

Effects of Non-Linear Thermal Stress on Fatigue Damage of Airport Concrete Pavements

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Abstract

Thermal stress caused by temperature distribution in concrete slab is important in the structural design of airport concrete pavements. Airport concrete pavement slab is very thick, therefore, temperature in the slab varies nonlinearly throughout the slab depth. In this study, a method for estimating thermal stress in a concrete slab with 3DFEM analysis and heat transfer analysis was developed. The thermal stresses for airport concrete pavements with various thicknesses and climate conditions were calculated with the method for one year period and relative frequency distributions (RFDs) of the thermal stresses were obtained. Influence lines of load stress due to aircraft gear were also calculated with 3DFEM. The fatigue damages were estimated from the RFDs, the lateral distributions of the gear, combined stresses and fatigue curve of concrete. Based on the results, effects of the nonlinearity of thermal distribution and air temperature on the fatigue damage of airport concrete pavements were investigated in terms of the optimal thickness of concrete slab.

Introduction

In the structural design of concrete pavement, fatigue damage is estimated to make sure that a concrete pavement slab will be able to carry traffic loads that are expected during a design period, taking into account traffic load stress and thermal stress. Therefore, it is important to calculate precisely the thermal stress in the concrete pavement. In the current design method in Japan, the thermal stress is calculated from the temperature differential between the top and bottom of concrete slab. Then, the fatigue damage is estimated as follows:

$$Fd = \sum_p \sum_l \sum_T \frac{f_p f_l f_T N_{total}}{N_{allowable}(\sigma_{pl}, \sigma_T)} \quad (1)$$

Where,

Fd = fatigue damage,

f_p = relative frequency of a wheel load p ,

f_l = relative frequency of a wheel position l ,

f_T = relative frequency of a temperature differential between the top and bottom of concrete slab ΔT ,

N_{total} = total number of wheel loads of aircrafts that are expected for a design period,

$N_{allowable}$ = allowable number of load repetitions estimated from fatigue curve of concrete,

σ_{pl} = load stress generated by a wheel load of p at a position l , and

σ_T = thermal stress generated by a temperature differential ΔT .

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In Japan, σ_T is estimated by the following equation that was proposed by Iwama (1968) for edge stress:

$$\sigma_T = 0.35C_w\alpha E\Delta T \quad (2)$$

Where,

C_w = factor of restraint depending on slab length,

α = coefficient of thermal expansion of concrete,

E = elastic modulus of concrete, and

ΔT = temperature differential between the top and bottom of concrete slab.

Eq. (2) was developed by modifying Westergaard's formula (Westergaard 1926) being based on the measurement results on 20 to 25cm thickness pavement slabs. Iwama's formula considers curling stress that is caused by linear temperature distribution throughout concrete slab depth and reduces the stress by 30% considering internal stress, which is caused as the result of nonlinear temperature distribution. However, airport concrete pavement slab is very thick compared with road concrete pavement slab, and the internal stress caused by the nonlinear temperature distribution would be much larger than that in normal road concrete slab. Therefore, it is expected that actual thermal stress of airport concrete pavement is different from that calculated by Iwama's formula (Tsubokawa et al. 2007, Shimomura et al. 2008, Nishizawa et al. 2009). Tsubokawa et al. (2007) proposed an equation of thermal stress at the interior of slab for airport concrete pavement as follows:

$$\sigma_T = \beta \frac{\alpha E \Delta T}{2(1-\nu)} \quad (3)$$

Where, $\beta = -0.772h + 0.854$, and h is slab thickness in meter. β in Eq.(3) is a factor to take into account the slab thickness, which was introduced based on the measurement on full scale test pavement. Basically Eq.(3) assumes a complete restraint condition ($C_w=1.0$).

FEM analyses considering nonlinear temperature distribution of concrete pavement have been conducted in many studies (Pane and Mohamed 1998, Shoukry et al. 2003, Mahboub et al. 2004) for road concrete pavements. These studies showed the great advantages of 3DFEM analysis to calculate thermal stress due to the nonlinear temperature distribution with considerations of slab configuration, subbase stiffness and load transfer at joints. For the thick airport concrete pavement, 3DFEM models, Pave3D, taking into account the nonlinear temperature distribution also has been developed (Shimomura et al. 2008, Nishizawa et al. 2009).

In this study, the thermal stress is directly estimated from 3DFEM simulation that takes into count the nonlinearity of temperature distribution in thick concrete slab. If the relative frequency distribution (RFD) of thermal stress for one year is known, Fd can be estimated as follows:

$$Fd = \sum_p \sum_l \sum_T \frac{f_p f_l f_{\sigma_T} N_{total}}{N_{allowable}(\sigma_{pl}, \sigma_T)} \quad (4)$$

Where, f_{σ_T} = relative frequency of thermal stress, σ_T . f_{σ_T} is obtained from 3DFEM simulations using the temperature distribution calculated from one dimensional transient heat transfer analysis. Based on the calculations, the thermal stresses for airport concrete pavements with various thicknesses and climate conditions were calculated for one year period and relative frequency distributions (RFDs) of the thermal stresses were obtained. Influence lines of load stress due to

aircraft gear were also calculated with 3DFEM. The fatigue damages were estimated from the RFDs, the lateral distributions of the gear, combined stresses and fatigue curve of concrete. Based on the results, effects of the nonlinearity of thermal distribution and air temperature on the fatigue damage of airport concrete pavements were investigated in terms of the optimal thickness of concrete slab.

3DFEM Analysis of Thermal Stress

Formulation of thermal stress. Three dimensional finite element method (3DFEM) was employed in this study to calculate thermal and/or wheel load stresses, because the method is able to simulate thermal behaviors of concrete slabs as well as the underlying layers accounting for mechanical interactions between them. Also, it is able to directly take into account the nonlinear temperature distribution throughout slab depth.

The thermal stress can be calculated by

$$\{\sigma\} = [\mathbf{D}](\{\varepsilon\} - \{\varepsilon_T\}) = [\mathbf{D}]\{\varepsilon_C\} \quad (5)$$

Where,

$\{\sigma\}$ = stress vector,

$[\mathbf{D}]$ = elastic matrix,

$\{\varepsilon\}$ = total strain vector, and

$\{\varepsilon_T\}$ = thermal strain vector.

In the three dimensional space, the thermal strain is:

$$\{\varepsilon_T\} = \{\alpha T \quad \alpha T \quad \alpha T \quad 0 \quad 0 \quad 0\} \quad (6)$$

Where, T is the temperature and is assumed to be a quadratic function of z . The stiffness equation of FEM with thermal stress becomes:

$$[[\mathbf{K}] + [\mathbf{J}]]\{\mathbf{d}\} = \{\mathbf{f}_w\} + \{\mathbf{f}_p\} + \{\mathbf{f}_t\} \quad (7)$$

Where,

$[\mathbf{K}]$ = stiffness matrix of concrete slab, base courses and subgrade,

$[\mathbf{J}]$ = stiffness matrix of joint and interface between the concrete slab and base course,

$\{\mathbf{d}\}$ = displacement vector,

$\{\mathbf{f}_w\}$ = self-weight load vector,

$\{\mathbf{f}_p\}$ = external load vector,

$\{\mathbf{f}_t\} = \int_V [\mathbf{B}][\mathbf{D}]\{\varepsilon_t\}dV$: thermal load vector and

$[\mathbf{B}]$ = displacement-strain matrix.

When a concrete slab is lifted off by a temperature gradient, some parts of the slab bottom surface are separated from underlying layer. This can be modeled by setting very weak vertical spring in the interface element in the separated parts. This method makes Eq.(7) nonlinear, because $[\mathbf{J}]$ in Eq.(7) changes according to $\{\mathbf{d}\}$. To solve the non-linear equation, a combination of the Newton-Raphson method and the load incremental method was employed. A 3DFEM program, Pave3D, was developed using the formulation and used to calculate combined stresses in the concrete slab due to wheel and thermal loads (Nishizawa et al. 2009).

3DFEM model. In order to validate the 3DFEM model, we compared the calculated thermal strains with ones measured in an experimental concrete pavement. The experimental concrete pavement has an 8.5m by 8.5m concrete slab with a

thickness of 460mm, resting on a 210 mm thick asphalt layer and a 400 mm thick granular base. Temperature and strain distributions throughout slab depth were measured hourly over one year (Shimomura et al. 2008, Nishizawa et al. 2009).

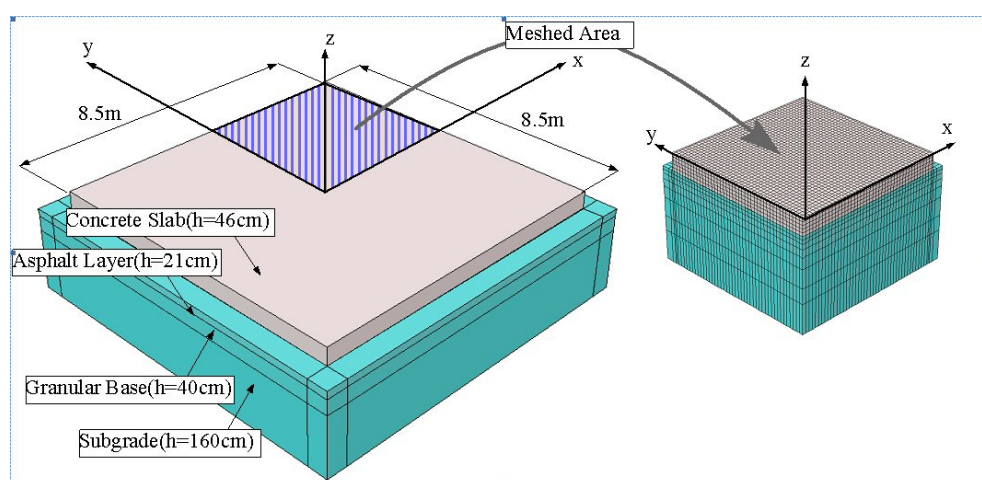


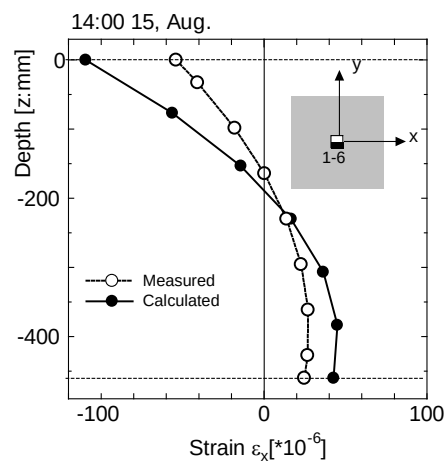
Figure 1. 3DFEM Modeling of airport concrete pavement for thermal stress analysis.

3DFEM model used in this study had the same dimension as that of experimental concrete pavement as shown in Figure 1. In the model, each pavement layer was divided into 8 node solid elements. The concrete slab was divided into six elements through depth to express the nonlinear distribution. Interface between the concrete slab and asphalt base course was modeled by an interface element that represents the interaction between the slab and base with three linear springs and accounts for the separation when the slab curls up. In this simulation, a smooth interface condition was assumed. Considering the symmetry of the structure, a quarter region of the pavement was meshed. The material properties of each layer and the interface condition are summarized in Table 1. Temperature distribution expressed by the quadratic equation at each time of day was input into the 3DFEM model and thermal stresses at the time were calculated. The FEM computation was repeated for each time of day to simulate thermal stress variation.

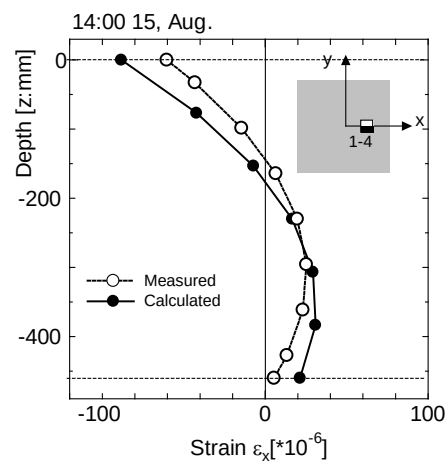
Validation of 3DFEM analysis. Comparisons of measured and calculated restraint strain distributions throughout the slab depth are shown in Figure 2. The restraint strain in this study was calculated as the difference between total strain and temperature strain ($=\alpha T$), in terms of increment from a reference time. The reference time was defined as the time when the temperature difference between the top and bottom of the slab was the minimum on each day. The entire shapes of the restraint strain distributions are very similar between the calculated and measured ones. Figure 3 compares the measured and calculated restraint strain variations at the top, middle and bottom of the slab in January, May and August. These variations also show a fairly good agreement between the measured and calculated restraint strains, which confirm the validity of 3DFEM analysis.

Table 1. Input Parameters for material properties of the concrete pavement.

Concrete Slab (Unit C)	
Elastic Modulus [MPa]	39900
Poisson's Ratio	0.206
Thermal Expansion Coefficient	0.00000889
Unit Weight [kN/m ³]	23.5
Thickness [mm]	300, 400, 460 500
Interface Element between Slab and Base Course	
In-plane Spring Constant [MPa/m]	0.1
Out-plane Spring Constant [MPa/m]	10000
Asphalt Layer	
Elastic Modulus [MPa]	2000
Poisson's Ratio	0.35
Thickness [mm]	210
Granular Base	
Elastic Modulus [MPa]	500
Poisson's Ratio	0.35
Thickness [mm]	400
Subgrade	
Elastic Modulus [MPa]	100
Poisson's Ratio	0.35
Thickness [mm]	1600



(a) at center of the slab



(b) between center and edge of the slab

slab

Figure 2. Comparisons of measured and calculated restraint strain distributions throughout the slab depth.

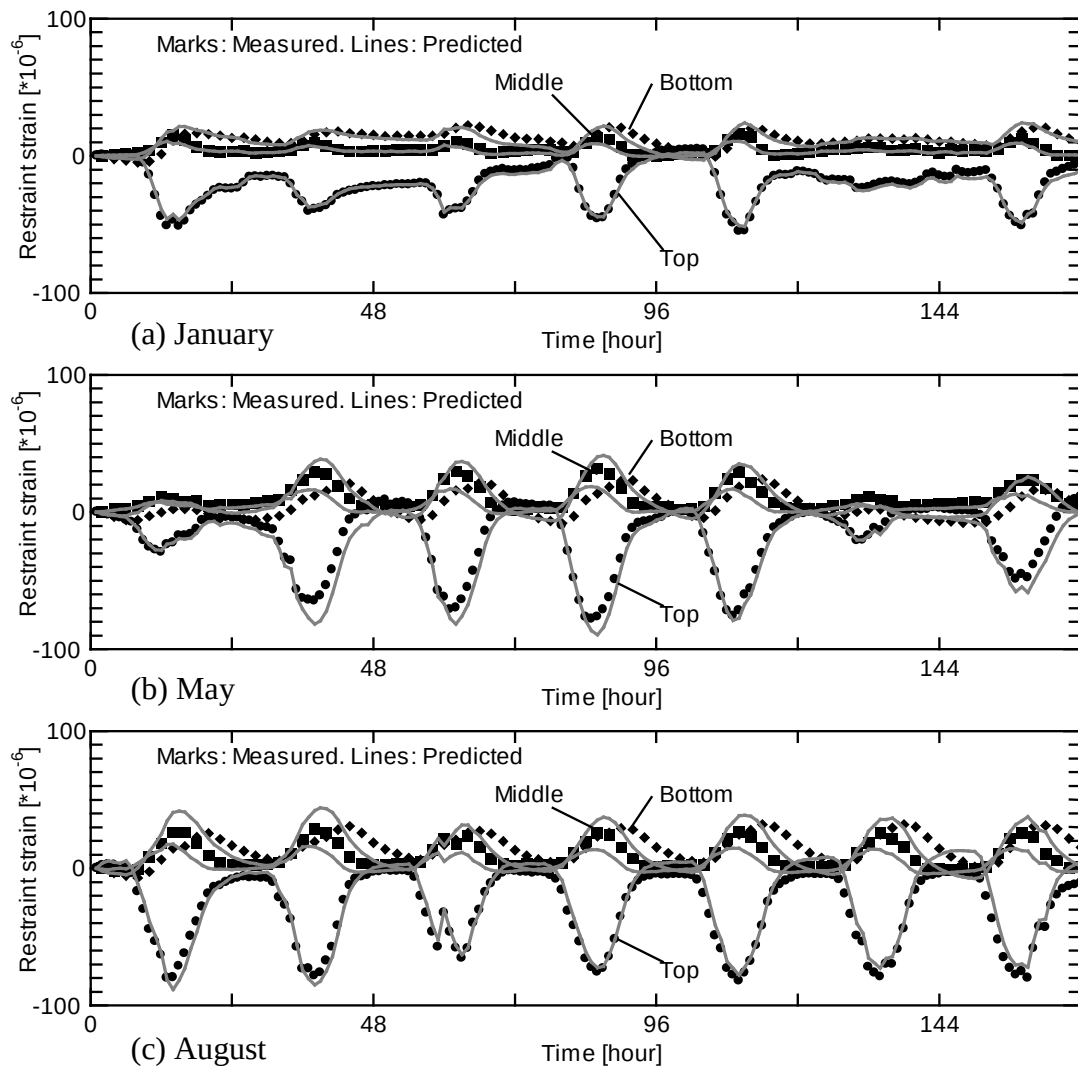


Figure 3. Comparisons of measured and calculated restraint strain variations.

Frequency Distribution of Thermal Stress

Figure 4 shows the relative frequency distribution (RFD) of the thermal stress at the bottom of the slab. RFD of the nonlinear stress distributes in a wider range at the slab center than at the slab edge. The shape of RFD of the nonlinear stress at the slab center is similar to that of Iwama's stress. High tensile stress appears more frequently in Iwama's stress than that in the nonlinear stress.

Figure 5 shows the effect of slab thickness on RFD. In thin slab (300mm), high frequency is observed in a range of high tensile stress, which increases the risk of fatigue cracking. In the figure, RFDs of thermal stress at interior and edge of the slab are also shown. High thermal stresses more frequently appear in interior than in edge.

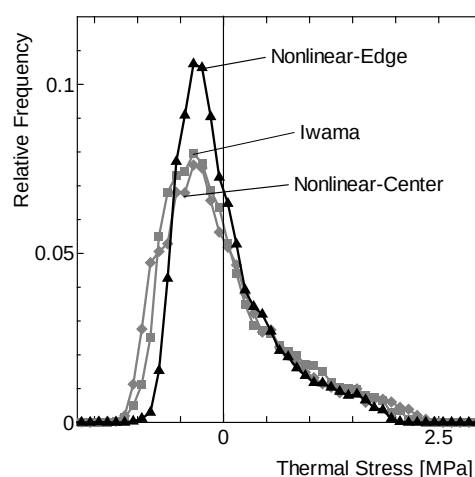


Figure 4. RFD of nonlinear and linear thermal stresses at the center and the edge.

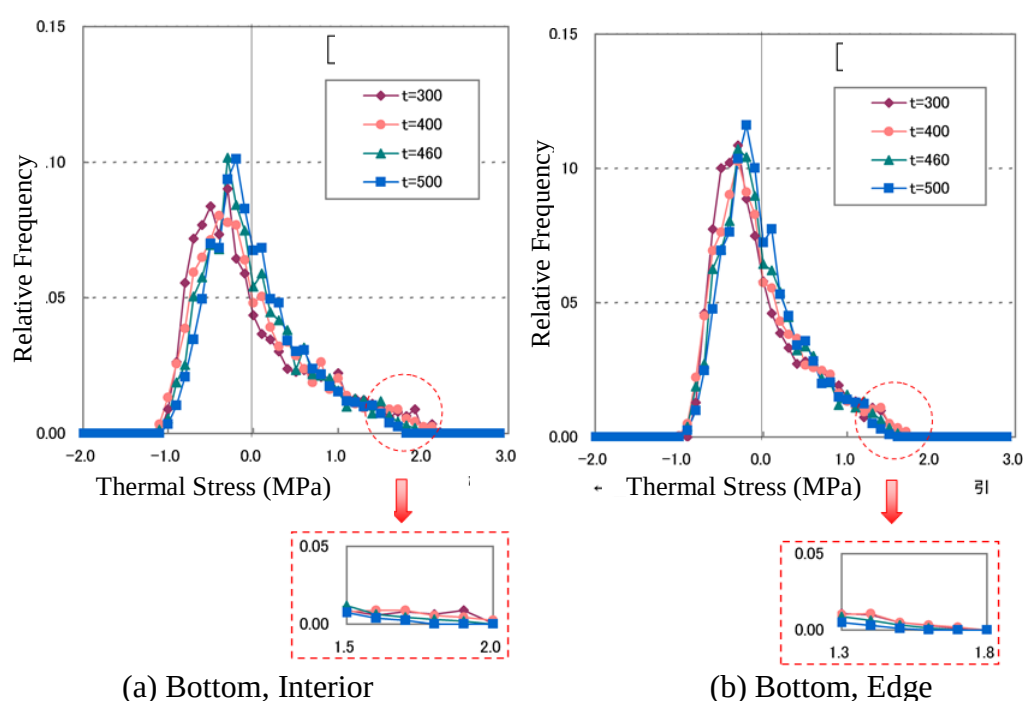


Figure 5. Effect of slab thickness on RFD of non-linear thermal stress.

Load Stress

Load stresses at the bottom of slab generated by an aircraft gear were calculated with Pave3D using a model as shown in Figure 6. In the model, nine concrete slabs were connected with doweled joints. Structural composition and material properties of the underlying layers were the same as the model used in the thermal stress simulation. At the joints, steel dowels with a length of 700mm and a diameter of 38mm were installed with a spacing of 400 mm. Their elastic modulus and Poisson's ratio were assumed to be 210GPa and 0.3, respectively. The joints were modeled with the refined dowel model developed by Nishizawa et al. (2001).

Wheel configuration of a gear of 747-400 is shown in Figure 7a. The total load of the gear was 932kN at departure and 672kN at arrival. The gear was applied at the

interior and edge of a slab as shown in Figures 7b and 7c. The gear was shifted in x-direction to take into account a lateral wandering of the aircraft.

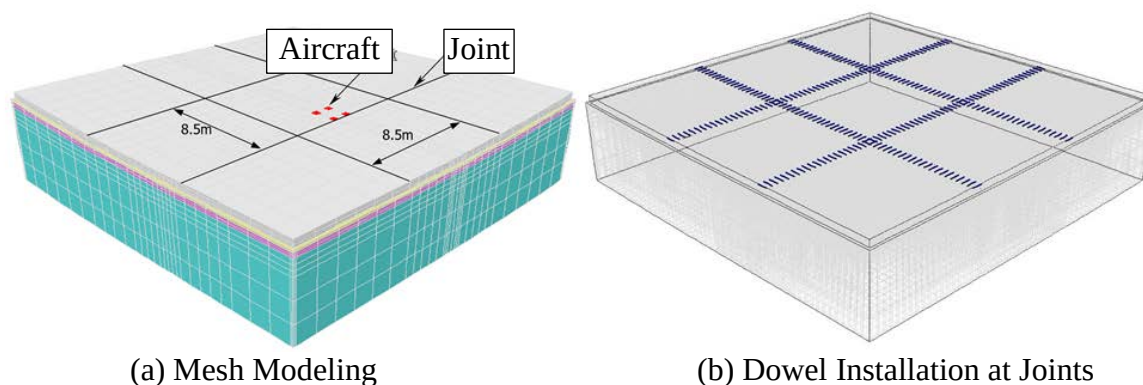


Figure 6. 3DFEM model for the load stress calculation.

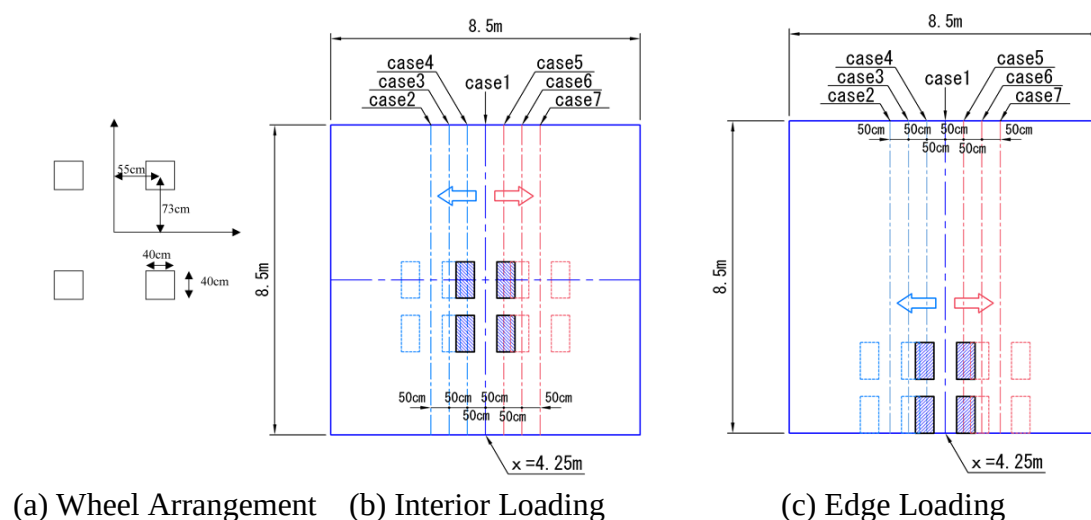


Figure 7. Configuration of aircraft gear (B747-400) and loading positions.

Figure 8 shows an example of load stress distributions of the 460mm slab along the slab edge. It was found that the peak magnitude of the stress was 2.5 MPa for all positions (Cases 1 through 7) and their entire distribution shapes are very similar to each other. The stresses at a particular point where the fatigue damage was to be estimated were taken from the distribution to obtain influence line. Similar distributions were calculated for all loading positions and slab thicknesses.

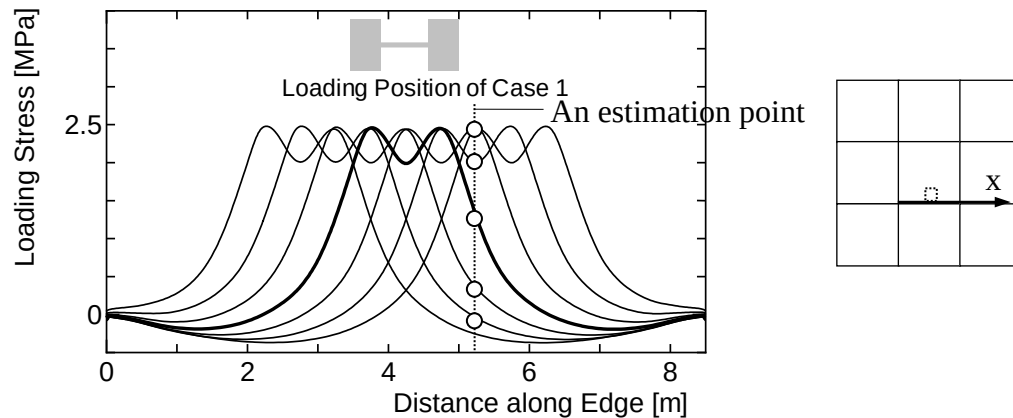


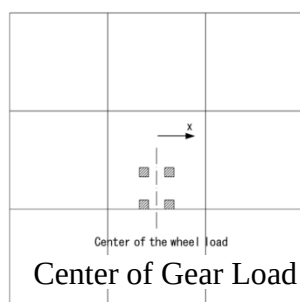
Figure 8. An example of load stress distributions along the slab edge.

Fatigue Analysis

Fatigue Curve. F_d can be estimated from Eq. (1) or (4) by applying the combined stress (=loading stress + thermal stress) to the following fatigue curve of concrete:

$$\log N_{allowable} = \frac{(1.13014 - \sigma_c / \sigma_a)}{0.09512} \quad (8)$$

Where, σ_c is combined stress and σ_a is flexural strength of concrete (=5.0 MPa). Eq. (8) is one of fatigue curves that were derived from an experiment performed on concrete for pavement by Koyanagawa et al. (1993), which accounts for the failure probability. Eq. (8) corresponds to a failure probability of 10%.



Case	Shift of the center of the gear	Relative frequency f_i
Case1	$x=0$	0.20
Case2	$x=-50\text{cm}$	0.18
Case3	$x=-100\text{cm}$	0.14
Case4	$x=-150\text{cm}$	0.08
Case5	$x=50\text{cm}$	0.18
Case6	$x=100\text{cm}$	0.14
Case7	$x=150\text{cm}$	0.08

Figure 9. Positions of aircraft gear and its relative frequency.

Traffic Condition. The total number of the aircrafts, N_{total} , was 1,000,000 for a design period of 20 years. In the daily operation, 40 % of the traffic is assumed to be in the night time (23:00 to 6:00) and the rest of 60 % is assumed to be in the day time (7:00 to 22:00). Obtained RFDs of the thermal stress for one day were divided into day time and night time accordingly. The gear was shifted in x-direction to represent lateral wandering of the aircraft. RFD of lateral wandering, f_l , was assumed as a normal distribution with a standard deviation of 0.9 m. In this study, the distribution was divided into seven portions as presented in Figure 9.

Fatigue Analysis Result. The fatigue damage was estimated from the load and thermal stresses and corresponding frequencies that were obtained in the previous sections. Figure 10 shows fatigue damage distributions along the transverse line (x-direction) and compares these values calculated with the nonlinear, Iwama (Eq.(2))

and Tsubokawa thermal stresses (Eq. (3)). Upper graphs are for $h = 400\text{mm}$ and the lower ones for $h = 460\text{mm}$. The left side graphs are for the interior loading and the right side ones for the edge loading. As for the interior loading, when $h = 400\text{mm}$, Fd exceeds 1.0 with thermal stress calculated by 3DFEM and Iwama's equation, while Fd with Tsubokawa's thermal stress is less than 1.0. When $h = 460\text{mm}$, only Fd with Iwama's thermal stress exceeds 1.0, while other Fd 's are less than 1.0. Generally, Fd of the interior loading is higher than Fd of the edge loading. Therefore, the interior loading is crucial in terms of determination of design thickness.

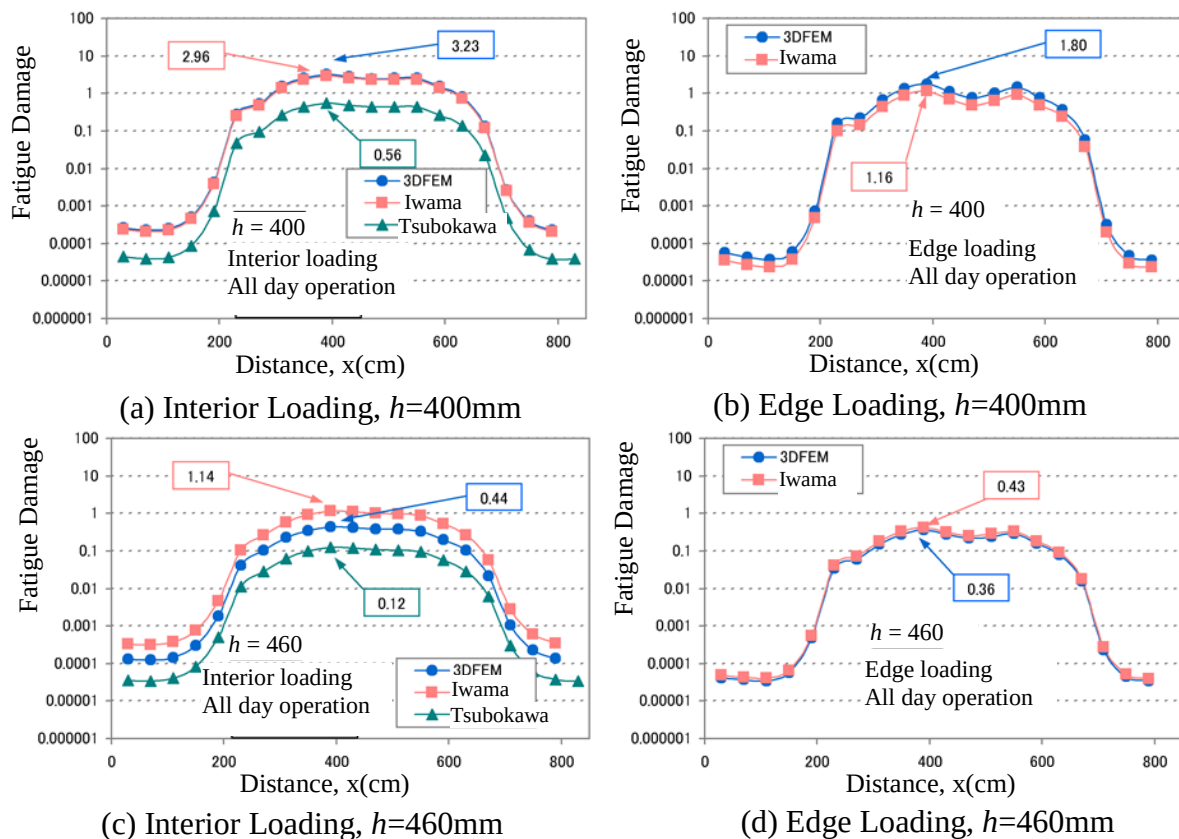


Figure 10. Fatigue damages estimated with nonlinear and linear thermal stresses.

Figure 11 shows effects of h on Fd distributions. Fd s of the interior loading are much higher than those of the edge loading. The reduction of Fd is very large when h increases from 300mm to 400mm and it becomes small when h increases from 400mm to 500mm. Thus, the reduction of Fd with h increasing seems to be exponential, which can be confirmed in Figure 12. The figure suggests that the relationship between Fd and h can be approximated by exponential equations. If the optimum design thickness is determined when $Fd = 1.0$, they are 470 mm for Iwama's thermal stress, 420 mm for 3DFEM thermal stress and 380 mm for Tsubokawa's stress.

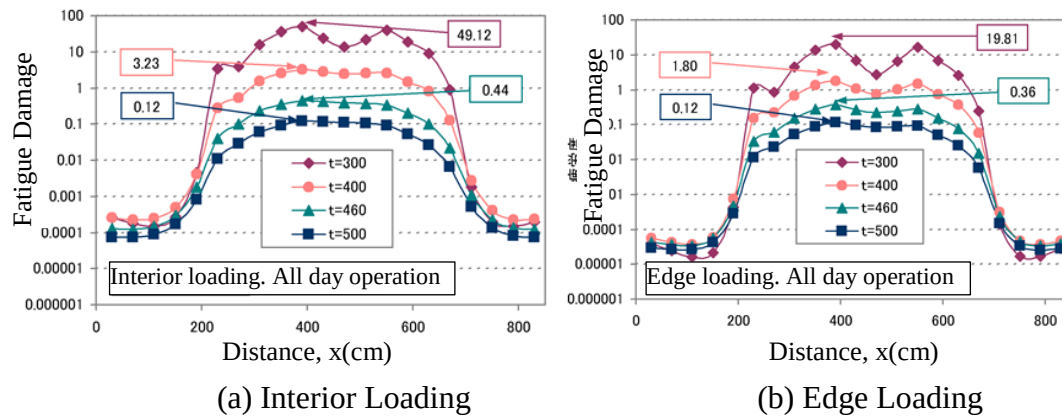


Figure 11. Effect of Slab Thickness on Fatigue Damage under Interior Loading.

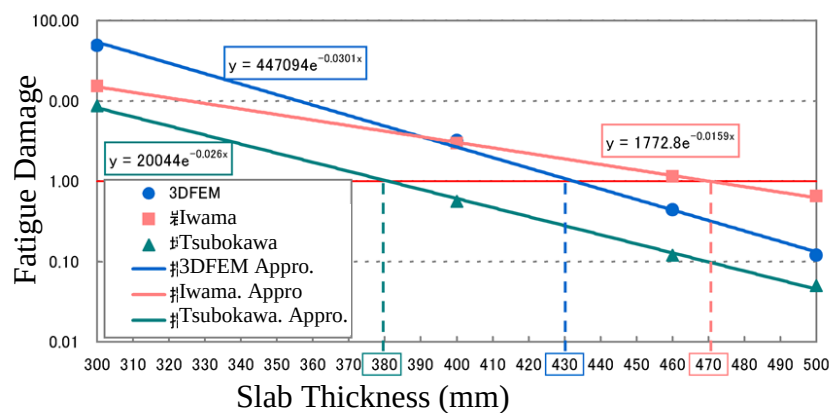


Figure 12. Exponential Approximation of Relationship between h and Fd .

Case study. Effects of climate conditions on Fd and design thickness were examined by simulating temperatures in concrete slab and calculating thermal stresses for one year under different climate (temperature) conditions. Two climate conditions of Sapporo and Fukuoka were employed. Sapporo is a city located in the northern island, Hokkaido, where the temperature is relatively low, while Fukuoka is a city located in the southern island, Kyusyu, where the temperature is relatively high, as shown in Figure 13.

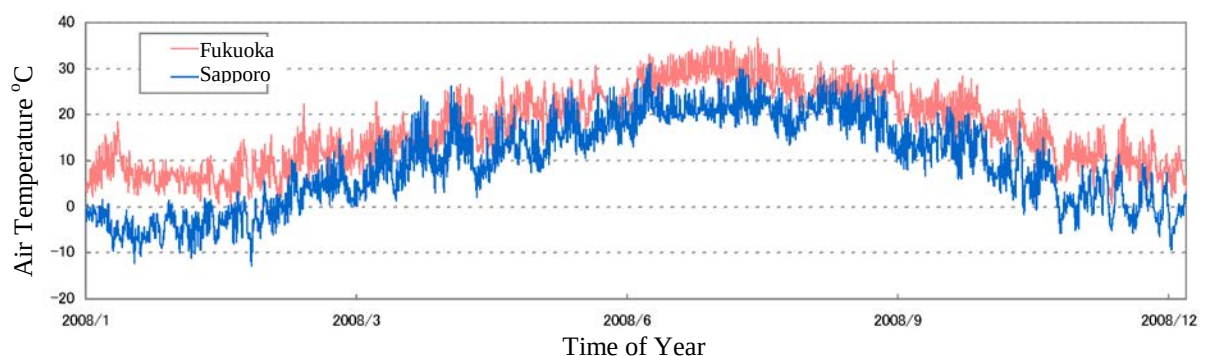


Figure 13. Yearly variations of air temperature in Sapporo and Fukuoka.

In order to obtain RFDs of thermal stress in Sapporo and Fukuoka, the temperatures in concrete slabs with thickness from 350mm to 500mm were calculated by solving 1D heat transfer equation with boundary conditions based on the metrological data measured at the cities and performing 3DFEM calculations using the calculated temperatures as input. Figure 14 shows a RFD of thermal stress for $h = 450$ mm. In this case, high thermal stress was more frequent in Sapporo than in Fukuoka (see a small box in the right). Also, it is noticed that the bottom thermal stress in the night time is mostly compressive.

Figure 15 shows Fd distribution along the transverse line for $h = 450$ mm. The loading condition was the interior and traffic condition was the same as the previous one. Fd is higher in Sapporo than Fukuoka. It is because the daily temperature difference between the maximum and minimum was greater in Sapporo than in Fukuoka, which causes higher thermal stress, even though the daily average temperature was higher in Fukuoka than in Sapporo.

Again, the optimal h determined from the approximation of the relationship between h and Fd at the condition of $Fd = 1.0$ were 490 mm for Sapporo and 470 mm for Fukuoka as shown in Figure 16.

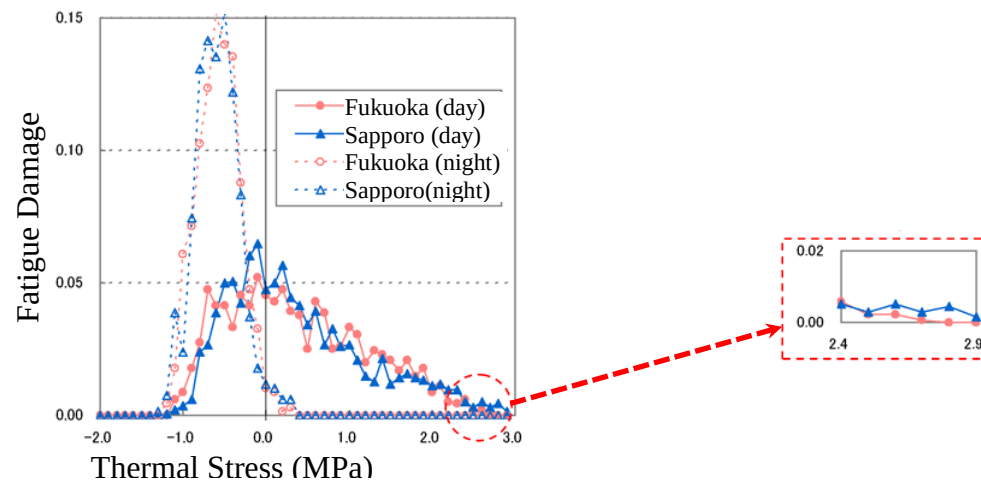


Figure 14. RFD of thermal stress for $h=450$ mm.

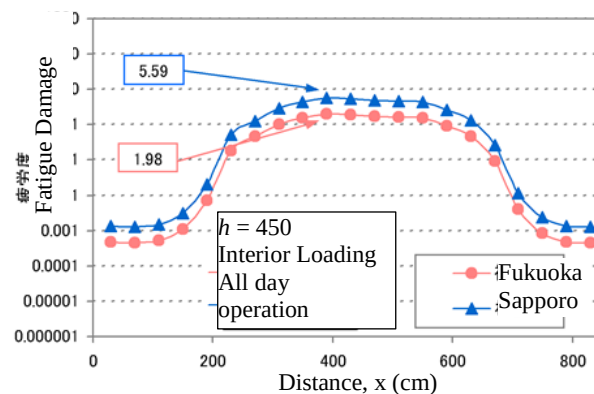


Figure 15. Fd distribution along the transverse line of Fukuoka and Sapporo

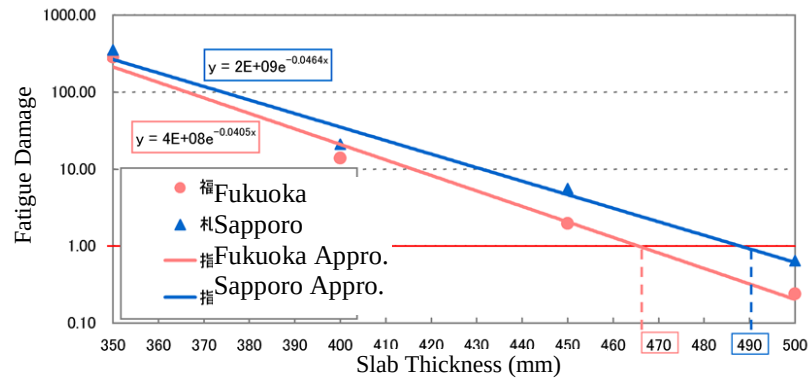


Figure 16. Determination of optimum design thickness for Fukuoka and Sapporo.

Conclusions

In this study, a method to estimate fatigue damage of thick concrete pavement taking into account yearly variation of thermal stress of thick concrete slabs induced by nonlinear temperature distribution throughout slab depth was presented. In the method, yearly temperature variations in the concrete slabs are calculated with 1D heat transfer analysis and RFDs of nonlinear thermal stress for a year are obtained with Pave3D program and the yearly temperature variations. Using the RFDs and load stresses calculated with Pave3D, Fd under various climate conditions is estimated. Therefore, this method can be applied to the structural design of airport concrete pavement for a wide variety of climate conditions. This paper presented some case studies applying the proposed method for concrete pavement design in high and low air temperature cities. The following conclusions were drawn:

1. Fd greatly depended on which equation or method was employed to calculate the RFD of the thermal stress.
2. Relationship between Fd and h was approximated by an exponential expression and an optimal h was easily determined from the relation. It should be confirmed that this exponential expression could be obtained for other loading conditions.
3. The optimal h was thicker in the area where the daily temperature difference was greater.
4. This method, however, requires a long computation time to obtain RFD of yearly thermal stress: a couple of days for one case. Therefore, the design cost of the method may be rather high.

REFERENCES

ARA, Inc, ERES Consultants Division (2004). *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*, National Cooperative Highway Research Program Project 1-37A.

Iwama, S. (1963). "Experimental Studies on The Structural Design of Concrete Pavement", JSCE.

Koyanagawa, M., Yoneya, Y., and Fukuda, T. (1993). "Flexural Fatigue Design Curve for Concrete Pavement in Consideration of Probabilistic Properties of Fatigue Phenomena", *Proc., 5th International Conference on Concrete Pavement Design and Rehabilitation*, Purdue University, pp. 237-244.

Mahboub, K.C., Liu, Y., and Allen, D.L. (2004). "Evaluation of Temperature Responses in Concrete Pavement, *J. Transportation Engineering*, ASCE, Vol.130, No.3, pp. 395-401.

Nishizawa, T., Koyanagwa, M., Takeuchi, Y., and Kimura, M. (2001). "Study on Mechanical Behavior of Dowel Bar in Transverse Joint of Concrete Pavement", *Proc., 7th International Conference on Concrete Pavement*, Orland Florida, pp. 571-588.

Nishizawa, T., Ozeki, T., Katoh, K., and Matsui, K. (2009). "Finite Element Model Analysis of Thermal Stresses of Thick Airport Concrete Pavement Slabs", *J. the Transportation Research Board*, No.2095, Transportation Research Board, pp. 3-12.

Shimomura, T., Nishizawa, T., and Ozeki, T., (2008). "Evaluation of Thermal Stress in Airport Concrete Pavement Slab by 3D-FEM Analysis", *Proc., 9th International Conference on Concrete Pavements*, San Francisco, California, pp.740-754.

Pane, I., Hansen, W., and Mohamed, A.R. (1998). "Three-Dimensional Finite Element Study on Effects of Nonlinear Temperature Gradients in Concrete Pavements", *Transportation Research Record*, No.1629, pp.58-65.

Shoukry, S.M., William, G.W., and Riad, M. (2003). "Nonlinear Temperature Gradient Effects in Dowel Jointed Concrete Slabs", *Int. J. Pavement Engineering*, Vol.4, No.3, pp.131-142.

Tsubokawa, Y., Mizukami, J., Hachiya Y., and Kameta, S. (2007). "Study on Thermal Stress Due to Daily Temperature Change of Airport Concrete Pavement." *Japanese J. of Pavement Engineering*, Vol.12, pp.157-164.

Westgaard, H.M. (1926). Analysis of Stresses in Concrete Roads Caused by Variation of Temperature, *Proc. of the Annual Meeting*, Highway Research Board.