Using Advanced "Birth and Death" APDL Code to Analyze the Thermal Transient Problem of Mass Concrete during Construction Phases

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ABSTRACT

For finite element analysis of the thermal transfer problem, solving the Boundary Condition (BC) change versus time appropriately, according to the concrete construction phases, is an important factor affecting the accuracy of the analysis result. The contact BC may change versus time from the convective boundary to the contact boundary between two bodies. In this paper, a technique using the "Birth and Death" element is applied to the heat transfer boundary of a mass concrete pier versus the time of construction phases. From the obtained results, it was concluded that the temperature distribution in the pier body can be determined according to the phases of construction. The achieved temperature field gives an input to the stress analysis allowing the determination of the possibility of thermal cracking of the structure and give appropriate alternatives to prevent thermal cracks.

Keywords-"Birth and Death" element; thermal boundary; temperature distribution; thermal crack; crack risk

I. INTRODUCTION

The "Birth and Death" is an element type that can be activated or deactivated during a structure analysis problem. The mentioned elements can be "born" in a certain time of assigned loading, meaning that these elements are deactivated at the initial step of the analysis process but they are activated when a new layer, of which the elements are modeled, is constructed. The elements can "die" during the assigned loading process and not participate in any significant mechanical behavior at this phase. The changes at different phases ("birth" or "death") occur at the beginning and the end of the assigned loading process [1-3]. "Birth and Death" is a nonlinear state varying gradually, not rapidly [4]. When an element "dies", it is not removed from the stiffness matrix, but its stiffness is reduced to a low value, which is interpreted as deactivation of the element. The element load vectors (such as pressure, temperature), which are associated with the element's "death", are removed. The mass, damping or stiffness matrices are set to zero. The stress and strain states of an element are reset to zero when the element is assigned as "dead". The "dead" element is excluded from the stiffness matrix, but included in the element system [5].

According to current standards, abutment and pier structures are considered as mass concrete structures, hence it is necessary to control thermal cracks at early ages. In particular, with a large amount of cement in the concrete mixture, the amount of heat due to cement hydration accumulating in the structure is very large. In addition, concrete has a poor coefficient of thermal conductivity. On the other hand, the surface of the abutment and pier structures exposed to the air should reduce the temperature rapidly compared to the center of the abutment block, resulting in a significant temperature difference between the center and the surface. When the temperature difference exceeds the allowable value, thermal cracks will form. There are many factors affecting the temperature field and the thermal stress field during the construction of bridge piers such as the cement content in concrete mixture, the temperature of the pouring block, the size of the pouring block, the ambient temperature, etc. [6-9].

In the present study, the "Birth and Death" model is applied at the thermal transferring boundaries to determine the temperature distribution in the pier body during the construction phases. The obtained results showing the temperature field in the pier structure corresponding to each construction phase, are the input data that determine the cracking risk in the structure so that appropriate solutions to control and prevent thermal cracks can be proposed.

II. MATERIALS AND METHODS

A. *Birth and Death Technique for the Heat Transfer Problem*

The "Birth and Death" boundary element is a tool built in the finite element environment and is widely used in to solve engineering problems. Midas, Ansys, and Abaqus are finite element analysis programs that allow users to declare the above elements. Convection Boundary Conditions (BCs) are applied to the upper surface of a concrete block when it is poured. When the next concrete block is poured, the convection BC is activated ("Birth"), but on the contiguous surface between two concrete blocks, the convection BC is deactivated ("Death"). In terms of heat transfer boundary, the convection boundary will born and die, but the element will still participate in the matrix of the structure [10]. Figure 2 depicts the stages of concreting from step (i - 1) to step (i + 1). For one element, the "Birth-Death" boundary is used simultaneously. When this condition is used, the analysis can be carried out using a unique construction progress grid [11].

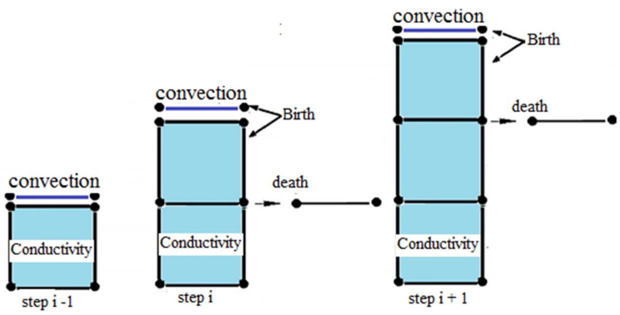

Fig. 1. Illustration of the "Birth-Death" thermal boundary.

It is assumed that the concrete blocks are constructed by multiple pours, with predetermined heights and rest periods between pours. The "Birth and Death" boundary elements used in the Ansys program are assigned at the interface between the adjacent concrete blocks. In the Ansys APDL program, assuming the construction of a concrete block by two lifts of pouring, the process of attaching the "Birth-Death" boundary condition to the two pouring blocks is illustrated as:

```
!Assign thermal boundary condition for the
1st layer
vsel,s,loc,y,0,h1
aslv,r
asel,u,loc,y,0
nsla,r,1
sf,all,conv,h_dl,t_mt
allsel
!Assign thermal boundary condition for the
2nd layer
esel,s,mat,,1      !Deactivate initial
boundary condition of the 1st layer
nsle,r
sfdele,all,conv
allsel
vsel,s,loc,y,h1,h
eslv,r
ealive,all        !Activate the elements of
the 2nd layer
allsel
vsel,s,loc,y,0,h
aslv,r
asel,u,loc,y,0
asel,u,loc,y,h1
nsla,r,1
sf,all,conv,h_dl,t_mt
allsel
```

In the software Midas/civil, the declaration of the boundary element "birth-death" is illustrated in Figure 2.

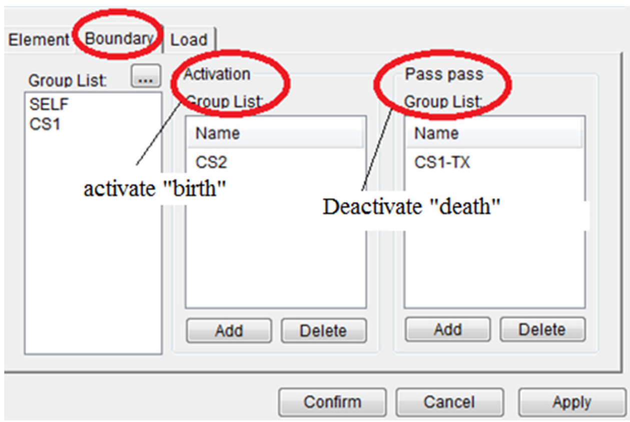

Fig. 2. Illustrating the declaration of the "birth-death" boundary in Midas/civil software.

B. *Data forthe Heat Problem*

This paper considers the temperature distribution of a bridge pier built during its whole construction. The mix proportions of concrete used for the pier construction are given in Table I. The slump is controlled at 14 cm and the specific gravity is 2,279 kg/m^3.

TABLE I. MIX PROPORTIONS OF CONCRETE

Cement (kg)	Sand (kg)	Stone (kg)	Water (kg)	W/C
405	457	1202	235	0.58

The dimensions of the bridge pier are: the pile cap is 8 m × 6 m × 2.5 m and the pier has dimensions of 4 m × 2 m × 6 m. The construction is divided into 3 blocks and each block rests for 3-5 days. Figure 3 describes the construction steps for the piers. The following function [12] represents the ambient temperature during the pier construction:

$$t_{air} = 26.5 + 5sin\left(\frac{2\pi t}{24}\right) \quad (1)$$

where t_{air} is the air temperature (℃) and t is the time (h).

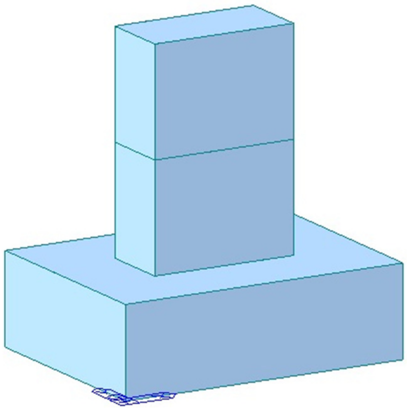

Fig. 3. Construction phases of the bridge pier.

Table II presents the properties of concrete and foundation, which are used in modeling the concreting process [13].

TABLE II. CONCRETE AND FOUNDATION PROPERTIES

Property	Concrete	Foundation
Heat conductivity coefficient, W/(m.°C)	2.31	3.59
Specific heat, kJ/(kg.°C)	0.96	0.85
Specific weight, kg/m^3	2279	2600
Surface convection coefficient, W/(m^2.°C)	13.88	14.5
Elastic modulus, N/m^2	2.56×10^{10}	
Thermal expansion coefficient, 1/°C	1.0×10^{-5}	1.0×10^{-5}
Poison's ratio	0.20	0.25
Cement content, kg/m^3	405	-
Compressive strength, MPa	34.7	-
Tensile strength, MPa	3.0	-
Initial temperature, °C	25	20

The construction of the bridge pier takes place in three phases: Phase 1 - construction of the pile cap, Phase 2 - construction of the lower half of the pier to a height of +3 m, and Phase 3 - construction of the upper half of the pier from +3 m to +6 m height.

As the pier is symmetrical, only one-fourth of the foundation block has been modeled to reduce calculations. The analysis results of the temperature distribution and the estimation of the cracking risk of the mentioned pier structure are presented in the Figures 5-10.

C. Approximate Method to Assess the Risk of Thermal Cracking

The Japan Concrete Association 2008 Guidelines for Crack Control in Massive Concrete [14-15] provides an approximate method to assess the cracking risk based on the crack index. The method is applied to specific components such as slabs, walls, and pillars. Therefore, the bridge pier structure is divided into the pile cap and the pier to assess the risk of cracking through the crack index.

The following formulas [16] are used to determine the thermal cracking index I_{cr} of the structure based on two main types of structures: wall structures and plate structures.

For wall structures:

$$I_{m\,ra-WT} = -0.0193T_a - 0.0028D - 0.0117Q_\infty + 0.0155r_{AT}^{SAT} + 0.0872log(H_R) + 0.476f_t - 0.165log_{10}(L/H) + 0.224log_{10}(E_c/E_R) + 0.015 \quad (2)$$

$$I_{cr} = I_{m\,ra-WT} - 0.3 \quad (3)$$

For plate structures:

$$I_{m\,ra-LT} = -0.0432T_a - 0.00103D - 0.093Q_\infty + 0.149r_{AT}^{SAT} - 0.312log(H_R) + 0.142f_t - 0.236log_{10}(L/H) - 0.0767log_{10}(E_c/E_R) + 5.98 \quad (4)$$

$$I_{cr} = I_{m\,ra-LT} - 0.3 \quad (5)$$

where $T\alpha$ - concrete temperature at pouring, °C; D - thickness of the wall-shaped structure (or the height of poured concrete in columns), m; Q_∞ - adiabatic temperature rise, °C; r_{AT}, s_{AT} - represent the rate of change of temperature; H_R- expression value of heat radiation effect from the surface of the member, W/m^2.°C; f_t- tensile strength of concrete after (28 ÷ 91) days, N/mm^2; L, H – length and width for concrete slabs or width and height for walls, m; E_c, E_R - elastic modulus of the member (wall or plate) and elastic modulus of the subfloor supporting the member, respectively, N/mm^2.

When the value of $I_{cr} < 1$, cracks begin to occur on the concrete structure. The probability of thermal cracking of the concrete members is determined by [17-19]:

$$P(I_{cr}) = \left[1 - exp\left\{-\left(\frac{I_{cr}}{0.92}\right)\right\}\right] \times 100 \quad (6)$$

where: $P(I_{cr})$ - probability of thermal cracking (%); I_{cr} - crack index of concrete members.

For concrete members, the safety cracking index is $I_{cr} \geq 1.85$ with probability of thermal cracking: $P(I_{cr}) \leq 5\%$. When the probability of cracking: $P(I_{cr}) > 5\%$, the member has a high risk of cracking. The limit value of the corresponding heat cracking index in this case is calculated by [20]:

$$I_{lim} = \frac{0.92}{\left[-log\left(1-\frac{P_C}{100}\right)\right]} \quad (7)$$

where: I_{lim} - the limit value of the cracking index with probability of thermal cracking exceeding 5%; P_c - the probability of thermal cracking exceeding 5%.

III. RESULTS AND DISCUSSION

A. Determination of the Temperature Field during the Construction of the Bridge Pier

1) Phase 1: Construction of the Bridge Foundation

The temperature distribution in the foundation base 72 h after concrete placement is shown in Figure 4. The temperature distribution inside the pier foundation base at 72 h is T_{max} = 77.82°C. The temperature difference at the center of the pour block and the surface of the block (node 41 and node 1741) is shown in Figure 5.

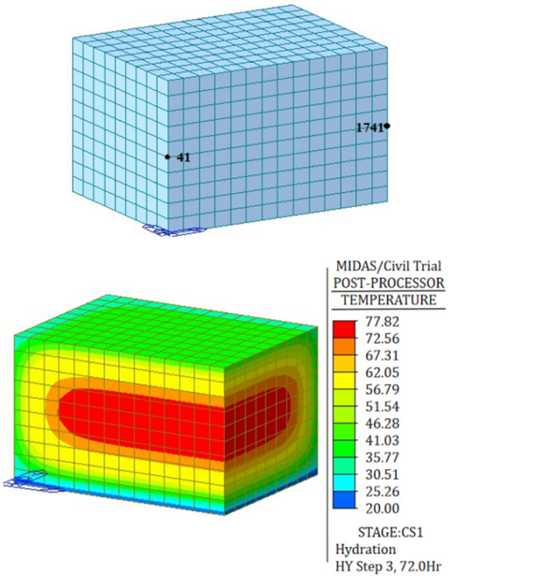

Fig. 4. Temperature distribution in the pier base 72 h after concrete placement.

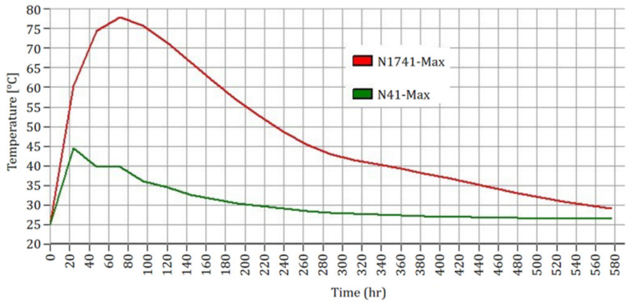

Fig. 5. Temperature difference between the center (node 1741) and the surface (node 41) of the foundation block versus time.

At 72 hours after concrete placement, the temperature difference between the center and the surface of the pier foundation base (ΔT) is 37.81^{o}C. The above temperature difference exceeds the allowable value, which may cause cracking on the surface of the concrete structure. There are numerous criteria and standards established for assessing accurately the risk of possible cracking. In this study, the crack index is calculated by a simple formula which is mentioned in [15].

2) Phase 2: Construction of the First Segment of the Bridge Pier

The temperature distribution in the pier 312 h after concrete placement is shown in Figure 6. The maximum temperature at the center of the pier body at 312 h (T_{max}) is 75.02^{o}C. The temperature difference at the center of the pour mass and the bridge piers surface (node 102 and node 103) is shown in Figure 7. After 312 h of pier construction, the temperature difference between the center and the surface of the pier base (ΔT) is 36.00^{o}C. The above temperature difference exceeds the allowable value, which may cause the appearance of cracks on the surface of the concrete structure.

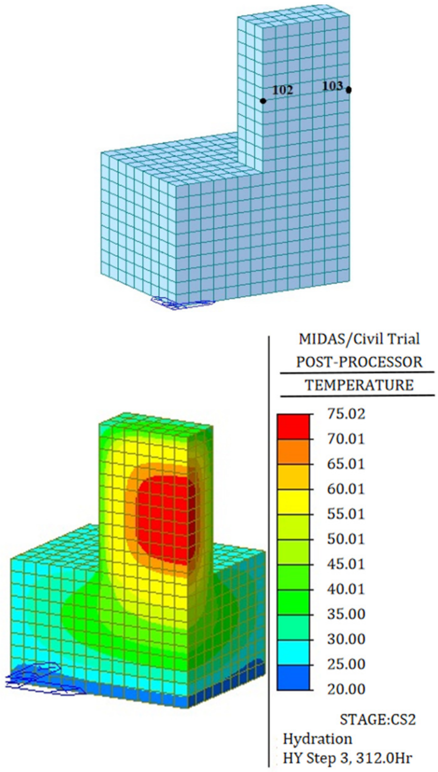

Fig. 6. Temperature distribution in the pier base 312 h after concrete placement.

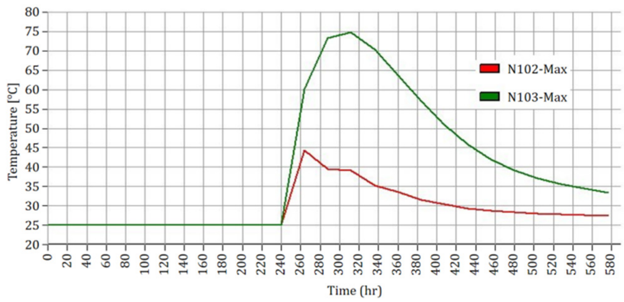

Fig. 7. Temperature difference between the center (node 102) and surface (node 103) of the pier body.

3) Phase 3: Construction of the Second Segment of the Bridge Pier

The temperature distribution in the second segment of the pier 480 h after concrete placement is shown in Figure 8. The maximum temperature in the pier body (T_{max}) is 74.82^{o}C. The temperature difference at the center of the pour mass (node 174) and the bridge piers surface (node 175) is shown in Figure 9. As can be seen, the temperature difference between the center point and the surface of the pier base (ΔT) is 35.00^{o}C, 480 h after casting. The above temperature difference exceeds the allowable value, which may may cause the appearance of cracks on the surface of the concrete structure.

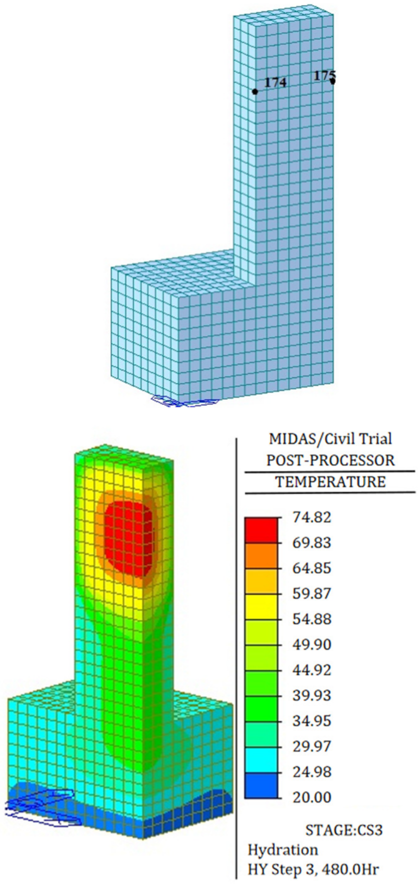

Fig. 8. Temperature distribution in the pier base 480 h after concrete placement.

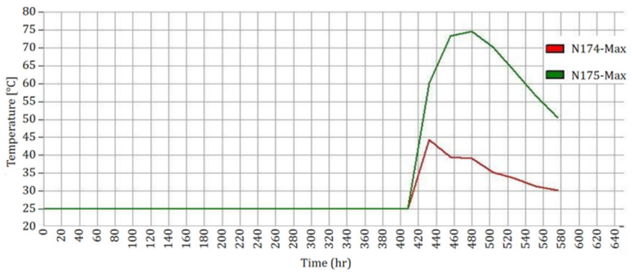

Fig. 9. Temperature difference between the center (node 174) and the surface (node 175) of pier body.

B. Simple Determination of Crack Index

Based on the input parameters of the material properties and the dimensions of the member, the necessary parameters for determining the crack index and the probability of crack appearing on the pier structure member sized 4 m × 2 m × 6 m can be obtained. The parameters which are used to obtain the crack index, are: T = 25 °C, D = 2 m, Q_∞ = 62.73 °C, r_{AT}^{sAT} = 1.78, H_R = 5.6 W/m^2.°C, f_t = 3.0 N/mm^2, L = 4 m, H = 6 m, E_c = 256000 N/mm^2, and E_R = 20 N/mm^2. Based on (3), the crack index is determined as I_{cr} = 0.963 < 1. Therefore, there is a probability of cracking on the surface of the pier body.

IV. CONCLUSION

The advanced "Birth and Death" APDL code was utilized in this study to analyze the thermal transient problem of mass concrete during the construction phases. The finite element modeling simulation of temperature rise due to hydration heat in mass concrete, which is a complex mechanism of the thermal convection process during the construction phases, allowed determining the maximum temperature in the mass concrete body versus time corresponding to the construction process. Based on the obtained results, the following conclusions can be derived:

- The advanced APDL code can be applied to enhance the ability in quickly and precisely predicting the temperature field in mass concrete.
- Using the "Birth and Death" method on the boundary elements gives a good reflection of the convective process at the interface between the concrete structure body and the surrounding environment.
- The risk of thermal crack formation can be determined through the preliminary evaluation of ΔT exceeding the permissible value and the thermal cracking index according to the controlled crack guidelines.
- The use of the advanced "Birth and Death" APDL code in FEM simulation process can contribute significantly in the practical applications, including design and construction processes, to control thermal cracks in mass concrete structures.

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