STUDY ON EFFECTS OF NONLINIAR DISTRIBUTION AND SLAB THICKNESS ON THERMAL STRESS OF AIRPORT CONCRETE PAVEMENT

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ABSTRACT

It is needed to consider loading stress due to an aircraft load on concrete slab, thermal stress due to temperature distribution in concrete slab and fatigue damage of concrete due to both stresses in design of airport concrete pavements. However, thermal stress and fatigue damage were considered by safety factor in empirical design method of airport concrete pavement used till 2008 in Japan. For the purpose of clarifying the effects of nonlinear temperature distribution and slab thickness on thermal stress of slab, experimental concrete pavement was constructed, and then, nonlinear distribution of both temperature and strain in the experimental pavement was measured for 1 year. As a result, it was clarified that thermal stress of thick concrete slab is smaller than that of thin concrete slab if temperature differentials between top and bottom of slab are same in both cases, and practical thermal stress equation based on theoretical warping stress equation developed by Westergaard was developed for airport concrete pavement design.

KEY WORDS

thermal stress, warping stress, internal stress, concrete pavement, airport

INTRODUCTION

The design method of airport concrete pavement used till 2008 in Japan was empirical method based on PCA (The Portland Cement Association in United States) method. To determine the thickness of concrete slab in this method, first, loading stress at the center of slab due to landing gear of an aircraft is calculated by computer program based on the chart developed by Picket ant Ray (1951). Next, thickness of slab is determined as the loading stress does not exceed allowable flexural strength of concrete which is design flexural strength of concrete (commonly 5 MPa in Japan) divided by safety factor (1.7-2.2, depending on design coverage). Thus, thermal stress due to temperature distribution across thickness of slab is not calculated quantitatively but considered by safety factor.

To change this empirical design method of airport concrete pavement to mechanistic-empirical method, thermal stress due to nonlinear temperature distribution across slab thickness has to be calculated. On the other hand, Iwama (1964) developed practical thermal stress equation for center bottom of slab as shown in Eq.(1) based on experimental research results for road concrete pavement.

$$\sigma = 0.7 \frac{E\alpha\theta}{2(1-\nu)} \qquad \text{Eq.(1)}$$

where,

σ : thermal stress at center bottom of slab (MPa)
E : elastic modulus of concrete (MPa)
α : coefficient of thermal expansion of concrete (1/^{o}C)
θ : temperature differential between top and bottom of slab (^{o}C)
ν : poisson's ratio of concrete

The fractional part of Eq.(1) is same as theoretical equation of warping stress due to linear temperature gradient developed by Westergaard (1927). The coefficient 0.7 of Eq.(1) was decided based on long-term observation result of experimental concrete pavements of which thicknesses are 20 and 25 cm (commonly thickness of road pavement in Japan). This result said the coefficient 0.7 was decided by the reason of that internal stress at slab bottom due to nonlinear temperature distribution tended to be -30% of daily maximum warping stress at a maximum as shown in Figure 1.

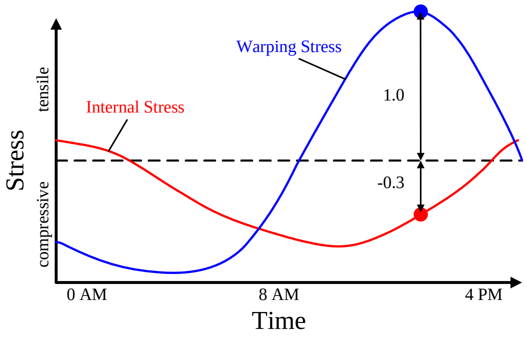


Figure 1: Daily variation of thermal stress (base of Eq. (1))

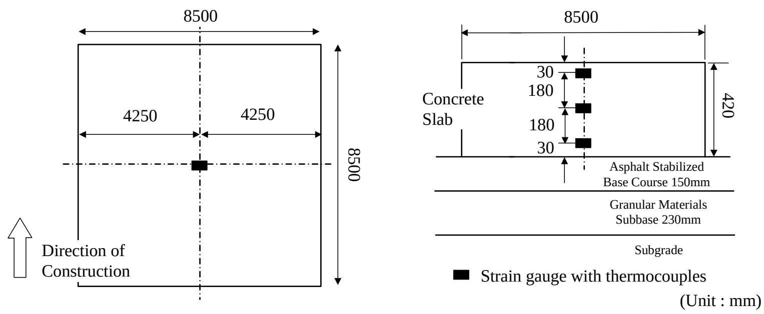
Eq.(1) has being used for design of road concrete pavement in Japan for about 40 years. To change the empirical design method of airport concrete pavement, the effect of slab thickness on thermal stress has been considered because of difference of slab thickness between road pavement and airport pavement. However, no one has confirmed the effect of slab thickness on the relationship between warping stress and internal stress. Zhang (2003) clarified analytically that thermal stress at slab bottom due to nonlinear temperature distribution decreased with increasing of slab thickness.

This paper describes the research results on the effect of slab thickness on thermal stress due to nonlinear temperature distribution across airport concrete slab thickness. First, experimental concrete pavement of which thickness is 42 cm was constructed, and then temperature and strain in the pavement was measured in every hour for 1 year. Next, the relationship between warping stress, internal stress and temperature differential between top and bottom of slab is clarified. Finally, practical thermal stress equation is proposed for airport concrete pavement.

In addition, thermal stress at slab center tends to be larger than that at joint (Westergaard, 1927) though loading stress at slab center is smaller than that at joint. Furthermore, thermal stress varied depending on temperature difference between top and bottom of slab and loading stress varied depending on kinds of aircrafts. These means that very laborious calculation is needed to estimate maximum fatigue damage and its position such as slab center, joint, middle point between slab center and joint based on total stresses, traffic volume of aircrafts and wandering of each aircraft. From these reasons, this paper focuses on thermal stress at slab center.

OBSERVATION OF EXPERIMENTAL PAVEMENT

An experimental concrete pavement was constructed to measure nonlinear distribution of both temperature and strain across the slab thickness as shown in Figure 2.



(a) Plan (b) Section

Figure 2: Plan and section of experimental concrete pavement

Thickness of the slab was 42 cm which was the standard thickness of apron concrete pavement for B747-400 in Japan. Joint spacing of the slab was 8.5 m which was allowable maximum length of airport concrete pavement in Japan. Thermocouples and strain gauges were buried at various depths in the center of slab as shown in Figure 2. Table 1 shows the design properties of cement concrete used for the experimental concrete pavement. After constructing the experimental concrete pavement, strain and temperature distribution across the slab thickness were measured in every hour for 1 year.

Table 1: Design properties of cement concrete

Design flexural strength (MPa)	Slump (cm)	Air content (%)
5.0	5.0	4.5

Calculation Method of Thermal Stress

Thermal stress can be divided to three components, axial stress, warping stress and internal stress as shown in Figure 3. Thus, these three components of thermal stress were calculated from distribution of temperature and strain measured in every hour for 1 year.

A cause of thermal stress is the difference of ideal deformations due to temperature change and actual deformations restrained by several reasons such as slab's own weight and friction between slab and base. To calculate thermal stress due to daily temperature change, first, thermal strain change is calculated as the product of temperature change from base time and coefficient of thermal expansion. Next, restrained strain is calculated as the difference of thermal strain change and actual strain change from base time. Finally, thermal stress is calculated as the product of the restrained strain and the elastic modulus of concrete.

In this study, base time is set at the time in which temperature differential between top and bottom of the slab become close to zero. It appears twice, morning and night, in a day and both warping stress and internal stress become almost zero because temperature gradient and nonlinearity of temperature distribution across slab thickness become almost zero.

Axial stress is very small compared with other two component stresses. Furthermore, axial stress is compressive in daytime and tensile in night time which acts oppositely to whole thermal stress. Thus, it is decided that axial stress is ignored and thermal stress is expressed by sum of warping stress and internal stress in this paper.

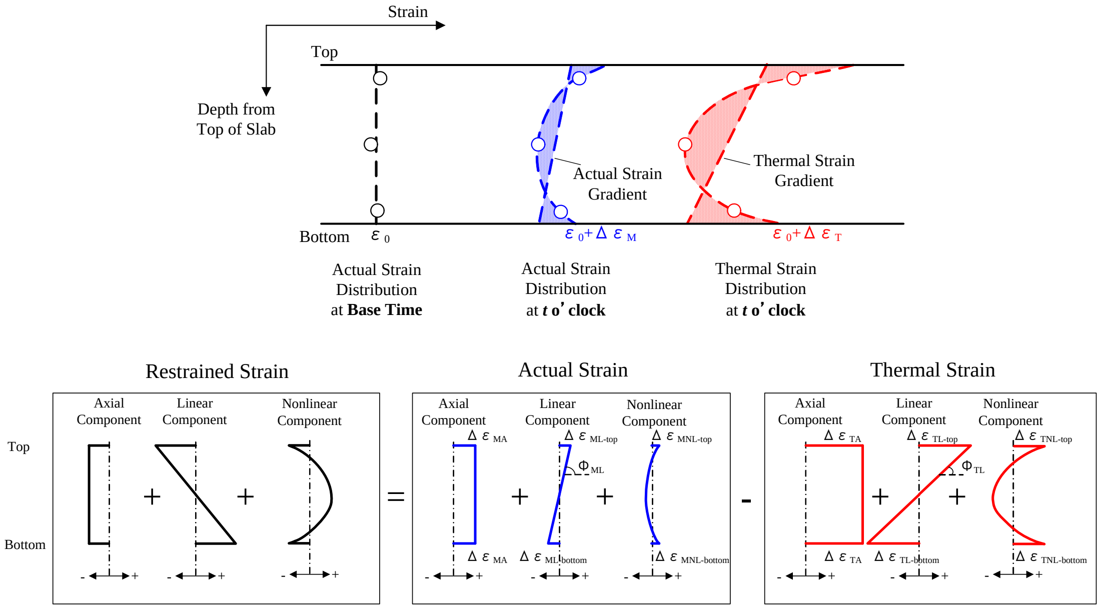


Figure 3: Three components of thermal strain

Warping Stress and Internal Stress

Figure 4 shows daily change of thermal stress at the slab bottom in a summer day. Warping stress at the slab bottom is tensile stress in daytime and increase with increasing of temperature differential of the slab. On the other hand, internal stress at the slab bottom is compressive stress in daytime. Due to the phase shifting of both stresses, thermal stress which is sum of warping stress and internal stress become largest at a few hours after temperature differential become largest in a day.

Figure 5 shows the ratio of internal stress to warping stress when warping stress becomes largest in a day. It is clarified that the mode value of the ratio is 0.5-0.6 and is smaller than 0.7 of Eq.(1) by Iwama (1964).

Figure 6 shows the relationship between daily maximum temperature differential of the slab and daily maximum thermal stress. This result indicates that the coefficient of thermal stress equation in 42 cm thickness slab is smaller than that of Eq.(1) decided by the observation result of 20 and 25 cm thickness slab.

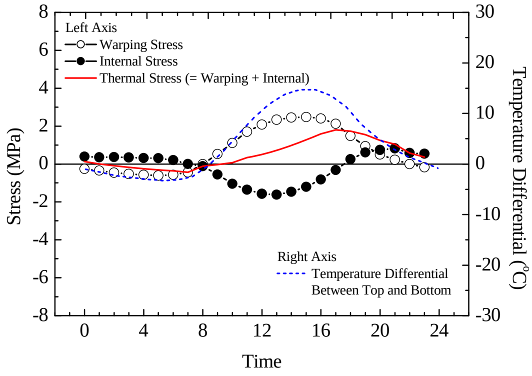


Figure 4: Daily change of thermal stress

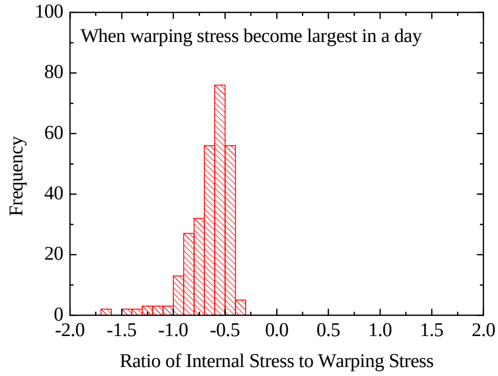


Figure 5: Ratio of internal stress to warping stress

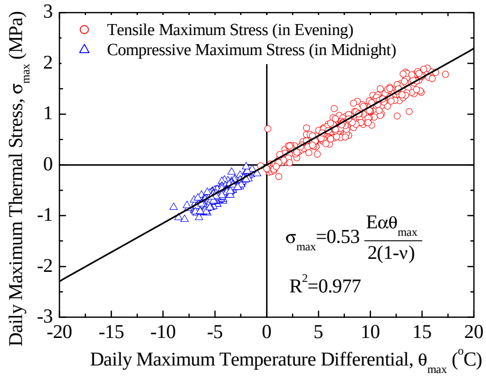


Figure 6: Relationship between daily maximum thermal stress and daily maximum temperature differential of slab

As shown in Figure 4, daily maximum thermal stress tends to appear at a few hours after temperature differential of slab become largest in a day. Thus, the relationship between hourly thermal stress at time *t* and hourly temperature differential of slab at time *t*-3 hours is examined. Figure 7 shows the result. It means that the equation shown in Figure 6 can be used to estimate not only daily maximum thermal stress but also hourly thermal stress by using temperature differential of slab at 3 hours before.

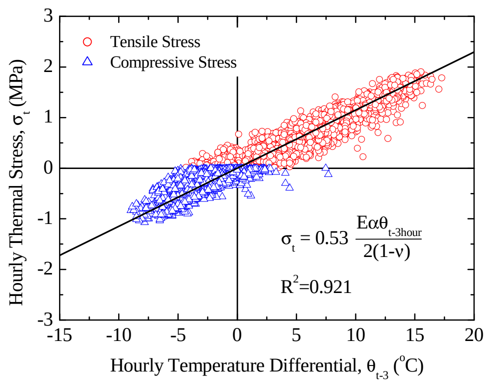


Figure 7: Relationship between hourly thermal stress and hourly temperature differential of slab

As a result of long term observation of the experimental pavements, thermal stress equation for 42 cm slab thickness can be expressed as shown in Eq.(2).

$$\sigma_t = \beta \frac{E\alpha\theta_{t-3}}{2(1-\nu)} \qquad \text{Eq.(2)}$$

where,

σ_t : thermal stress at time t (MPa)

E : elastic modulus of concrete (MPa)

α : coefficient of thermal expansion (1/°C)

θ_{t-3} : temperature differential between top and bottom of slab at time t-3 hours (°C)

ν : poisson's ratio

β : coefficient of thermal stress equation (=0.53 in 42 cm thickness)

EFFECT OF THICKNESS ON THERMAL STRESS

By means of heat balance analysis, temperature distributions of various thicknesses are estimated. In the heat balance analysis, heat conduction in pavement material, heat transfer between slab surface and air and sol-air temperature due to solar radiation are considered. The heat balance analysis is conducted by 2D-FE analysis by using model as shown in Figure 8.

Figure 9 shows the temperature distribution of 26-58 cm slab thickness calculated by using climate conditions in a summer day within the term of experimental pavement observation. Vertical axis in this figure shows the depth from slab surface which is normalized by the slab thickness. This result indicates that temperature differential between top and bottom of the slab of which thickness over 40 cm is almost same but nonlinearity of temperature distribution become larger with increasing of the slab thickness. Thus, internal stress is expected to be larger with increasing of slab thickness.

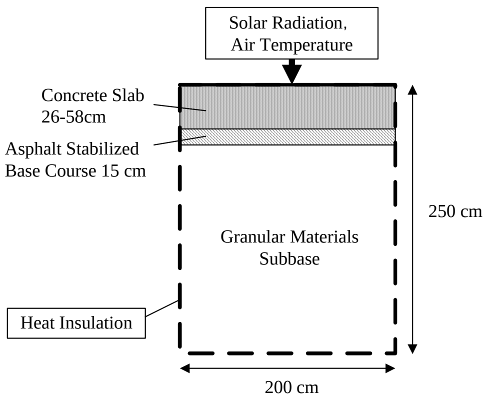


Figure 8: Section of heat balance analysis model

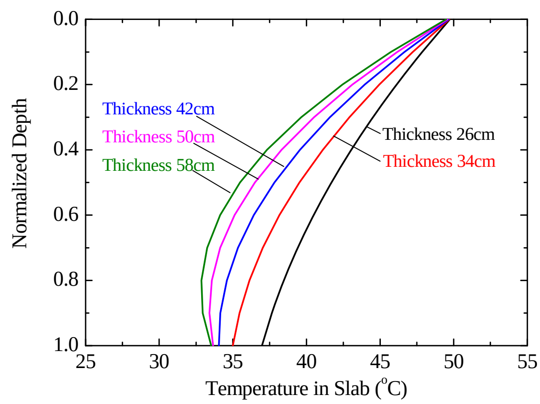


Figure 9: Temperature distribution by heat balance analysis

Based on the hypothesis that actual strain distribution of various thickness of slab due to temperature change are same as that of 42 cm thickness slab measured in the experimental pavement, warping stress and internal stress are calculated by using the temperature distribution shown in Figure 9. Figure 10 shows the relationship between thermal stress coefficient in Eq.(2) and slab thickness. The coefficient tends to decrease with increasing of slab thickness. Considering Eq.(1) by Iwama (1964) and Eq.(2) by this study, the coefficient of thermal stress equation seems to be fall in proportion to slab thickness and thermal stress equation for various thickness can be expressed as shown in Eq.(3).

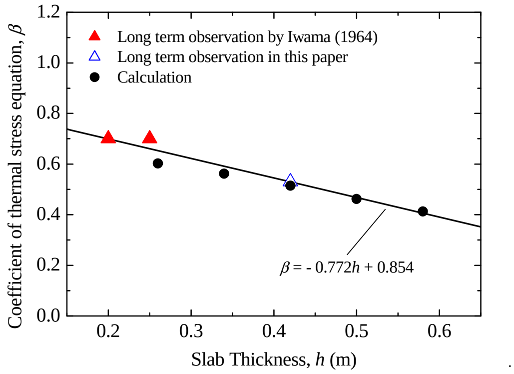


Figure 10: Relationship between thermal stress coefficient and slab thickness

$$\sigma = \beta \frac{E\alpha\theta}{2(1-\nu)} \qquad \text{Eq.(3)}$$

where,

$\beta = -0.772h + 0.854$

h: slab thickness (m)

REVISION OF DESIGN METHOD

The design method of airport concrete pavement in Japan was revised in 2008 based on Eq.(3). In new design method, the loading stress at slab center is calculated by FEM (slab on winkler foundation) and the thermal stress at slab center is calculated by Eq.(3). Next, the thickness of slab is determined as fatigue damage, which is calculated by total stress, number of load repetition, wandering of aircraft, design flexural strength and fatigue criteria of concrete, does not exceed 1.0.

Table 2 and Table 3 show the design conditions and the slab thicknesses designed by old and new design method of airport concrete pavement. Since the safety factor in old design method is constant value 2.0 corresponding to coverage 10000 to 40000, the slab thicknesses of all cases by old method are 42 cm. On the other hand, the slab thicknesses in new method are varied from 39cm to 43cm since safety factor is not used.

Table 2: Traffic volume on taxiway

Case	B747-400	B747-400D	B777-300D	A300-600	B767-300
A	2,250	13,500	45,000	18,000	45,000
B	5,000	30,000	100,000	40,000	100,000
C	11,000	66,000	220,000	88,000	220,000

* "5,000" means 5,000 times landing and 5,000 times departure

Table 3: Design conditions and slab thicknesses

Design conditions	Old method			New method		
Flexural strength of concrete	5.0 MPa					
Coefficient of bearing capacity on base	70 MN/m^3					
Traffic volume on taxiway (see Table. 2)	Case A	Case B	Case C	Case A	Case B	Case C
Coverage based on traffic volume	10,000	20,000	40,000	N/A		
Safety factor	2.0			N/A		
Temperature differential of slab and its frequency	N/A			-9^oC to 17^oC (see Figure 7)		
Slab thickness	42 cm			39 cm	41 cm	43 cm

SUMMARY AND CONCLUSION

The effects of nonlinear temperature distribution and slab thickness on thermal stress was studied. The following conclusions were obtained.

(1) The coeffisient of thermal stress equation is smaller with increasing of slab thickness because internal stress due to nonlineality of temperature distribution across slab thickness is larger with increasing of slab thickness.

(2) Thermal stress equation for various thickness of slab is proposed. This equation can be used for estimation of not only daily maximum thermal stress but also hourly thermal stress.

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