varepsilon\sigma \left( T_1 | z=0 - T_z \right)^4 - \left( T_a - T_z \right)^4 \]  \hspace{1cm} (7)

\( q_r \) = effective radiation of the CP surface, W/(m\(^2\)·℃);
\( \varepsilon \) = CP surface emissivity (blackness), \( \varepsilon = 0.7 \);
\( \sigma \) = black body radiation coefficient; \( \sigma = 5.6697 \times 10^{-8}\) W/(m\(^2\)·K\(^4\));
\( T_1 | z=0 \) = CP surface temperature;
\( T_a \) = atmospheric temperature;
\( T_z \) = absolute zero degree value, \( T_z = -273℃ \).

NUMERICAL ANALYSIS of CP

FORTRAN subroutines of heat transfer of CP surface with atmosphere, solar radiation, and air are programmed on ABAQUS heat transfer platform. On thermal conductance function, the thermal conductivity between the CP and the base is defined.

Table 1. Thermal Physical Parameters and Size of CP.

| Material | Heat \( J/(kg·℃) \) | \( \rho \) g·m\(^{-3}\) | \( \lambda \) J·(m·h·℃\(^{-1}\)) | Thick (m) | E (MPa) | \( \mu \) | Ex (℃) |
|----------|----------------|----------------|-------------------------|-----------|--------|--------|--------|
| CP       | 973            | 2500           | 8388                    | 0.2       | 3.25×10\(^4\) | 0.15   | 1×10\(^{-5}\) |
| Base     | 912            | 2200           | 5616                    | 0.4       | 1200   | 0.2    | -      |
| Sub      | 1040           | 1800           | 5500                    | 0.6       | 45     | 0.4    | -      |

On these bases, temperature field, stresses, and deflection that are calculated in summer and winter extreme weathers. On temperature field, 8-node first-order thermal conduction hexahedral elements DC3D8 are used. On stresses, 8-node first-order stress hexahedral elements (C3D8) are used, and the total number is 15840. The thermodynamic parameters and the geometrical dimension of CP are shown in Table 1.

Numerical Analysis of the CP Temperature Field

Only a half of cross section is analyzed. The lowest air temperature appears at 6:00AM
in winter, and the highest at 14:00PM in summer as figure 1-2. Step of temperature field appears on the contact area of the CP with the base.

![Figure 1. T of CP at 6:00AM in winter.](image1)

![Figure 2. T of CP at 14:00PM in summer.](image2)

The CP temperature field within 24 hours in summer and winter extreme weathers as figure 3-4: the temperatures at points such as (surface h=0m, center h=0.12m, bottom h=0.24m) present periodical variation rules. And at the edges, they are more obvious than center.

![Figure 3. Temperature of CP with time.](image3)

![Figure 4. Temperature-depth of CP.](image4)

Note: W-Winter, T-Temperature, S-Summer, h-depth; 6-6:00AM; 14-14:00PM.

Although the temperature gradient in winter is smaller than summer, the temperature gradient direction is operated to summers', that lead to the CP slab end warped by the sum of temperature gradient vectors in winter and summer.

**CP Temperature Stresses**

The temperature field is imported into the mechanical model of the CP to calculate temperature stresses. The temperature stresses and the slab end warped are analyzed at 14:00PM and 6:00AM, respectively, in typical summer cloudless weather:

**CP TEMPERATURE STRESSES VEHICLE LOAD COUPLED ANALYSIS**

The center positions of nine axles load are selected on the basis of the above CP temperature stresses analysis as shown in 7-a: It produces 1.8MPa compressive stress by over-axle-load(300KN), and 0.624MPa compressive stress by standard-axle-load(100KN), which are arranged respectively 1.15m off the center and limited four ranges of 0.2m×0.2m. The tensile stresses at the bottom are analyzed that are caused by coupled vehicle load and temperature stresses, and the above temperature stresses are
produced at 6:00AM and 14:00PM in summer and winter. The results are in table 2, and positions are in figure 5b-f.

**Table 2. Tensile Stress of CP Bottom (MPa).**

| position | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
|-----------|----|----|----|----|----|----|----|----|----|
| 14:00 summer Over | 6.20 | 4.02 | 3.89 | 4.37 | 3.01 | 2.69 | 3.82 | 2.63 | 2.58 |
| Over Standard | 3.13 | 2.39 | 2.32 | 2.48 | 2.00 | 2.00 | 2.15 | 1.78 | 1.77 |
| 6:00 summer Over | 4.51 | 2.37 | 2.19 | 3.02 | 1.62 | 1.51 | 2.56 | 1.34 | 1.27 |
| Standard | 1.42 | 0.67 | 0.60 | 0.97 | 0.53 | 0.47 | 0.80 | 0.40 | 0.37 |
| 14:00 winter Over | 5.85 | 3.66 | 3.45 | 4.08 | 2.63 | 2.53 | 3.88 | 2.57 | 2.43 |
| Standard | 2.65 | 1.88 | 1.80 | 2.00 | 1.51 | 1.48 | 1.89 | 1.45 | 1.41 |
| 6:00 winter Over | 4.80 | 2.60 | 2.39 | 3.25 | 1.82 | 1.70 | 3.12 | 1.78 | 1.63 |
| Standard | 1.58 | 0.81 | 0.74 | 1.14 | 0.64 | 0.58 | 1.08 | 0.62 | 0.56 |

The temperature and vehicle loads and positions of vehicle load have a great influence on the tensile stresses of the pavement bottom. The tensile stresses at the inner corner of pavement are the maximum with 6MPa appearing at 14:00PM, in summer and winter, which have reached or even exceeded the tensile strength of the concrete. These can lead to pavements crack. The tensile stresses at the bottom of the pavements are also around 3MPa in the other positions. The linear fatigue theory of concrete is not applicable, because only once coupled overload and temperature stresses can lead to pavements damage.
By coupled standard-axle-load and temperature stresses, the tensile stresses at the bottom of the inner side of CP are the maximal of 3MPa appearing at 14:00PM in summer and 1~2MPa at other time, the concrete stress rate is about 0.2, at this time. The fatigue stress of vehicle load and temperature stress can be calculated respectively by

\[
\begin{align*}
\text{a) Axle load position} & \quad \text{b) } S11 \text{ in 3d position} \\
\text{c) } S11 \text{ along length 300kN axle load} & \quad \text{d) } S11 \text{ width under 300kN axle load} \\
\text{e) } S11 \text{ length under 100kN axle load} & \quad \text{f) } S11 \text{ width under 100kN axle load}
\end{align*}
\]

Figure 5. T-stresses of CP lower layers under coupled temperature and vehicle.
using the linear fatigue theory of concrete, and the linear superposition method adapt to
determine the fatigue life of the CP.

CONCLUSIONS

The coupled thermo-mechanical analysis of the tensile stresses at the bottom of CP in
winter or summer extreme weathers within 24 hours are mainly based on ABAQUS heat
transfer analysis platform. By comparing the damage of the CP, verified the rationality of
the numerical analysis, and deduced the mechanism of CP damage under heavy load
traffic.

The temperature field of the CP is affected strongly by ambient temperature and solar
radiation, and a nonlinear periodic change with the change of time and depth is presented.
Contact-Thermal-Resistance of the base can effectively hinder heat transfer between the
CP and road bed, and make the temperature field appears a step on the contact surface. In
summer, changes from 20°C to 46°C, the highest appearing at 14:00PM. In winter, the
temperature variation amplitude is synchronous with air temperature, though the phase
has a slight deviation appearing at 14:00PM. Therefore, the change of the CP temperature
is mainly decided by air temperature.

In summer and winter extreme weather, the temperature stresses of the CP are periodic
variation with the temperature field. In winter, the maximum temperature tension stresses
is 10MPa appearing at 6:00AM. The temperature gradient is 12.5MPa/m. In summer, the
maximum temperature tension stresses is 2.4MPa and the temperature gradient is
16.3MPa/m at the same time.

By the coupled temperature stress and overloading vehicles, the maximum bottom
tensile stresses at the inner corner is 6MPa, and it may cause slab corner crack. The
bottom tensile stresses are around 3MPa at other positions. At this time, the linear fatigue
theory of concrete is not applicable, because the only once coupled overload and the
temperature stresses will lead to damage of the pavement.

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