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THERMAL AND STRUCTURAL FINITE ELEMENT ANALYSIS OF EARLY AGE MASS CONCRETE STRUCTURES

by

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A Thesis
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ABSTRACT

This thesis addresses key issues related to the rehabilitation of cracked leaking concrete dams. In order to perform a rehabilitation procedure, an in-depth understanding of the stresses involved in the failure mechanism at the peak load is key to a successful fix.

Dams, like other massive concrete structures are most likely to fail at the construction joints. The construction joint is first to fail due to the development of internal stresses during the early construction stages.

In the early stages of erected concrete structures, temperature rise occurs due to hydration of cement. Two theoretical models, namely, a transient thermal model and a transient stress model are developed to predict the behaviour of young concrete. The models account for several factors such as arbitrary concrete block pour history, convective heat exchange between concrete and air, and a variable modulus of elasticity.

First, a model of concrete test specimens prepared as part of this research program was used to investigate what ultimately drives the potential for failure. Subsequently, the specimen size is enlarged and the size effect is captured. In addition, the pour time effect is analyzed.

Finally, a model, which presents an actual dam's upper structure (two blocks), is analyzed. The numerical analysis is carried out using commercial software, which uses

the finite element method revealed the magnitude and the internal residual stress distribution.

Passive rehabilitation is the kind of rehabilitation that could contain the leaking problem at least for a short period of time, until a definitive solution is found. Ice forms out of the cracked downstream surface due to leaking through the joint. The expansion of ice inside the joint and its falling from the side of the dam becomes more and more dangerous with time. Using the Long-Spruce Dam as a case study, a tunnel heated by electric heaters on the downstream side is designed to keep ice from accumulation on the surface of the cracked down stream surface. Heat exchange analysis is carried to estimate the heat power required to maintain the air temperature inside the tunnel above zero throughout the year. The results were adopted for the Long Spruce and, today, the tunnel is fully functional. No ice has formed on the surface of downstream face of the Long Spruce Transition Structure.

Active rehabilitation attempts to solve the leaking problem permanently by completely eliminating the leak were examined. Based on the results of this investigation and other related results on the behavior of the bond between concrete and different commercially available repair materials at different temperature, it is recommended not to repair the cracked joint of the Long Spruce Dam. As it is anticipated that cracking would occur due to the combined extremely high stress level.

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Finally, thanks to all my friends and family, especially to my little son Milan and my husband Denis for their love, support and patience during the development of this work.

1 INTRODUCTION

1.1 GENERAL

The main difference between mass concrete and all other concrete types is its thermal behaviour. Mass concrete is a type of concrete used mainly for incrementally constructed dams. Heat generated by the hydration of cement in mass concrete produces high temperature which can not quickly dissipate. Significant thermally inducted stresses must be develop and produces cracks.

Thermal load remains in dam structures until a dam is stabilized thermally. The control of this load is not an easy task. The thermal behaviour of mass concrete depends on several factors, such as mix portion of concrete, size of blocks, amount of pozzolans, chemical admixture, the use of air-entraining admixtures, ambient conditions and so on.

If the intensity of thermally induced stresses is larger than the tensile strength of concrete cracks initiate. Once cracks are initiated at the upstream face of a dam, water and ice (in cold regions) will produce higher pressure than those assumed. This usually leads to loss of structural integrity and shorter service life of the structure.

Precooling of concrete materials to obtain lower maximum temperature in the mass concrete during the period of cement hydration is used since 1940s [1]. Precooling of concrete means introducing crushed ice into the mixing water and cooling the aggregate. In addition, in some large dams precooling and postcooling refrigeration by embedded pipes has been used. Those are the most effective ways to reduce temperature. In order to get more reduction in temperature: low-heat-generating cement with pozzolans should be used and the amount of cement content should be controlled; control size of aggregate, i.e., use large size with reduced cement content; use chemical mixtures and air-entraining admixture in order to improve properties of concrete; use proper block size for placement; control time of placement for new block [1].

Usually, a couple of those parameters can be controlled. Some of them depend on site topology, foundation characteristics and availability of materials for construction. Economy should not be forgotten. It may even determine the type of structure.

Compressive and tensile strength, modulus of elasticity, Poisson's ratio, adiabatic temperature change, thermal conductivity, specific heat among all the other properties must be defined prior to construction. Some of those parameters are approximated because they depend directly on the mix proportion of concrete. Usually, before construction of a dam is started, a laboratory investigation must be done.

Volume change is another concrete characteristic that effect cracking. Volume change or shrinkage is caused by drying of fresh concrete. In the early stage of maturing, concrete is relatively elastic and stresses in time of maximum temperature can be assumed near zero. After that, in the cooling stage, concrete gains strength and elasticity [1].

Investigations on concrete in this early stage are performed using finite element method (FEM). There are different approaches on how to use this method. In this thesis, FEM is applied using commercial software, ANSYS. ANSYS is a finite element analysis package that performs 2-D and 3-D structural, thermal, electromagnetic, and fluid analysis. The components of interest are ANSYS/Structural and ANSYS/Thermal. ANSYS/Structural performs linear or nonlinear structural analysis that can accurately simulate the performance of different kind of structures, from small simple structures to large, complex models. ANSYS/Thermal is a program that can work alone and perform steady state and transient thermal analysis.

1.2 OBJECTIVE

The main objective of the thesis is to study thermally induced internal stresses caused by the heat of hydration in massive concrete. The main question to answer is whether the residual stress is responsible for the apparent loss of strength in construction joints of massive concrete structures. In other words when does the internal stress develop in mass concrete and what are its order of magnitude and profile in construction joints form the key questions to answer in this work.

Additional objectives include the development of inexpensive rehabilitation procedures for concrete dams which fail/leak at the construction joints.

1.3 SCOPE

This thesis contains finite element modeling algorithms for thermal and structural analysis of incrementally constructed massive structures. In the case of the young concrete, when the properties of the structure are changing quickly, transient analysis must be carried out. Residual stresses are usually mishandled at the design phase of mass concrete structures. This work provides a framework which may be used to access the magnitude and distribution of the internal residual stress at construction joints.

The thesis is divided into six chapters. Chapter 1 presents the overall subject of this research. Chapter 2 is a review of the pertinent literature, which is discussing thermal, stress, crack, and young concrete problems in mass concrete. In addition, this chapter contains relevant material parameters and overview of techniques for modeling. Chapter 3 contains a description of leak containment design in hydroelectric structures. Leakage through joints increases with time. A heating tunnel on the downstream side of a case-study structure is designed to provide what we refer to as a passive solution to the problem. The energy needed for heating of the tunnel and design of the tunnel is described in this chapter. Chapter 4 contains a thermal analysis algorithm and detailed procedure used in making of the algorithm. Detailed analysis of material properties of concrete is carried out in order to make all parameters as close to reality as possible. In Chapter 5, procedures for stress analysis are explained and results are discussed. The size effect is analyzed and the optimum time for pouring concrete blocks from stress field respect is calculated. Finally, conclusions and recommendation for future work are presented in Chapter 6.

Several appendices contain supplementary information related to the thesis work. Appendix A presents detailed analysis of the heating tunnel. Appendix B provides an explanation of the heat of hydration of cement used as a load for thermal analysis. In Appendix C, a detailed process for predicting the evolution of the modulus of elasticity is presented. Appendix D contains a listing of the program used for thermal analysis. Appendix E is the program code used for structural analysis.

2 LITERATURE SURVEY

2.1 INTRODUCTION

Thermal analysis of massive concrete structures is a common topic in many massive concrete publications. In most of those publications, the focus is the thermal load caused by heat of hydration of cement, in other words, thermal studies of young concrete. Many papers address aspects of structural analysis of concrete in its mature stage, however, very few of them deal with stresses in the early stage of concrete.

The main characteristic of mass concrete is the thermal behaviour. Although mass concrete is low in cement content, it develops high temperature field. The reason for this is its large volume. Low cement content can be allowed for this type of structures because the loads applied on the structure can be partly carried by the structure weight.

The high temperature developed by heat of hydration can be very dangerous with respect to cracking. This temperature must be controlled. Different ways for control of this temperature field is described in the Chapter 4 in detail.

Stresses of concrete blocks with thermal and mechanical effects should be analyzed for massive concrete structures. Thermal effects are related to the heat of hydration of cement, change of material properties (i.e. modulus of elasticity) and exchange of heat with environment. Mechanical effect deals with the change of the geometry of the structure, which means generation of new blocks of concrete during construction.

The behaviour of concrete depends on the heat produced by cement hydration and ambient temperature. The influence of ambient temperature is largest on external surfaces of concrete blocks.

2.2 MASS CONCRETE STRUCTURES

Mass concrete is defined as:

"Any large volume of cast-in-place concrete with dimensions large enough to require that measures be taken to cope with generation of heat and attendant volume change to minimize cracking"

Mass concrete is basic concrete made from fine and coarse aggregate, water and portland cement. Usually it contains larger aggregate size and smaller cement content. The main characteristic of mass concrete structures is strength. However economy, durability, workability must be considered too. Mass concrete structures are required for large volume of concrete pours, therefore the need for economy in the use of concrete is magnified [8].

In mass concrete structures, temperature rise that occurs in hardening from the hydration process is the largest problem nowadays. In the process of temperature rise, structures expand. However, structures are usually constrained from deforming and this constraint prevents expansion. Stresses are consequently induced in structures, and often, when the magnitude of these stresses are high, cracking occurs [7].

Mass concrete is concrete used mostly for dams, large bridge piers, foundations and other massive structures. Although massive concrete has low cement content the heat that has been developed in these structures can produce significant stresses. A structure must be thermally controlled otherwise cracking due to thermal behaviour may cause loss of structural integrity and monolithic action, or may cause excessive seepage and shortening of the service life of the structures, or may be esthetically objectionable [1].

Different processes for temperature control in concrete has been used. One of the factors that plays an important role in choosing which process will be applied for temperature control is economy. Some of the ways to solve this problem are: low-heat generating cement, pozzolans, aggregate size, precooling of aggregates and water, appropriate block size, construction schedules, circulating cold water through embedded piping and so on [1].

The most effective way to reduce temperature is the use of low cement content. This rule has limitations because a construction needs a minimum amount of cement to provide workability of concrete.

2.3 THERMAL LOAD DUE TO CEMENT HYDRATION

Heat generated by hydration of cement warms concrete to a different degree depending on size and mixture of concrete blocks and surrounding temperature. Dissipation of temperature depends directly on ambient temperature, but also on type of framework and number of surfaces exposed to ambient air. The temperature quickly dissipates from surfaces that are closer to ambient air. The temperature in the core of the block is high and dissipates slowly. This is the reason for stress appearance. The outer surfaces dry quickly and tend to shrink. This is the reason for appearance of tensile stresses. However, in the core, compression usually dominates. Once tensile stresses become larger than tensile strength, concrete cracking occurs. More complications occur due to loss of moisture, which also may create new cracks [8].

Heat generation is actually the outcome of the chemical process between cement and pozzolans and water. The heat of hydration directly depends on the type and amount of cement and pozzolan in concrete. Most of the heat is generated in the first seven days after mixing. In the same time, the concrete is gaining its early strength [8]. More about heat of cement hydration is explained in Appendix B.

In addition, pozzolans generate heat. Pozzolans are materials that replace cement in concrete structures. Usually pozzolanic materials, fly ash or a natural pozzolan, replace 35% of portland cement [15]. The reason for this replacement is, pozzolans generate about 40% less heat than cement.

Reaction between cement and water is exothermic and produces a considerable quantity of heat. This can be easily proven if cement in combination with water is placed in vacuum flask or other insulated container and temperature of the mass read at intervals [13]. This heat is usually neglected in construction where mass concrete is not involved, i.e., thin structures. Heat of hydration in construction, such as gravity dams, has considerable importance. The temperature in the middle of these structures can be 50°C higher than the temperature at time of placing concrete [13]. This high temperature can remain for many years. Also the shrinkage due to temperature change with time is the principal cause for cracking.

For heat evaluation, the adiabatic method is usually used. This method consists in a concrete sample and an adiabatic calorimeter from which no heat lost can occur. To get this condition the calorimeter is surrounded by an outer bath, the temperature of which is caused to rise by automatic means at exactly the same rate as that of the concrete [13]. This presents a condition, where no outward heat loss occurs. The time-temperature curve obtained from this kind of experiment simulates actual thermal history of the interior of a large mass concrete where conditions are almost adiabatic in the first few days. The temperature rise can be converted into calories per gram of cement with water equivalent of the concrete. This method can be satisfactorily used up to 7 or 28 days with larger error [13].

2.4 BEHAVIOUR OF CONCRETE

The main characteristic of mass concrete behaviour is its thermal behaviour. In addition, an important characteristic is its cracking behaviour. These two characteristics could be controlled but not be avoided.

As we mentioned before, chemical reaction between cement and water produces heat. In ordinary structures, this heat dissipates very quickly, in a couple of hours. However, in mass concrete, thermal stability is achieved after a couple of years. As thickness increases, the possibility for temperature rise increases. This can impair structural integrity.

In mass concrete, thermal stresses are affected by two elements: heat of hydration of cement and ambient temperature change. We usually can not influence ambient conditions. Daily change in temperature influences the behaviour of exposed surfaces of concrete. The temperature change on those surfaces is almost the same as change in the air. Cracking due to ambient temperature changes is usually at and near the surface [1]. In some cases, it is necessary to prevent propagation of the cracks. Leaving a formwork for longer period in cold days can help in avoiding this problem. However, when the formwork is removed, concrete surfaces can experience a large temperature change. This phenomenon is known as "thermal shock" [1].

2.5 CONTROL OF DAM CONCRETE CRACKING

Concrete structures are subjected to volume change. If volume change is uniform, it will not produce cracks. Uniform volume change occurs if a structure is relatively free to change volume in all directions. Free volume change is very rare in mass concrete [9]. Mass concrete is usually constrained. This constraint is in many cases enough to produce cracking.

Some methods for temperature control that have been regularly used in construction of dams are explained in this thesis. Which method will be used for cracking control mostly depend on the economic situation. Some of the control methods that we are going to discus in this part are restraint and control of volume change. The volume change can be reduced by reducing cement content, using pozzolans, precooling, postcooling, control of rate for heat gain and loss and similar methods mentioned before. However, adding reinforcing steel can help to distribute cracking so that one large crack can be replaced by many smaller cracks of acceptable width [9].

Restraint acts to limit change in dimension produced by stress. Stress usually exists in a structure. Stress can be produced by supporting elements (constraint) or by different parts of a structure. This is the reason for dividing restrain into two categories external restraint and internal restraint.

Continuous external restraint exists on the surface that is in contact with surface where concrete has been cast. How much restraint appears in structure depends on the size of the structure, strength of concrete, modulus of elasticity and restraining material. The stresses in concrete increase due to restraint. Cracks are formed in restrained concrete when stresses exceed tensile strength. They will continue to grow until stresses reach a magnitude that is insufficient to continue crack generation. These cracks in some cases can grow through the entire block [9]. In addition, cracks do not stop immediately when stresses are smaller than tensile stress of concrete. They usually continue to growth even at half of the stress field necessary to initiate crack.

Internal stresses are very usual for dam structures. These stresses exist in structures where interior temperature is greater than surface temperature. Magnitude of the restraints caused by internal stresses is added to the external restraints but usually internal restraints are negligible in comparison with external ones.

Three main reasons for volume change are shrinkage due to dissipation of construction temperature, annual thermal boundary condition patterns, and drying shrinkage [6]. Adjusting the following elements can control drying shrinkage effect: cement content, type of aggregate, modulus of elasticity, control of temperature rate and others. In addition, annual temperature change influences volume change, especially in the regions where difference in temperature during the year can be as high as 80°C. Daily temperature difference can produce small cracks that are not structurally considered.

3 PASSIVE REHABILITATION AND LEAK CONTROL

3.1 INTRODUCTION

Cracks are a major economic problem. Gravity dams and other massive concrete structures are subjected to significant thermal loads which are producing considerable stress fields. When these stress fields become larger than the material strength, cracks initiate. Variations of temperature in Northern regions of Canada can be sometimes as high as 80°C and severe condition like these present a considerable challenge which can seriously affect the integrity of a structure. This change deals with a case study of a dam, which has cracked as a result of the action of thermal loads.

The Long Spruce dam in northern Manitoba, Canada, has a crack that goes along the structure from downstream side to upstream side. Monitoring of this crack has been observed for six years. Following three years of observation crack has opened 0.2 mm in upstream and downstream side [10]. This opening explains increase of leakage with time. Water leakage in the worst case is around 100 liter/min. This amount of water is extremely dangerous especially in winter time. In winter time, ice formations on the downstream side are large and can be dangerous for people who work around the dam.

Heat traced drainage system was installed on the downstream side of Long Spruce generation station. The function of this system is to capture leaking water on the downstream side, which causes icing problem in winter.

3.2 LEAKAGE OF THE DAM

Problem of leaking in dams is a major problem and practical solutions are not yet found. This problem is more emphasized in dams in severe climate conditions. This is the case with the Long Spruce generation station.

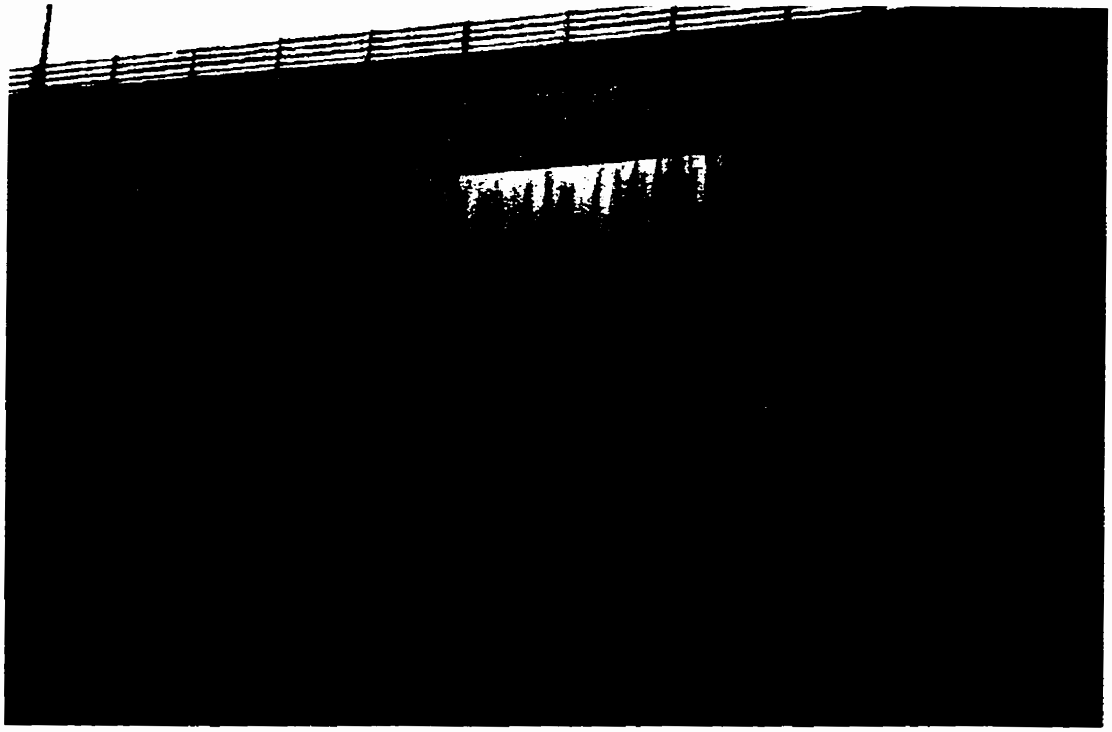
Photographs 3.1-3.4 present the history of crack growth at Long Spruce. All photographs are taken from the same place and present the downstream side of the dam.

The leakage shown on photograph 3.1 is not severe because as the photograph is taken in June 1987. This is the beginning of crack formation. Photograph 3.2 is taken in August 1992 when the leakage started to be important which means the width of the crack is larger and more water appears on the downstream side.

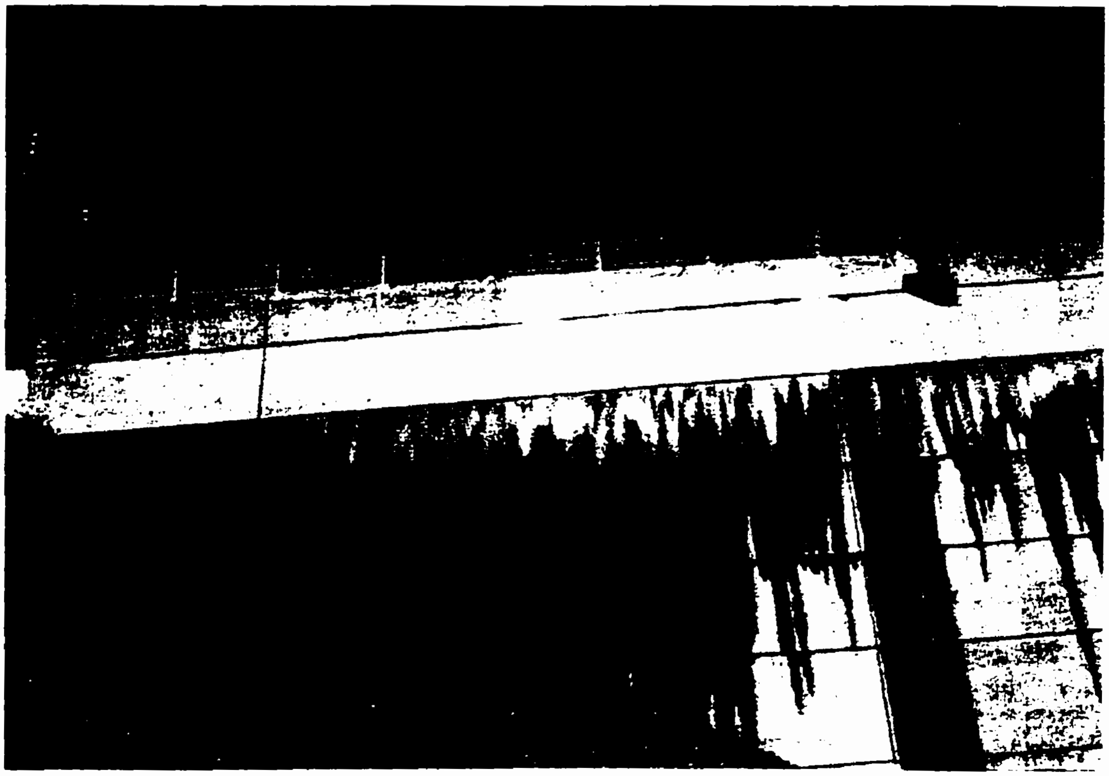
Photograph 3.3 shows a typical winter situation. Ice formations are big and people who works on the dam are in a dangerous situation from ice falling from the dam especially at spring time when ice melts. This is the main reason for installation of heat traced drainage system on the downstream side.

Heat traced drainage system is presented in photograph 3.4. The photograph was taken November 1996 and it is obvious that leaking in the downstream side has stopped. This solution does not solve the real problem, i.e. stop crack growth and deterioration. That is the reason why additional investigations have to be carried out.

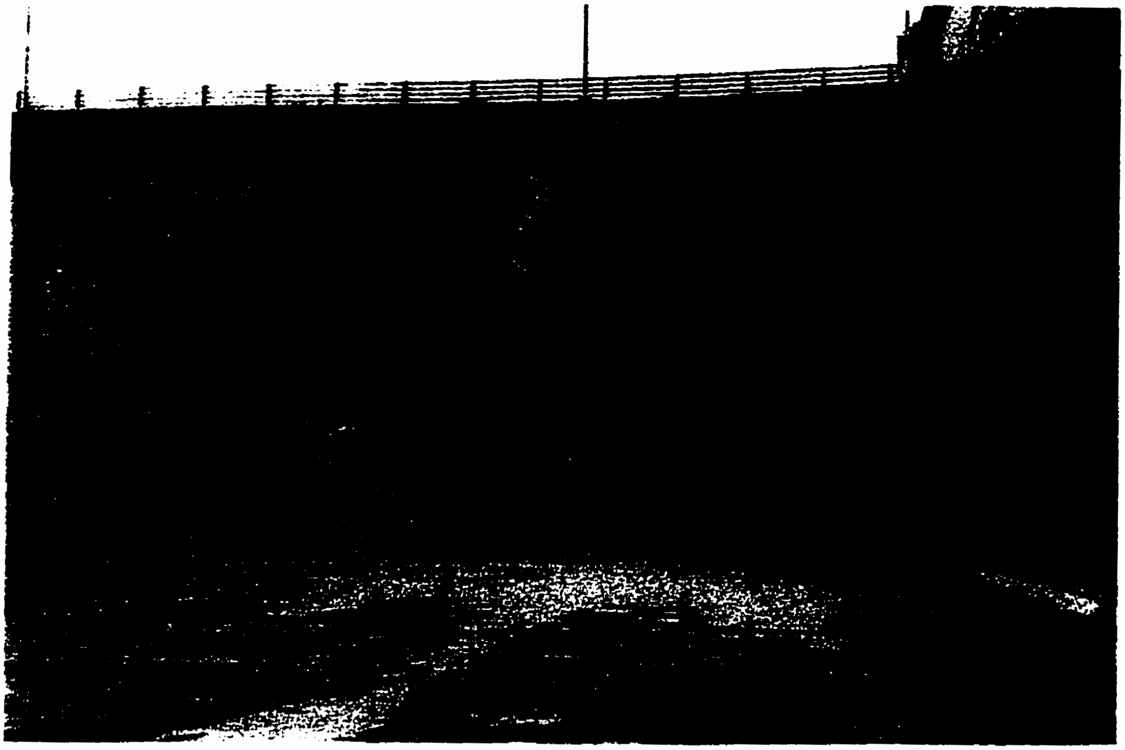
In order to present ice from forming and accumulating during winter, the amount of heat necessary is evaluated next. This procedure may be used commonly in cold regions, at last as a temporary measure, while a more permanent solution is being considered.



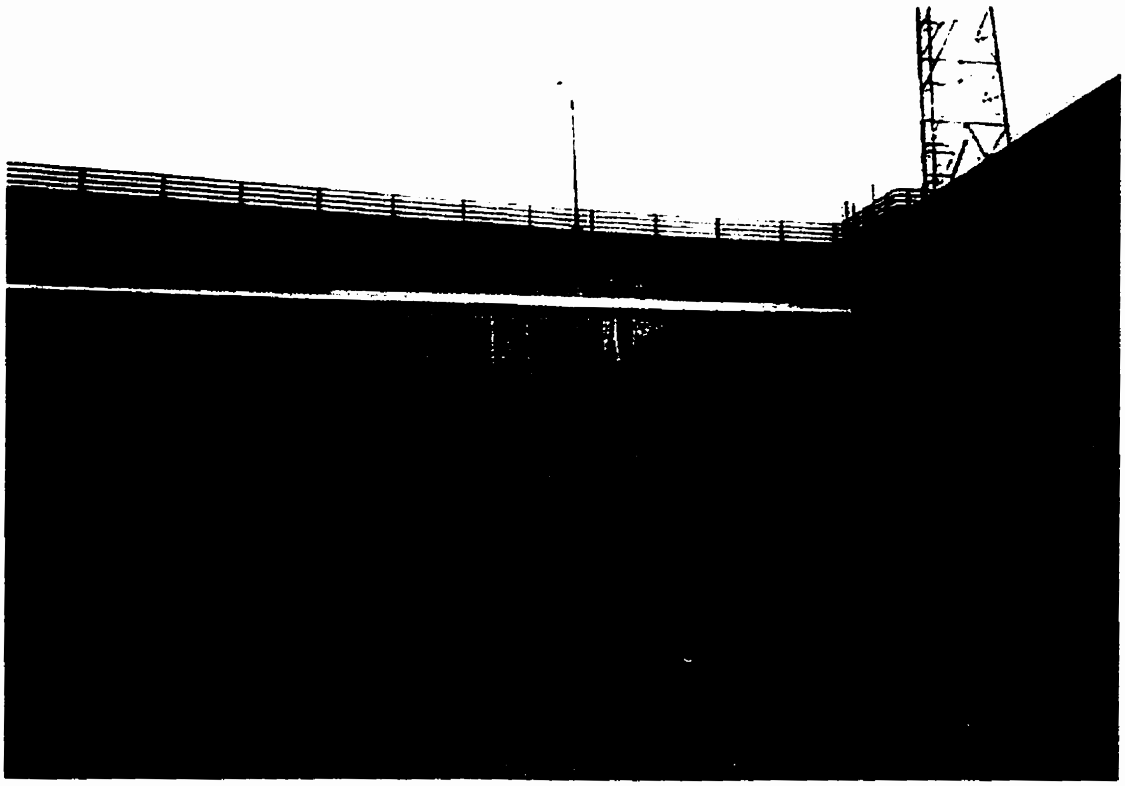
Photograph 3. 1 *Downstream Side of Long Spruce Dam at June 1987*



Photograph 3. 2 *Downstream Side of Long Spruce Dam at August 1992*



Photograph 3.3 *Downstream Side of Long Spruce Dam at December 1992*



Photograph 3.4 *Downstream Side of Long Spruce Dam at November 1996*

3.3 ESTIMATION OF HEAT ENERGY

The passive rehabilitation is the kind of rehabilitation that could contain the problem of leaking for a short period of time. It is done here because the falling of the ice from the side of the dam becomes more dangerous with time. In this work the energy required to maintain the air temperature around the crack above freezing point is estimated. The tunnel is 0.25 m half round enclosure. It is heated by electric heat traces. Temperature can be monitored and heat can be reduced if necessary.

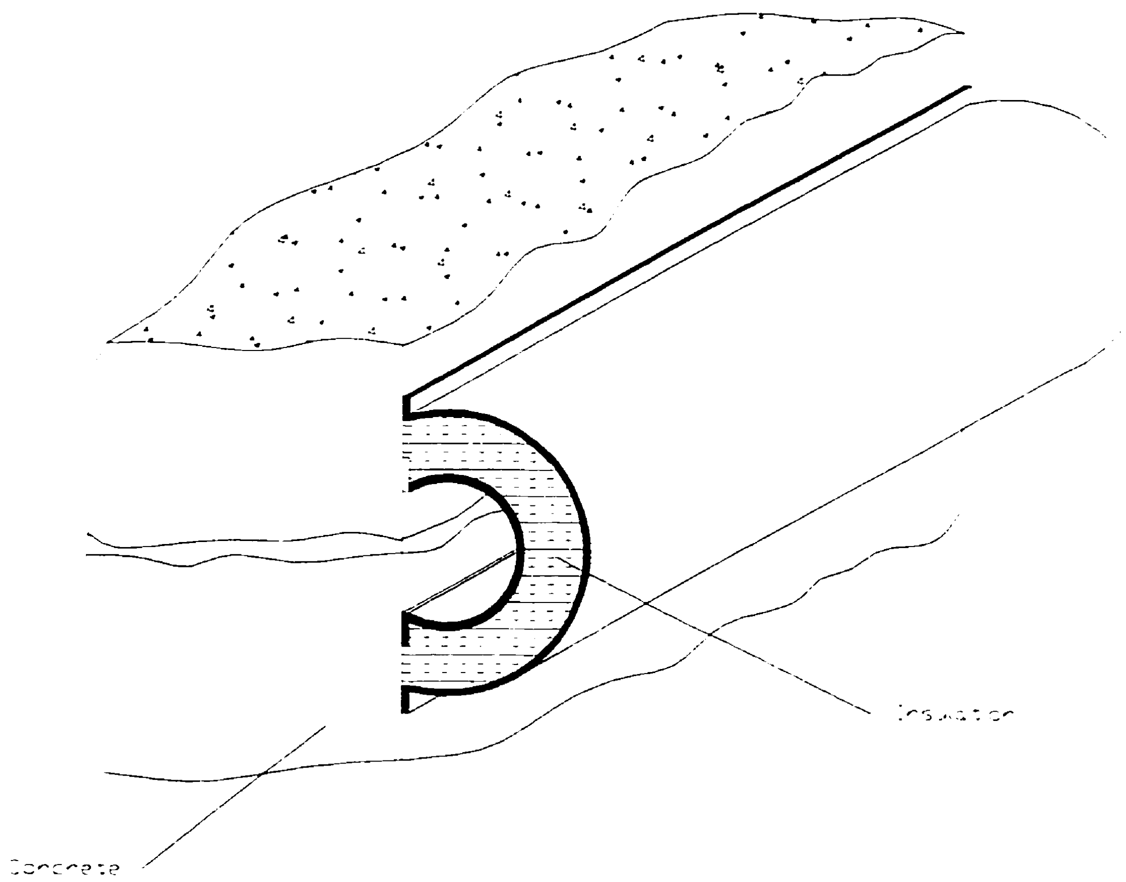


Figure 3.1 *Heat Traced Drainage System*

From the Figure 3.1, we can see that three kind of heat loss may occur,

q_1 *[W]* is the heat loss through the wall of the dam by convection

q_2 *[W]* is the heat loss per unit length through the insulation by conduction

q_3 *[W]* is the heat loss with water

Those three kinds of heat losses in the tunnel are actually energy needed to be supplied through heating. All three heat losses will be discussed separately.

First as, the heat loss through the wall of the dam by convection can be expressed:

$$q_1 = Ah_c(T_c - T_\infty) \tag{3.1}$$

where,

h_c *[W/(m² K)]* is the convective coefficient between air and concrete

T_∞ *[K]* is the air temperature in the tunnel

T_c *[K]* is the concrete temperature

The heat loss per unit length through the insulation by conduction:

$$q_2 = \frac{[3.82Lk(T_\infty - T_0)]}{ln\left(\frac{r_1}{r_2}\right)} \tag{3.2}$$

where,

k *[W/(m K)]* is thermal conductivity of the insulation material

T_∞ *[K]* is the air temperature in the tunnel

T_0 *[K]* is the outside temperature

r_1 *[m]* is the radius of the pipe

r_2 *[m]* is the radius of the insulation

The heat loss with water transport can be presented as a sum of three heat losses:

$$q_3 = q_a + q_b + q_c \tag{3.3}$$

where,

q_a *[W]* is energy needed for increase temperature of ice from -10°C to 0°C

q_b *[W]* is energy needed for melting ice (changing phase)

q_c *[W]* is energy needed for increase water temperature from 0°C to 7°C

Energy that is necessary for ice temperature increase from -10°C to 0°C can be presented by following formula:

$$q_a = m^{\cdot} c_{ice} (T_1 - T_2) \tag{3.4}$$

where,

$m^{\cdot}$ *[kg/s]* is the mass of ice to be eliminated per second

c_{ice} *[kJ/(kg K)]* is the specific heat of ice

The energy needed for phase change (from ice to water) can be expressed as:

$$q_b = m^{\cdot} h_{sf} = m^{\cdot} \left(h_f - h_s\right) \tag{3.5}$$

where,

h_{sf} *[kJ/kg]* - the latent heat of melting

Energy needed to increase water temperature from 0*°C* to 7*°C*, in order to make sure that this water will not freeze, is:

$$q_c = m' c_w (T_3 - T_4) \tag{3.6}$$

where,

c_w *[kJ/(kg K)]* is the specific heat of water

Finally, the total energy necessary for heating this kind of structure can be estimated as:

$$q = q_1 + q_2 + q_3 \tag{3.7}$$

This estimation is done on maximum water leakage. Water leakage is most of the time in winter period smaller than maximum, which occurs during spring. It is not very important for this calculation to overestimate because amount of heat to be determined can be easily reduced.

3.4 THE DRAINAGE PIPE

The maximum amount of water seeping from the crack is $V' = 100$ *l/min*. This is the base for the determination of the diameter of the drainage pipe. The slope of the tunnel is 1/2 %, and the mass flow rate is:

$$m' = \rho V' \tag{3. 8}$$

where,

ρ *[kg/m³]* is specific density of water

The velocity of water through the tunnel should be estimated. Velocity is a parameter needed to determine the radius of the drainage pipe.

Using the second Newton's low, we can write:

$$\Sigma F = ma \tag{3.9}$$

$$v^2 = v_0^2 + 2a(x-x_0) \tag{3.10}$$

$$v = \frac{m'}{\rho A} = \frac{m}{\rho r^2 \pi} \tag{3.11}$$

where,

v *[m/s]* is velocity of water through tunnel

a *[m/s²]* is acceleration of the water through tunnel

From the equation (3.11), the radius of the pipe can be determined. Detailed analysis is presented in the Appendix A.

3.5 DISCUSSION

The heat trace drainage system analyzed in this chapter has been installed at the Long Spruce generation station since the winter 1996. The energy that is estimated of 12 kW for thickness insulation of 1 inches is slightly high, for details see Appendix A. This was expected for the analysis of this kind because the analysis was based on a maximum leakage that can happen. However, after construction of the tunnel in the downstream side of the dam, leakage almost does not exist and the tunnel function is very well.

4 THERMAL ANALYSIS

4.1 INTRODUCTION

Thermal behaviour of concrete in its early stage is investigated in this chapter. Although concrete for a massive structures like dams have small cement contents, the temperature produced by cement hydration becomes extremely high if it is not controlled.

The problem analyzed here is transient in nature. Transient thermal analysis is the most common of all thermal analyses. Almost all heat transfer processes are transient in nature. This kind of analysis is used to determine temperature and other thermal quantities in the body due to different thermal loads. Thermal loads applied to the structure are time dependent. For practical problems, transient thermal analysis can be a difficult task especially when dealing with complicated shapes and long periods.

Among different methods of analysis, the finite element method is a very acceptable and commonly used method for such kind of problems. In this particular problem, the commercial finite element program, ANSYS is used.

In order to obtain reliable results, the model should capture the thermal behaviour of mass concrete in its early stage. All factors such as changes in model geometry, heat of hydration of cement, boundary conditions, transient incremental procedure must be included. In addition, the framework around the model is considered because influence of this part on the temperature field is not negligible, specially for small size specimens. Analysis results are interpreted systematically and in a way are important for this kind of work.

4.2 TRANSIENT THERMAL ANALYSIS

To make a good simulation of the real model many different factors that can influence thermal behaviour of young concrete have to be included in the algorithm. Some of those factors are: concrete block size, placing frequency, change of ambient temperature, influence of formwork, heat of hydration as a thermal load and other factors in the analysis algorithm which will be discussed later.

As we mentioned earlier, transient thermal processes are common processes in nature. To perform transient analysis we have to introduce loads that are a function of time. Heat produced by hydration of cement and change of ambient temperature are two important loads which are dependent on time. Change in ambient temperature is neglected in this analysis. For laboratory specimens this change of temperature does not even exist because the curing process is taking place in a closed area, where temperature is constant. In the dam model change in the ambient temperature is neglected because the dam model is observed for small period of time. Loads from hydration of cement are changed every six hours. For results that are more accurate, a smaller time step should be used. However, when a dam model is analyzed the time step is increased at the end of the analysis as the effects of initial conditions are no longer important. The loads used in the algorithm caused by the heat of hydration of cement are presented in Appendix B.

The first step in a transient analysis is to apply the initial conditions. Usually, the initial conditions are uniform temperature at all nodes. Later the transient process starts and the thermal field is obtained by solving the classical heat equation. For each time step, the loads as a function of time must be defined.

4.2.1 Heat Balance Equation

The basis for thermal analysis is the heat balance equation or governing heat transfer equation, which is based on the principle of energy conservation. The governing heat transfer equation in the global Cartesian system can be expressed in the following form:

$$\rho c_p \frac{\partial T}{\partial t} = q + \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) \qquad (4.1)$$

where:

ρ is density

c_p is specific heat

T is temperature $T = T(x,y,z,t)$

t is time

q is heat generation rate per unit volume

k_x, k_y, k_z is conductivity in the element x, y and z directions, respectively

The boundary conditions are pretty much the same for all models analyzed in this thesis. The major differences in boundary conditions between laboratory models and the dam model are in the boundary conditions and outside temperature.

The boundary conditions used for thermal analysis are presented below:

1. Prescribed temperature acting on surface S_1 (surface which is in contact with ground):

$$T = T^* \qquad (4.2)$$

where T^* is a prescribed temperature.

2. Prescribed heat flow on the surface S_2 (all surfaces which are in contact with air):

$$\left(k_x \frac{\partial T}{\partial x} + k_y \frac{\partial T}{\partial y} + k_z \frac{\partial T}{\partial z}\right) = q^* \qquad (4.3)$$

where q^* is a prescribed heat flow

Equation (4.1) can be expressed in the matrix form:

$$[C]\{\dot{T}\} + [\overline{K}]\{T\} = \{\overline{Q}\} \qquad (4.4)$$

where:

$[C]$ is specific heat matrix

$[\overline{K}]$ is heat conductivity matrix

$\{\overline{Q}\}$ is heat flux vector

$\{T\}$ is nodal temperatures vector

$\{\dot{T}\}$ is time derivative vector of above nodal temperatures

Nodal temperatures are calculated by integrating equation (4.4). From the nodal temperatures other thermal quantities can be derived. Temperature field is calculated for better understanding of early thermal behaviour of massive concrete structures and for subsequent stress analysis. In the stress analysis, temperature field is applied as a classical thermal load.

4.3 ANALYSIS ALGORITHM

Early thermal behaviour of concrete is observed in two separate models, a model of laboratory concrete specimen and a dam structure model. In the dam model, only two blocks of concrete are analyzed. The other conditions that should be calculated before these two blocks such as temperature of the bottom block are simulated using results from [6]. Placement technique is considered by placing a new block and changing the boundary conditions. Thermal load, in the form of heat of hydration of cement is applied in every step. Between the time intervals, the program calculates average values for thermal load.

The incremental thermal analysis algorithm is presented in the flowchart below. This is the easiest way to present the sequence behind the simulation of lift generation.

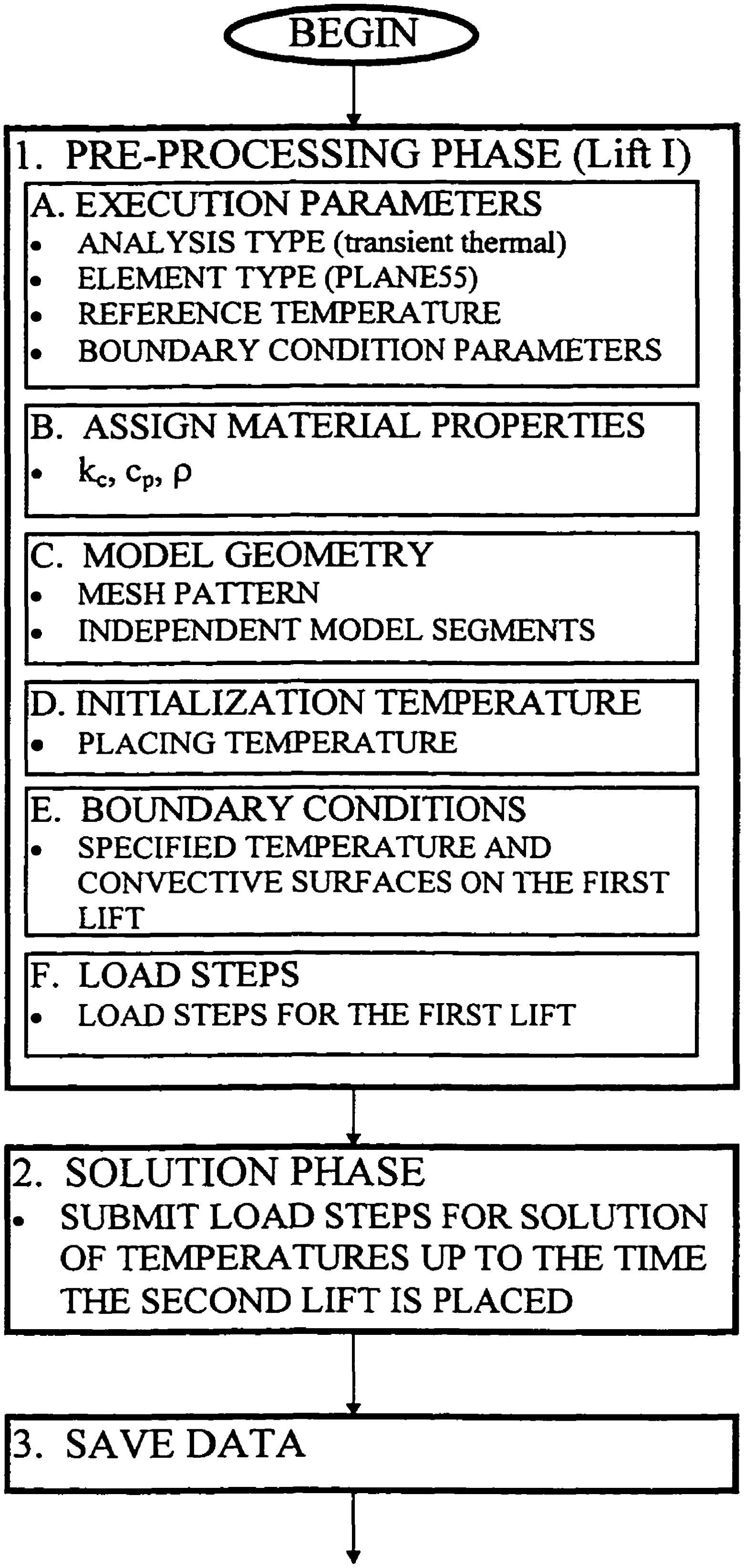


Figure 4.1 *Finite Element Modeling Algorithm for Thermal Analysis (page 1 of 2)*

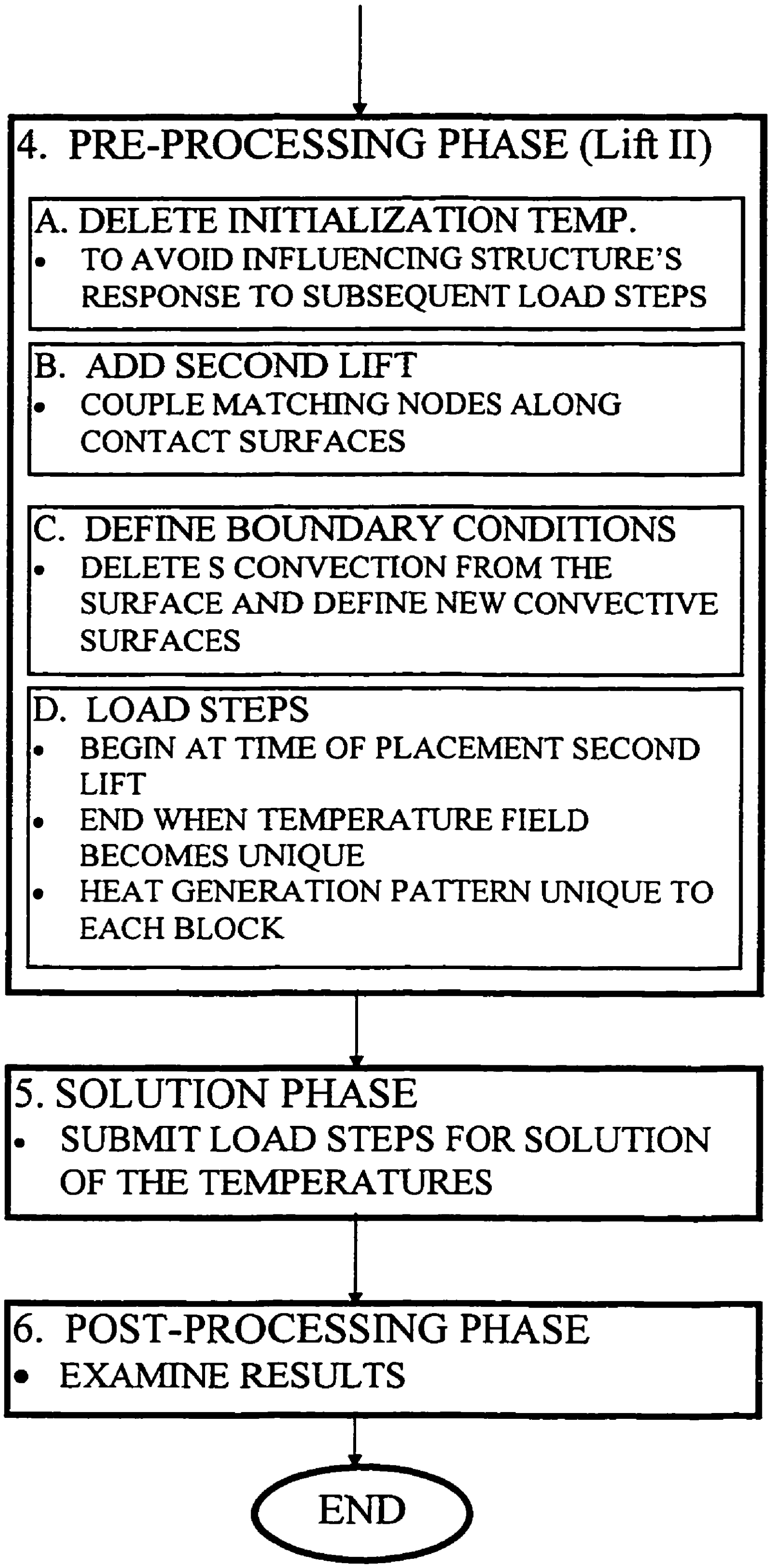


Figure 4.1 *Finite Element Modeling Algorithm for Thermal Analysis (page 2 of 2)*

4.3.1 Execution Parameters

In this algorithm, the first step presents a definition of execution parameters, material properties, model geometry, initialization temperature, boundary conditions and load steps.

Execution parameters (part 1.A. in the algorithm) in this program are analysis type, type of element used for finite element analysis. Analysis type is thermal analysis and this type of analysis calculates thermal quantities of the model. The most common thermal quantities of interest are temperature field, thermal flux and thermal gradient. In many cases, thermal analysis is preformed and the temperature field is used as a load for stress analysis.

When we are dealing with thermal analysis the element type must have thermal properties. Analysis is two-dimensional and element type is two-dimensional, isoparametric, four-node quadrilateral thermal solid element. In ANSYS, these are called PLANE55 - 2D Thermal Solid.

Reference temperature or initial temperature is the temperature of concrete at the moment of its placing in a formwork. In laboratory specimens, we are dealing with small amount of concrete and room temperature is accurate enough for concrete reference temperature. For larger structures such as dams concrete is mixed with ice water and in many cases cold aggregate and placing temperature is much lower.

4.3.2 Model Geometry

The key points are defined first. The laboratory model is divided into nine areas that are presented at Figure 4.2. Each area has four key points. The whole model has 24 key points. These key points are actually corners of the rectangles for this model. The whole model is rectangular and the easiest way is to divide this model into smaller rectangles. For dam model a similar procedure has been used.

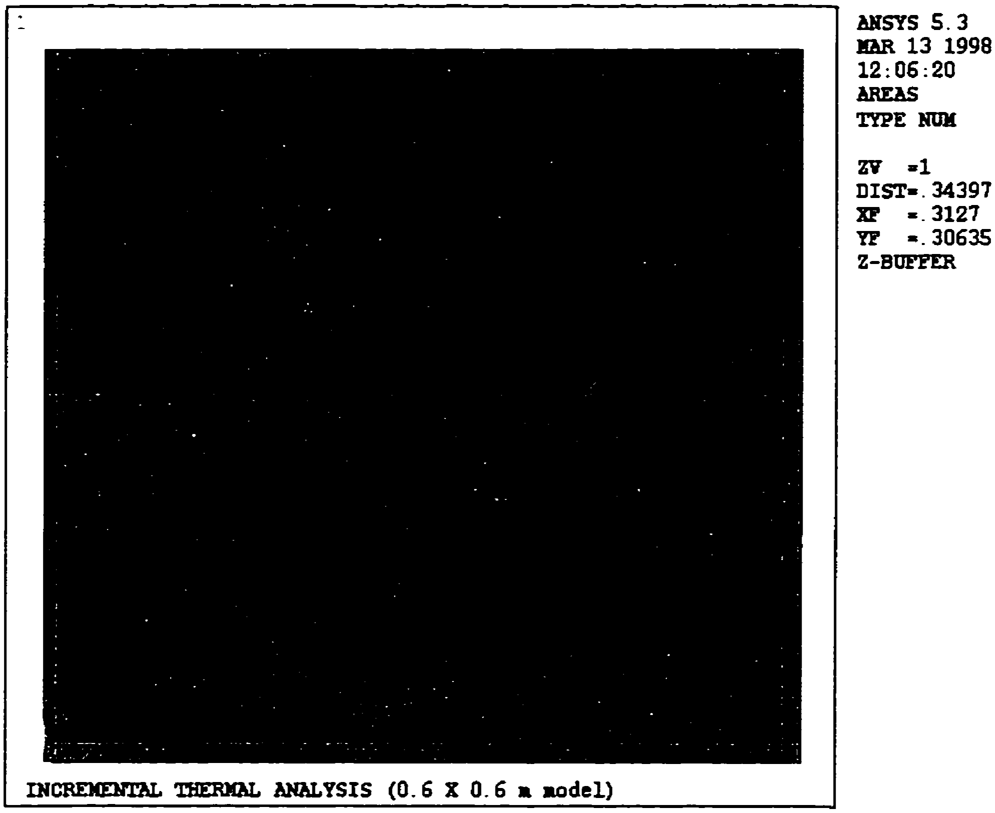


Figure 4.2 *Laboratory Model (0.6 x 0.6 m specimen)*

After definition of key points, the lines were defined. The lines are connections between key points and there are 30 lines. Some lines have identical coordinates. The reason is that the whole model is not observed at the same time. Some portions of the model are added later.

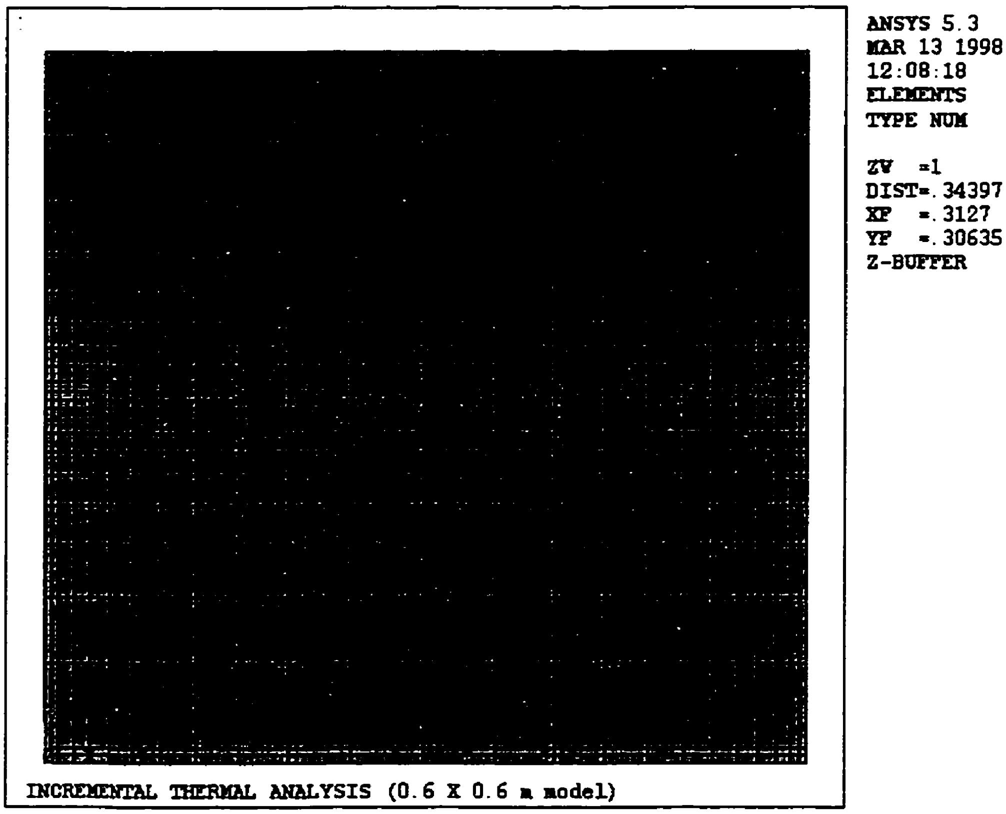


Figure 4.3 *Elements of 0.6 by 0.6 Model*

Lines are divided into smaller portions that are later used for mesh pattern. The framework is meshed into elements of equal size. The mesh on the concrete blocks is refined on the outside part of the blocks. In the middle part of the blocks, the mesh is coarse which is obvious from Figure 4.3. The reason for this is temperature variation that is faster on the border of the model (model is exposed to the ambient) while temperature variation in the middle of the structure is relatively small.

The formwork for the laboratory model is divided into seven areas and concrete model consists of two. For the dam model four areas are observed, two concrete blocks and two formwork blocks. The two concrete blocks are geometrically independent. It means that all nodes in the model are common to only one segment. There is no interaction between the segments until the coupling of nodal degrees of freedom takes place at the time when the block is placed in the model.

4.3.3 Material Properties of Concrete

Thermal properties of concrete necessary for this kind of analysis, are thermal conductivity, density, specific heat, and convective heat transfer coefficients. However, coefficient of linear thermal expansion and modulus of elasticity are necessary to know for structural analysis and will be analyzed in this chapter.

It is not easy to determine these properties, which are mostly dependent on the composition of concrete, age of concrete and temperature. The range of these properties is large. For example, the thermal conductivity varies between 4.97 and 15.55 *kJ/hr m °C* for normal saturated concrete between 10 °C and 65 °C, the specific heat varies between

0.84 and 1.17 *J/g/°C*, and coefficient of thermal expansion between 6.3x10^{-6} and 11.7x10^{-6} *1/°C* [2].

4.3.3.1 Thermal Conductivity

Thermal conductivity is the ability of a material to conduct heat through itself. In other words, it is a measure of the rate of heat flow. As mentioned above, the range of thermal conductivity coefficient for concrete is wide. The reason is the composition of concrete, which means: type of cement, type of aggregate, water content and so on. For example, quartz aggregate is particularly noted for its high value of thermal conductivity [1]. However, air inside concrete is an insulator and it has the biggest influence in the reduction of thermal conductivity.

The value of thermal conductivity adopted in this analysis is 8.41 *kJ/kg °C* and is assumed to be temperature independent during the analysis.

4.3.3.2 Specific Heat

Specific heat is measure of heat capacity. It is the amount of heat needed to change temperature of 1 *g* of material by 1 °C. The main factors that influence the specific heat of concrete are water and temperature.

4.3.3.3 Coefficient of Linear Thermal Expansion

Coefficient of linear thermal expansion represents change in volume with change of temperature. Besides temperature, the composition of concrete and moisture have a big influence on the coefficient of linear thermal expansion. Natural aggregate has great variations in coefficient of thermal expansion. In addition, moisture content influences the thermal expansion coefficient of cement paste.

This coefficient is almost constant for dry concrete at temperature between -9 ℃ and 21 ℃ [2]. Moist concrete shows increase in the coefficient of thermal expansion with temperature increase.

4.3.3.4 Modulus of Elasticity

One of the most important characteristics of concrete is the modulus of elasticity. In order to obtain appropriate simulation of concrete behaviour in its early stage, the modulus of elasticity must be assumed to be variable. In our model, the modulus of elasticity is changed every day until it reaches the age of 28 days. This modulus can be changed more frequently for more accurate analysis. After 28 days, the modulus of elasticity for concrete is considered constant. Although concrete is not an elastic material, it is assumed to behave elastically. The elasticity modulus varies from concrete to concrete. For dam concrete, the range is from 19,000 to 38,000 *MPa* at 28 days [2]. The modulus of elasticity depends on the strength of concrete, and concrete with higher strength usually has higher value of modulus of elasticity. Aggregates also have influence on the modulus of elasticity. Many factors influence this value, but up to now there is no universal test method for determining this modulus.

All these influences are not included in our analysis. The effect of age of concrete on the modulus of elasticity is the most important influence when we are dealing with young concrete. The best interpretation of the modulus of the elasticity in young concrete is given by Rusch [3]:

$$E_t = \beta_e E_{28} \tag{4.5}$$

where,

E_t is instantaneous modulus of elasticity at a time of loading

β_e is coefficient dependent on the age of concrete

E_{28} is modulus of elasticity after 28 days

Modulus of elasticity E_{28} is easy to find in the literature. β_e is coefficient presented by Rusch in Figure 4.4.

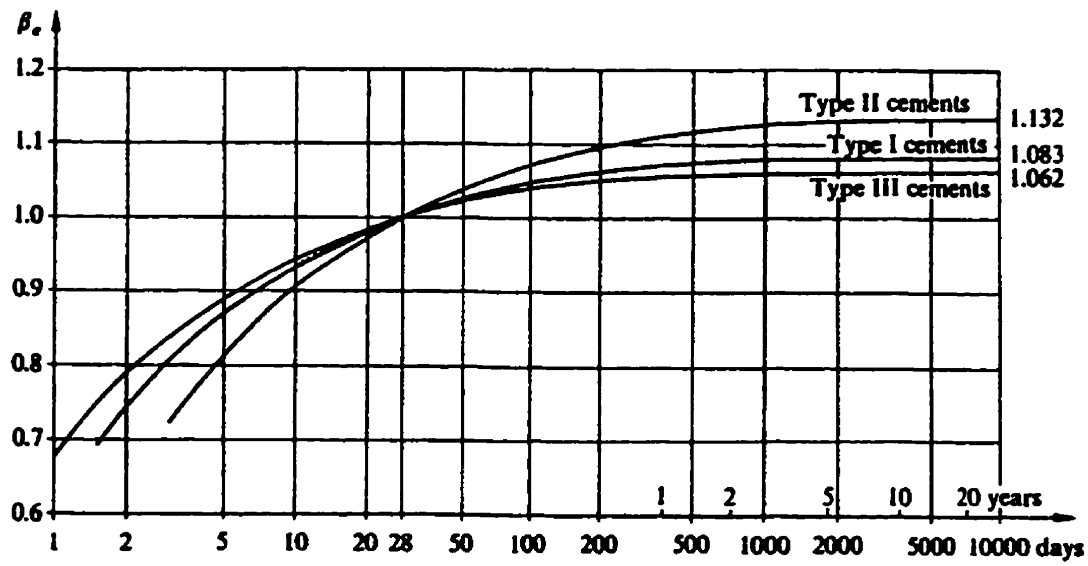


Figure 4.4 *Effect of Concrete Age on Modulus of Elasticity*

As it can be seen from the diagram, there are curves for three different type of cement. Type I is normal cement, type II is slow cement, and type III is rapid cement. In our case, we are dealing with normal type of cement. For the normal type of cement, we can calculate the modulus of elasticity from time approximately 1.7 day that is not accurate enough for small specimens. In a paper published in Japan [4], the test method is established for the determination of the modulus of elasticity and the results of the tests are in a good agreement with curve proposed by Rusch [3]. The effect of hardening acceleration for mass concrete can be properly evaluated if the correct concrete age is applied. The correct concrete age is determined from the following formula:

$$t_e = kz \cdot \Sigma \frac{T+10}{30} \cdot \Delta t \tag{4.6}$$

Where,

t_e *[day]*is corrected concrete age

kz is coefficient showing the effect of hardening speed for cement

(ordinary cement kz=1)

T *[℃]* is temperature of concrete

Δt is increment of time for which temperature remaining at T *[day]*

Calculating the modulus of elasticity using the above formula and comparing results with the results published in [4], it can be seen that they are in good agreement.

4.3.3.5 Properties of Framework

There are two materials in the model. One is concrete, which is the domain of interest in this analysis, and the other is the formwork, which surrounds the concrete material. The formwork is considered because its influence on the temperature field is not negligible, especially for laboratory specimen. However, in this analysis is very important to know the temperature field on the boundary of concrete. The boundaries are places for crack initiations and to get more realistic model, the framework should not be neglected.

The material constants obtained from literature and from the field which are adopted here are:

Concrete:

k = 1.13 *[kJ/m s K]* is heat conductivity

c_p = 880 *[kJ/kg K]* is specific heat

ρ = 2240 *[kg/m³]* is density

Framework:

k = 0.30 *[kJ/m s K]* is heat conductivity

c_p = 2400 *[kJ/kg K]* is specific heat

ρ = 820 *[kg/m³]* is density

These characteristics are applied to the laboratory model. For the dam model, the characteristics are slightly different because the aggregate is larger.

4.3.4 Initialization Temperature

Sometimes we are dealing with concrete with initial temperature different for each block. This is the case with dam concrete. The huge blocks are pre-cooled or ambient temperature is changing during the process of placing the concrete. Those are reasons for different initial temperature of concrete.

In the case of laboratory specimens we are dealing with relatively small blocks of concrete and assume that concrete is at room temperature in time of placing is good enough. It means the initial temperature of the concrete for both blocks is 23 ^0C. For the dam model, ice water was used. The initial temperature of concrete was 10 ^0C.

4.3.5 Boundary Conditions

Boundary conditions in transient thermal analysis are thermal boundary conditions and for those models, it is mostly convection, which occurs on all sides of the model except the bottom where temperature is fixed. The model is exposed to the ambient conditions, which means that heat convection occurs between model and air. Convective surfaces are not the same all the time because the new concrete block is added. The bottom of the model is not exposed to the ambient conditions and specific temperature is prescribed here. This is a common type of boundary condition for this type of thermal analysis.

On the bottom of the model a prescribed temperature is applied. It is not exactly what happens in reality but we can use that approximation and still get good results. Also, in a dam, the bottom of the dam is far away from the surface of interest and this boundary can be totally neglected because there is no influence from it. The rest of the boundaries change with time. First, one surface of the first block and formwork are in contact with air where convective heat transfer is applied. When the upper block is poured convection is deleted from the one surface of the first block and couple of surfaces of the framework. However, the top surface of the upper block becomes the new surface where convection occurs.

4.3.6 Load Steps

In the first phase of the load steps, the lower block is observed. The lower block is observed for 24 hours for the 0.6 X 0.6 *m* laboratory specimen. Each step is six hours long and has one substep. This interval can be smaller, but sometimes we do not get desirable improvement in results and we spend much more time obtaining results with smaller steps. In addition, small time steps can cause numerical difficulties. For the upper block same time interval is used, just different load is applied. In other words, load from the heat of hydration is now applied on the upper and on the lower block every six hours.

For the dam model, the upper block of concrete is cast after 102 hours. This time is obtained from field records. In the beginning of the thermal process, the dam model is analyzed every six hours. Later, the time step was increased; first it was 12 hours, then 24 hours. The end of the time span is not that important for this analysis, that is why time step is so large. However, we need to know when stable conditions from heat of hydration load takes place. That is the reason why the dam model is observed for 960 hours only.

4.3.7 Internal Heat Generation Rates

Heat of hydration directly depends on the amount of cement in concrete. Portland cement is composed of three principal chemical compounds: tricalcium silicate, dicalcium silicate, tricalcium aluminate and ferrite phase. Small amounts of other phases can also be found [12]. If tricalcium aluminate is reduced to a minimum, heat of hydration would be smaller. Heat of hydration is the highest in first few days, further heat development depends on the type of cement. Although cement mixes used for dams are leaner than cement mixes for bridges, piers and similar constructions, maximum temperature in some cases reaches 69 °C [13].

The internal heat generation rate due to cement hydration is calculated for each step of the analysis algorithm. The internal heat generation rate depends from time on placing temperature of concrete. The assumption for this work is that the heat generation rate pattern depends only on time. This is a usual assumption for this kind of work.

The heat generation rate under adiabatic condition depend on cement type, unit cement content and initial temperature of mixing material [14].

General expression for the adiabatic temperature rise due to heat of hydration was proposed in[14]:

$$T(t) = K(1 - e^{-\alpha t}) \tag{4.7}$$

Where,

t *[day]* is a time

K *[°C]* - values shown on the Figure (4.5)

α - value shown on the Figure (4.5)

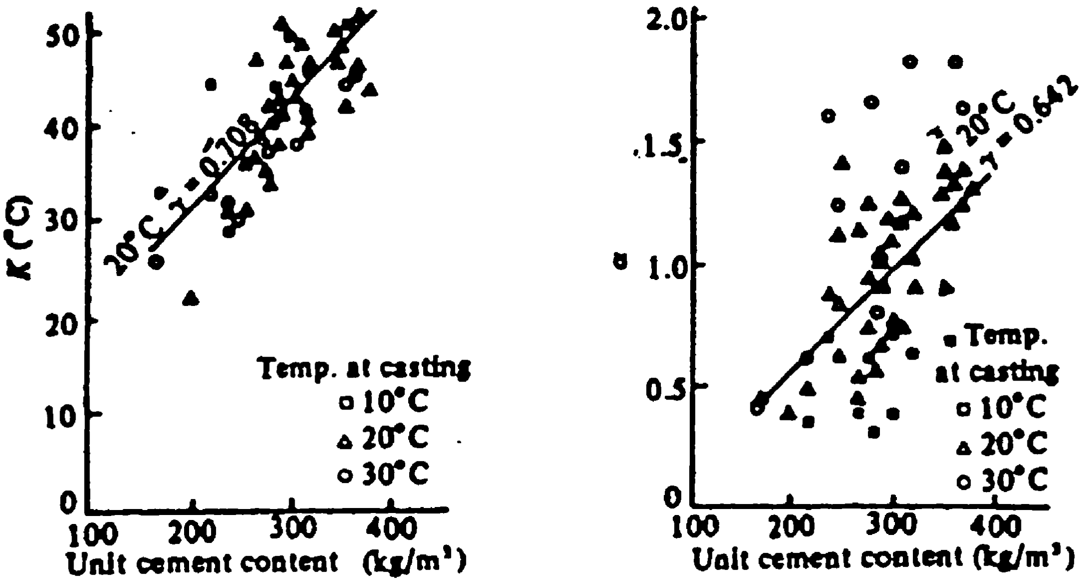


Figure 4.5 *K and α Values of Adiabatic Temperature Rise*

Total amount of heat generated per unit volume can be presented by the following equation:

$$Q(t) = C_p \rho T(t) = K C_p \rho (1 - e^{-\alpha t}) \tag{4.8}$$

For our work, the unit rate of heat generation is required. The heat generation rate can be calculated as:

$$R(t) = \frac{\partial Q}{\partial t} = K C_p \rho \alpha e^{-\alpha t} \tag{4.9}$$

On this basis, the internal generation rate is calculated.

The applied heat of hydration for the cement used in the models is described in more detailed in Appendix B.

4.3.8 Phase when Second Lift is Placed

This phase is very similar to the first phase. Almost all steps are the same as in the first phase except time. Now the time continues from 24 hours for laboratory specimen until the solution is stable, which means when temperature is almost the same for each nodal point. The stable solution time for the model is after 120 hours (five days).

The second lift for the dam model is placed after 102 hours and similar procedure to that of the laboratory specimen is applied. This specimen is observed for 960 hours.

4.3.9 Solution Phase

All above defined data is submitted for solution in this phase. Actually, the program calculates the temperature field for each time step and substep. In this way, we can follow the temperature field pattern, heat flow pattern and other similar parameters. In addition, temperature distribution at each nodal point during time integration can be observed. All those results are explained in the next paragraph.

4.4 ANALYSIS RESULTS

Different kind of results can be displayed using ANSYS. The results are actually a solution of the equation 4.4. The results of the solution are nodal degree-of-freedom temperature values. From nodal solution element solution are derived and from element solution different values can also be later obtained as stresses and displacements.

Figure 4.6 to Figure 4.9 present the results from incremental thermal analysis of laboratory concrete specimen 0.6 X 0.6 *m*. The model is two dimensional and observed in Cartesian coordinate system.

The type of element chosen for this type of analysis is PLANE55. The element has two-dimensional thermal conduction capabilities. However, the element has four nodes with single degree of freedom, temperature, at each node. This element can be used in two dimensional, steady state or transient thermal analysis.

Using finite element software ANSYS, two different types of modeling are possible: solid modeling and direct generation [11]. For solid modeling the geometric boundaries of model, size and shape of elements have to be established, and then, instruct ANSYS to generate all nodes and elements automatically. For this work, the direct generation is more suitable, because we are dealing with a simple model. With direct generation method, the location of nodes, size, shape and connectivity of every element is determined. The mesh of the model is more reasonable to catch the local variation of the temperature. It means that the mesh is refined on the border of the model. This mesh control is much easier with direct generation than with solid modeling.

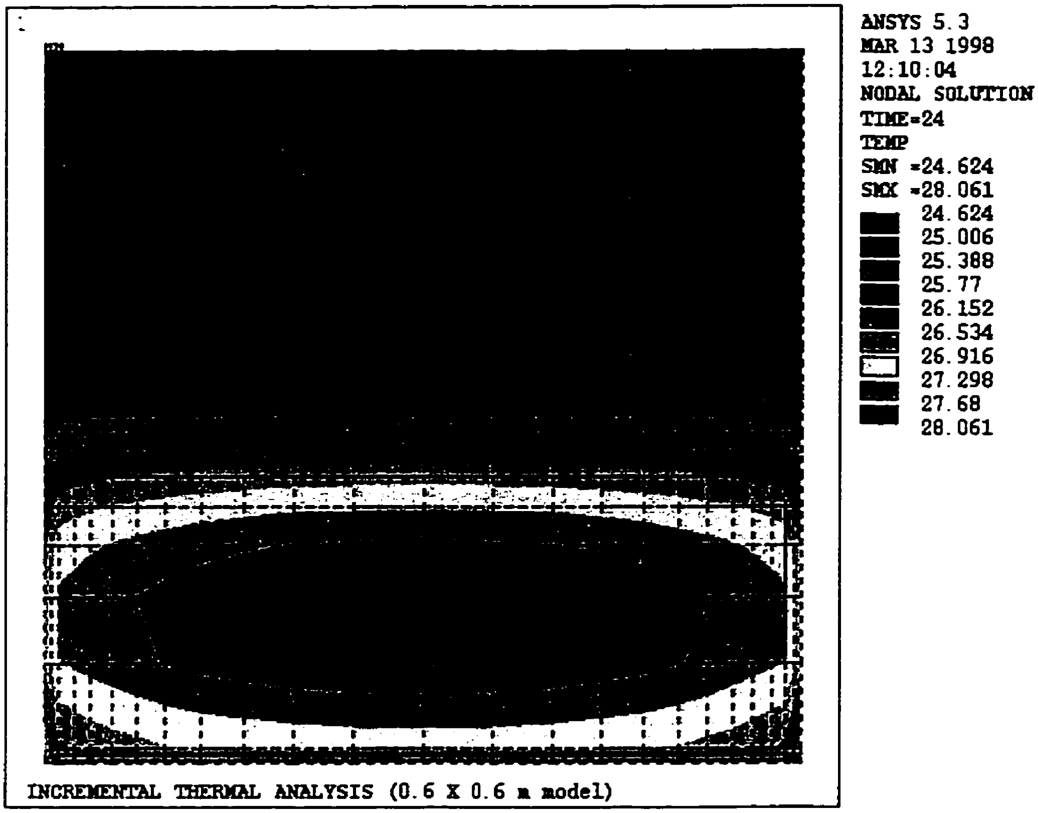


Figure 4.6 *Temperature Field of 0.6 X 0.6 m Model at Time 24 hours (time before second block is poured)*

Figure 4.6 presents the temperature field at 24 hour, just before upper block is cast. The largest temperature is in the middle part of the specimen and it decreases closer to the sides of the model. This is what we would expect the solution to be. The middle part is losing heat slowly in comparison with borders that are exposed to air and loose heat very quickly. The maximum temperature at time 24 hours is around 29°C and minimum is on the side of specimen and has a value almost equal to air temperature. At this time the upper block is placed.

The maximum temperature occurs in the upper part of the specimen. Time is now 36 hours from the beginning of the analysis. The temperature field is presented at Figure 4.7. The temperature at this time is around 38°C and this temperature is maximum that this specimen reaches during the analysis.

Figure 4.8 is last step of this analysis, 120 hours after first block is placed. Difference in temperatures between points at this time is 3°C. This is a reasonable difference in the temperature and it is not necessary to go further and get more stable field.

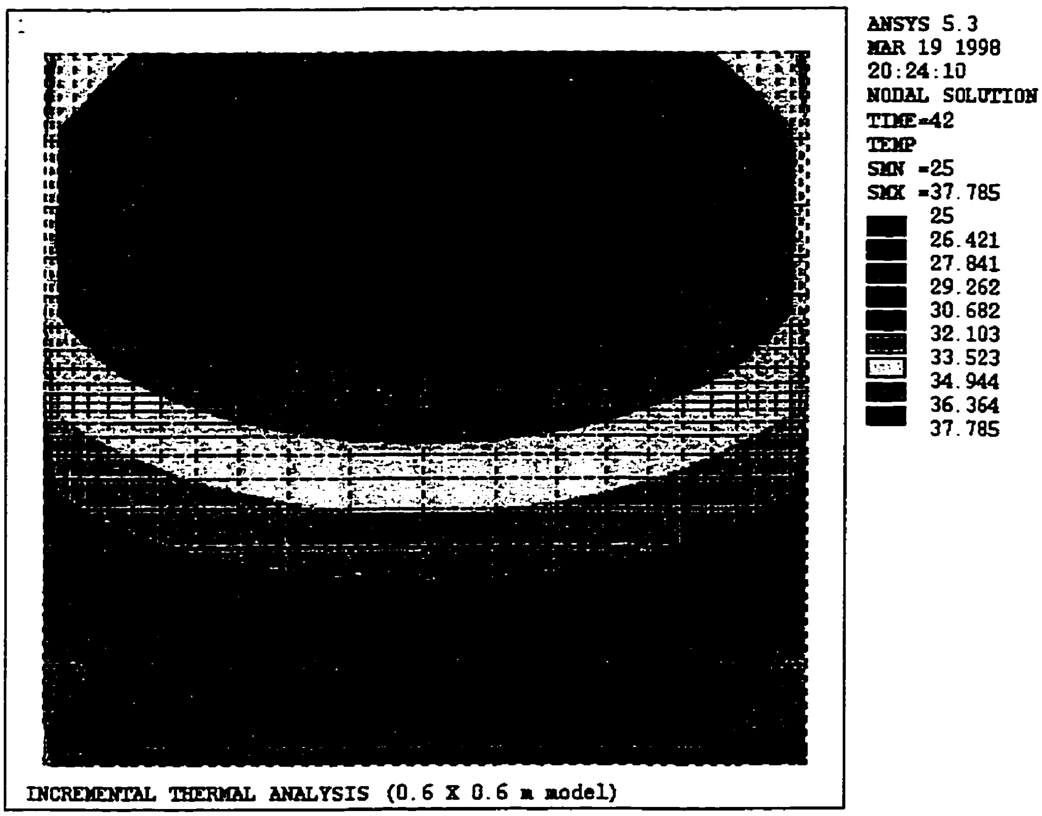


Figure 4.7 *Temperature Field of 0.6 X 0.6 m Model at Time at 42 hours (time when maximum temperature occur)*

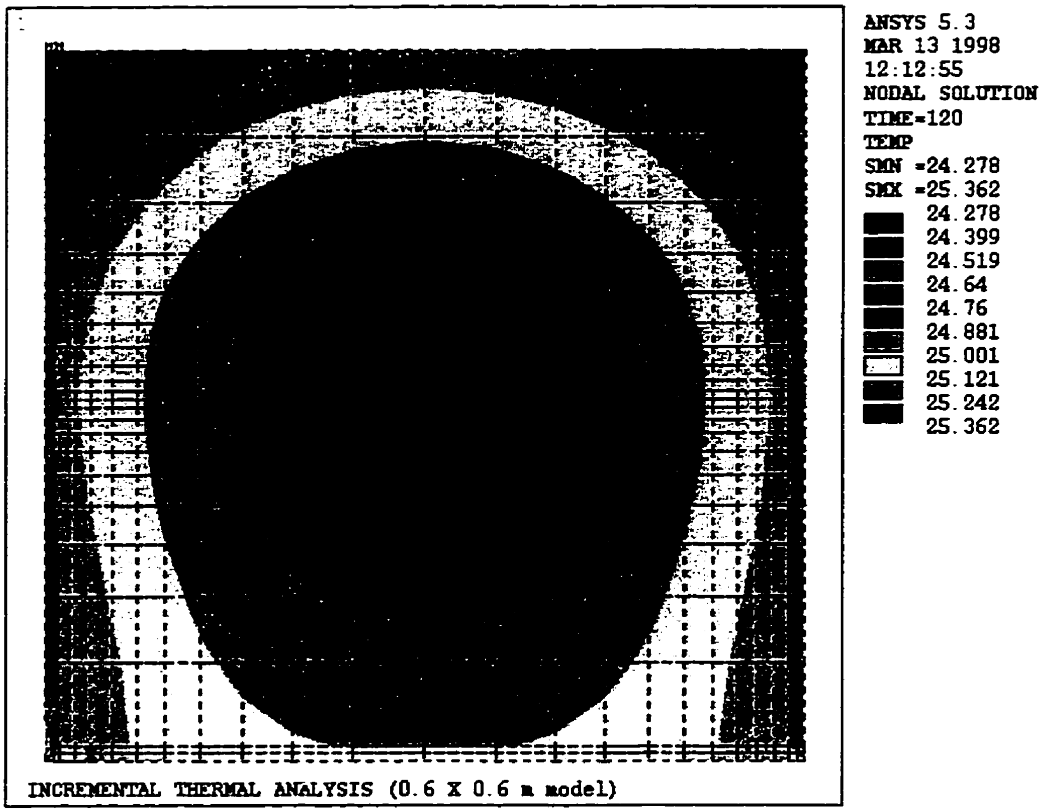


Figure 4.8 *Temperature Field of 0.6 X 0.6 m Model at Time 120 hours (time when temperature field become stable)*

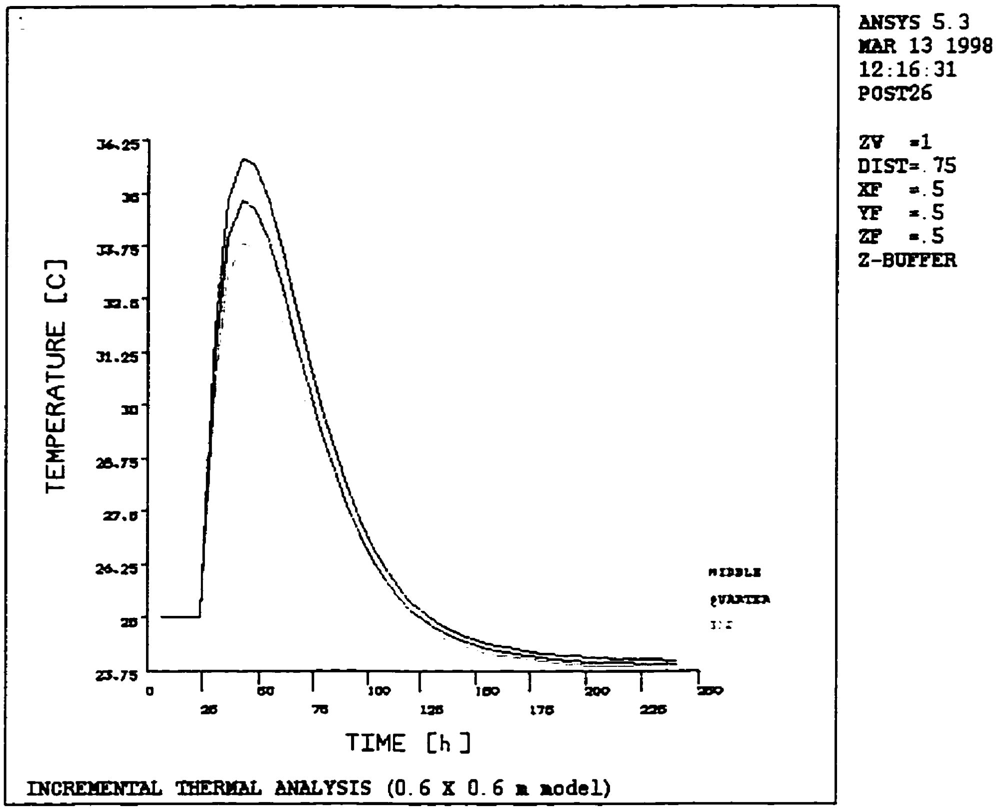


Figure 4.9 *Time - Temperature Diagram of 0.6 X 0.6 m Model for Specified Nodes on the Interface (end, quarter and middle node)*

Figure 4.9 presents temperature versus time diagram. Three characteristic nodes at the interface between the two blocks are observed. One node is on the left side of the interface and it experiences fast heat dissipation and low maximum temperature. The other node is in the quarter of the length of interface and the last one is in the middle. From the diagram it is easy to see that middle node has the highest temperature among all nodes on the interface. More nodes were observed and from this diagram, it is obvious that all nodes on the end have almost the same temperature. It means that process of heat hydration is finished.

4.4.1 Effect of Size of Specimen

The laboratory specimen that has been observed is too small (0.6 X 0.6 *m*) to realistically predict the behaviour of massive concrete structures. This is the reason why this model is enlarged to different sizes. Size of the model has been enlarged by two, five and ten orders of magnitude.

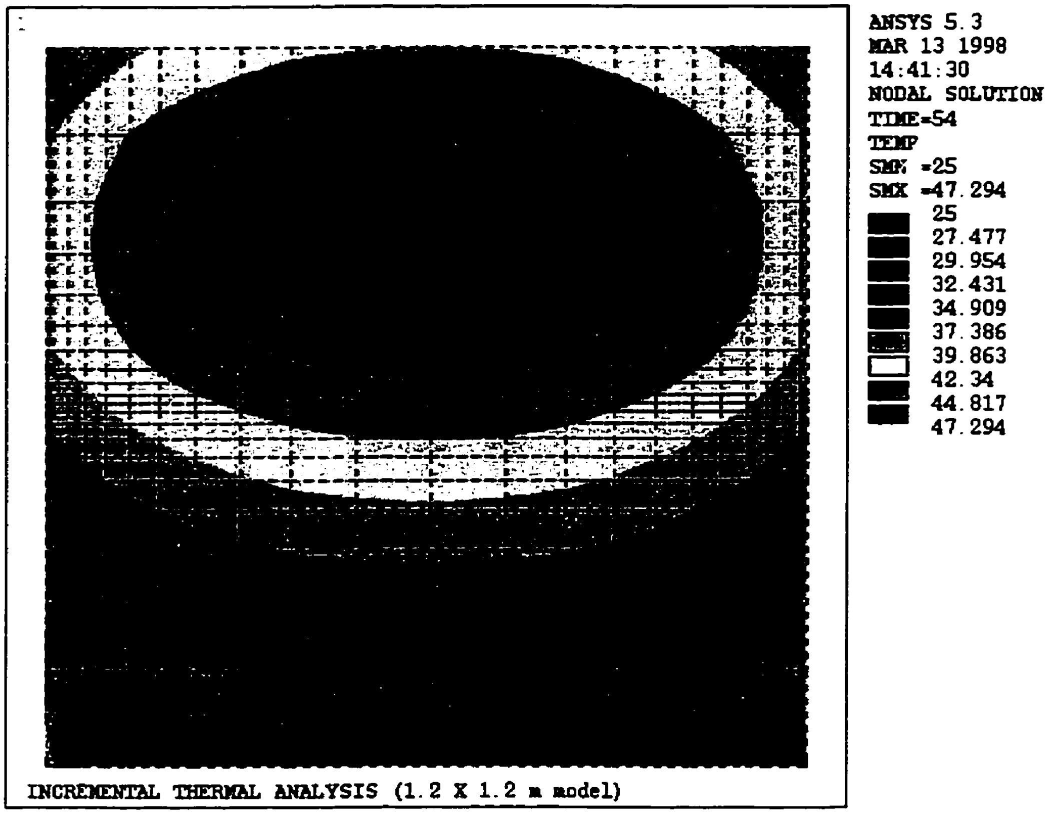


Figure 4.10 *Temperature Field of 1.2 X 1.2 m Model at Time 54 hours*

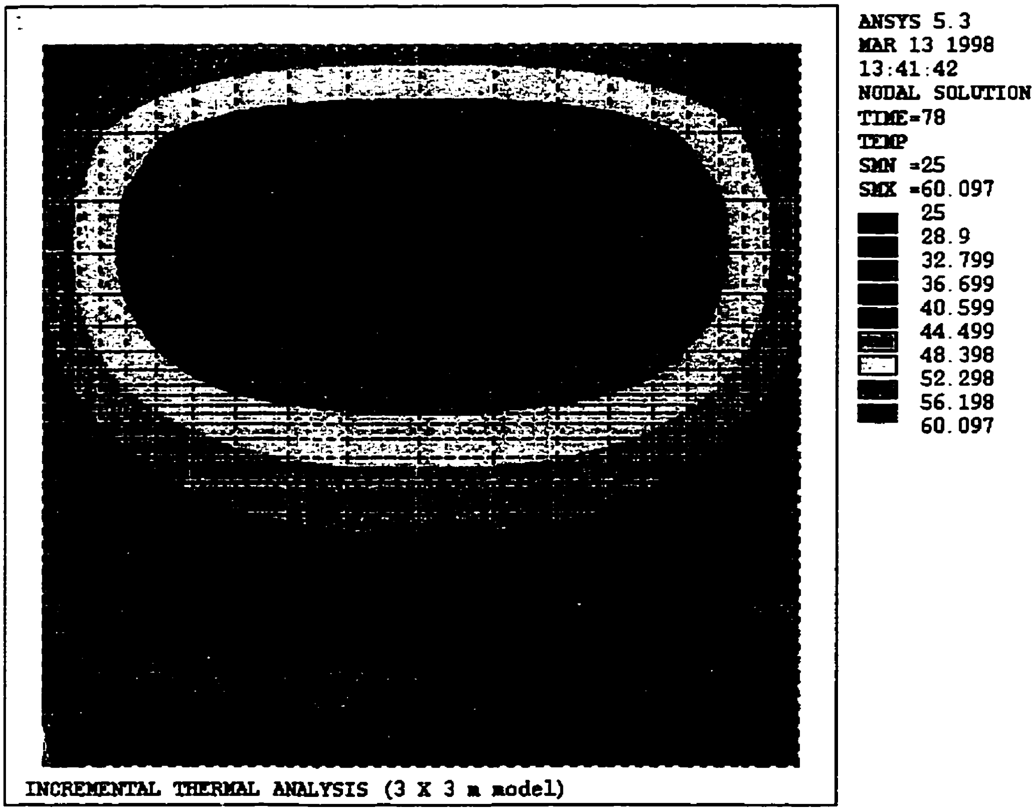


Figure 4.11 *Temperature Field of 3 X 3 m Model at Time 78 hours*

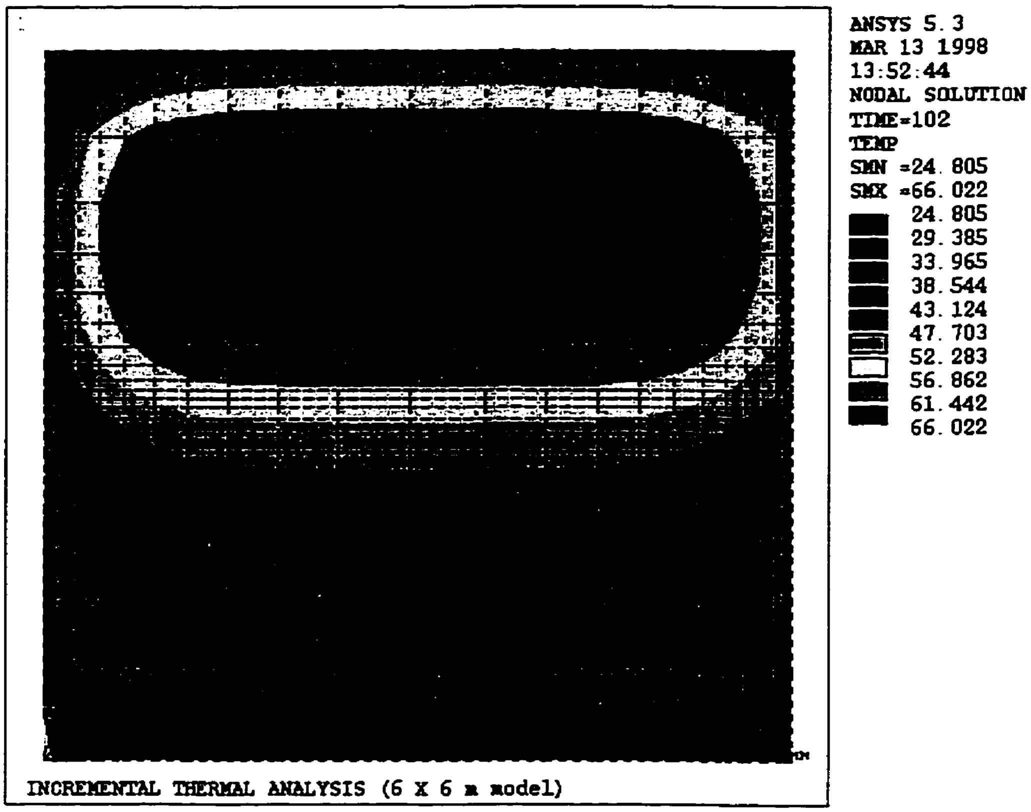


Figure 4.12 *Temperature Field of 6 X 6 m Model at Time 102 hours*

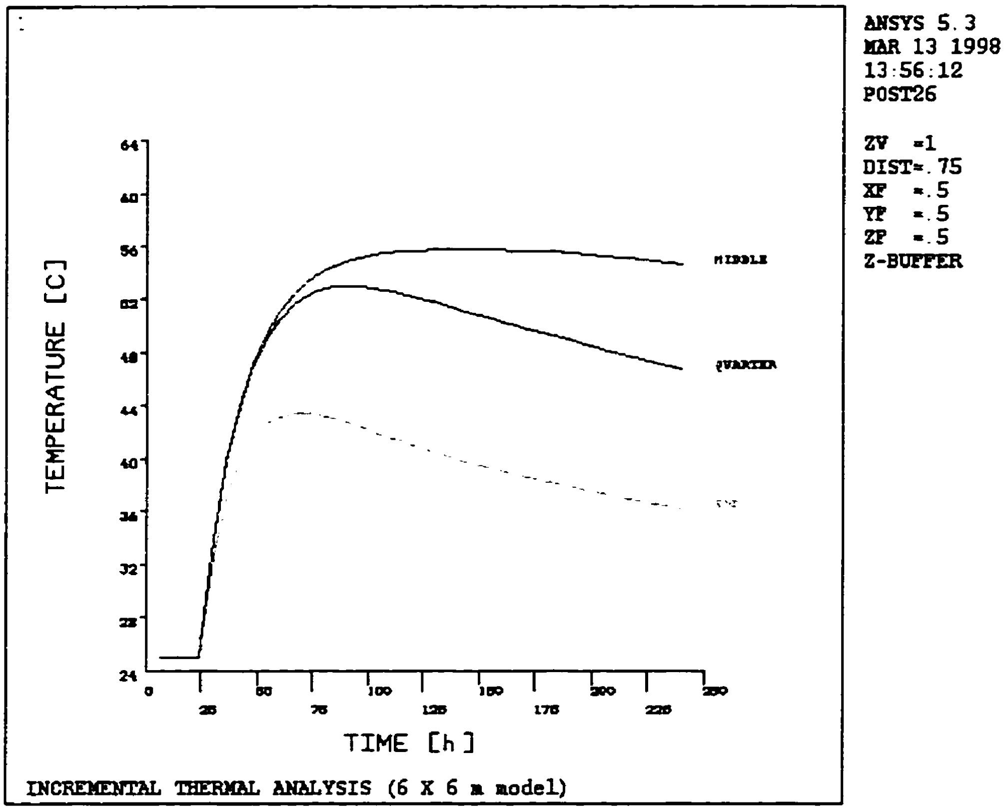


Figure 4.13 *Time - Temperature Diagram of 6 X 6 m Model for Specified Nodes on the Interface (end, quarter and middle node)*

4.4.2 Time of Casting Effect

The model that has been chosen to study this effect is 6 X 6 *m* because this one is the most similar to the dam model. The upper block is cast at following times: 24, 48, 72, 96, 120, 144 and 240 hours. In the field, they cast the upper block of the dam after temperature of the lower block passes the maximum value. The goal of this analysis is to find the best time to pour a subsequent block.

From results it can be concluded that the temperature distribution on the interface is better when upper block is cast 240 hours after the first one. This statement is only valid for temperature distribution on the interface. This, however, does not represent the best time of casting. Complete temperature field is in worse position from concrete cracking respect because lower block is cool at this stage. Also temperature on the interface does not dropping too much for some time. Economic side should be satisfied, because ten days is a long time to wait.

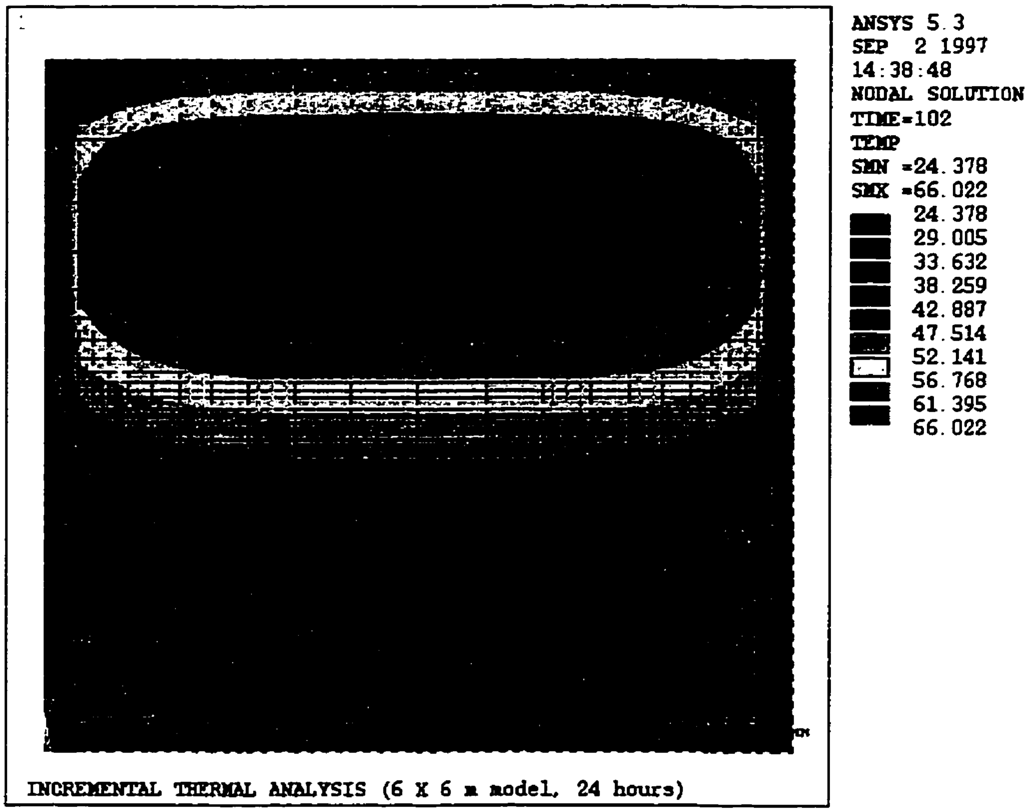


Figure 4.14 *Temperature Field of 6 X 6 m Model at time 102 hours*

(upper block cast 24 hours after the first one)

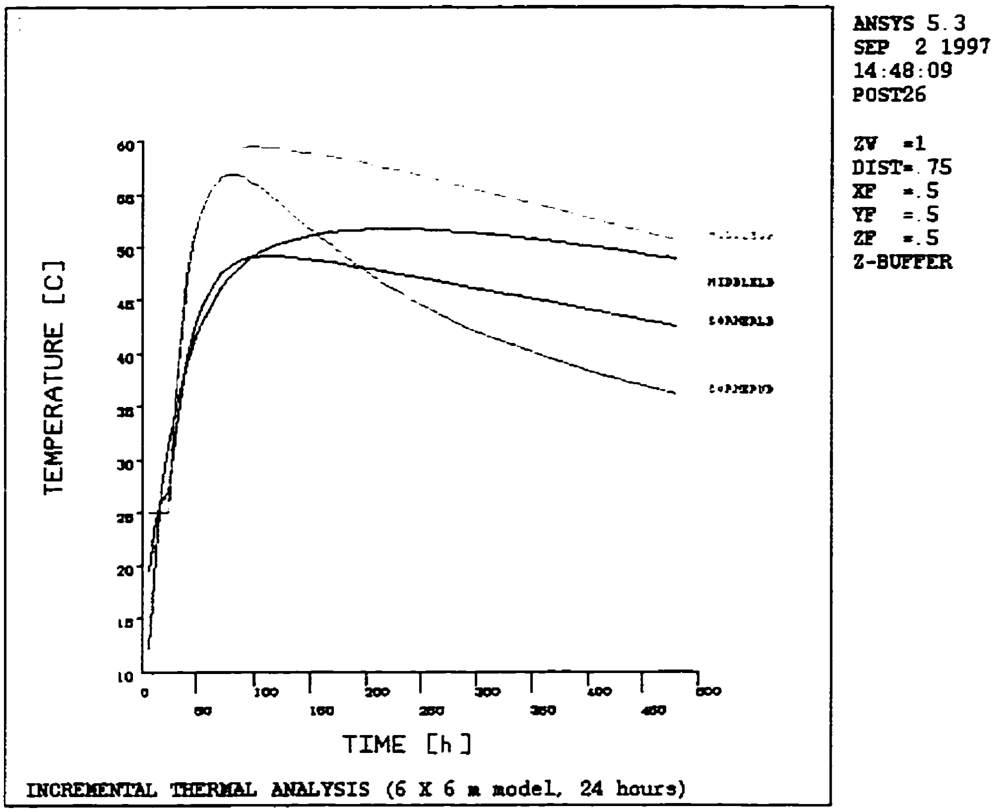


Figure 4.15 *Temperature-Time Diagram for Four Characteristic Nodes at Interface (upper block cast 24 hours after the first one)*

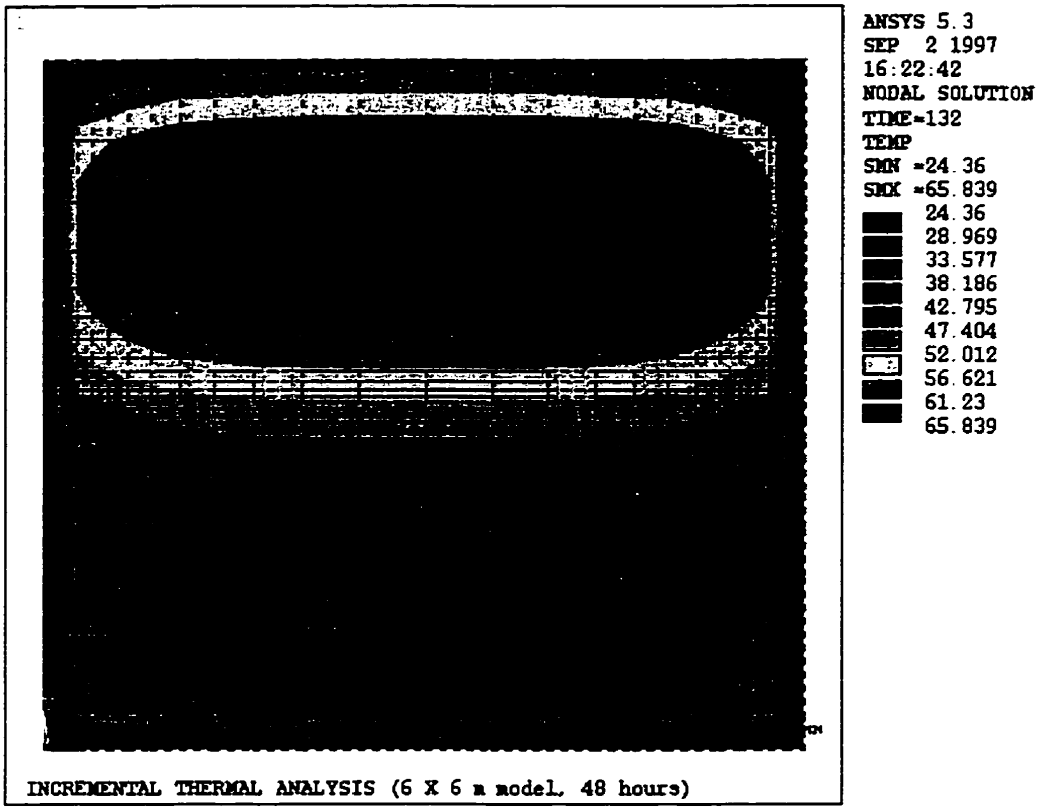


Figure 4.16 *Temperature Field of 6 X 6 m Model at Time132 hours*

(upper block cast 48 hours after the first one)

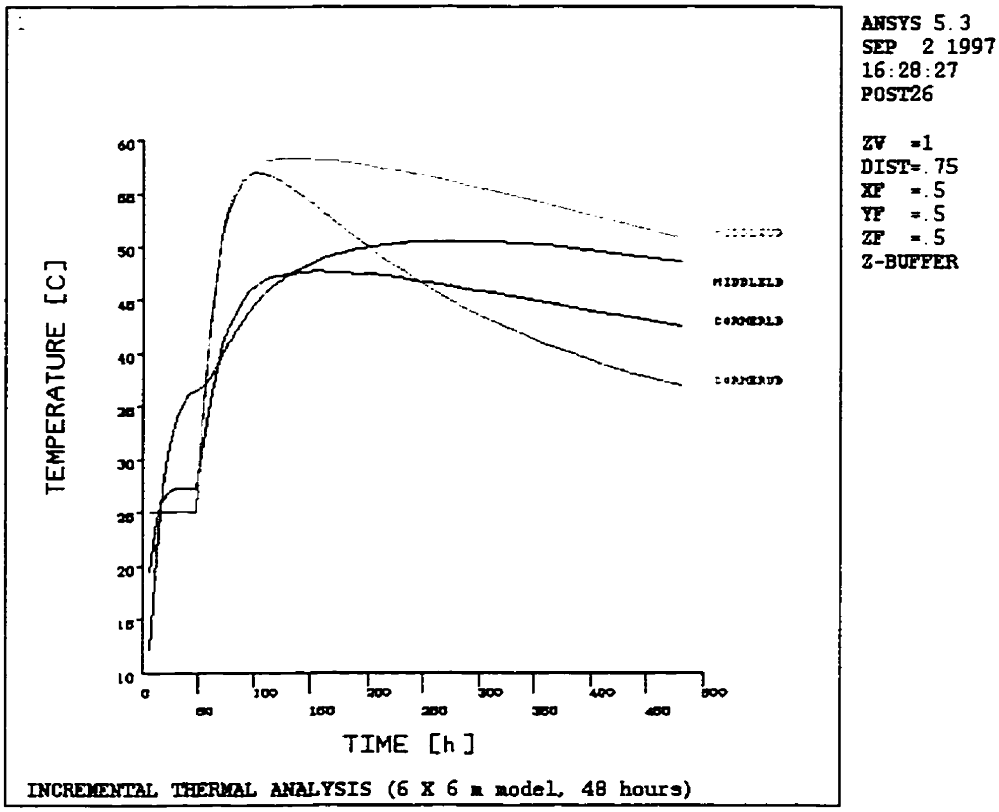


Figure 4.17 *Temperature-Time Diagram for Four Characteristic Nodes at Interface (upper block cast 48 hours after the first one)*

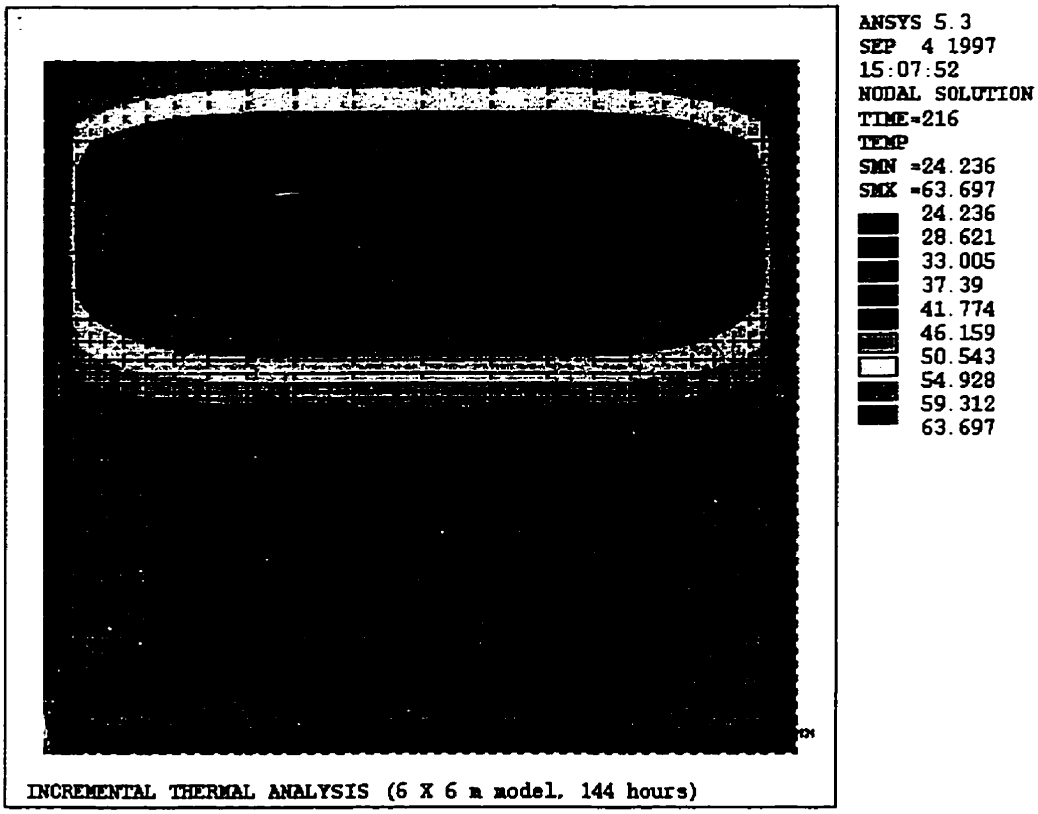


Figure 4.18 *Temperature Field of 6 X 6 m Model at Time 144 hours*

(upper block cast 72 hours after the first one)

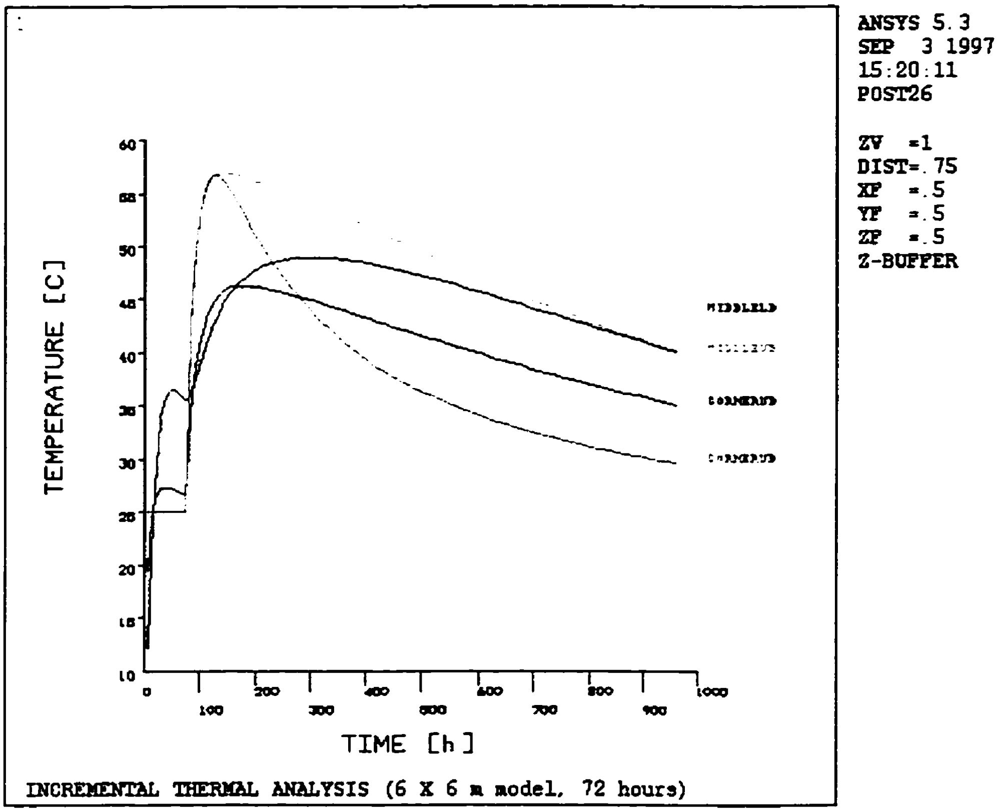


Figure 4.19 *Temperature-Time Diagram for Four Characteristic Nodes at Interface (upper block cast 72 hours after the first one)*

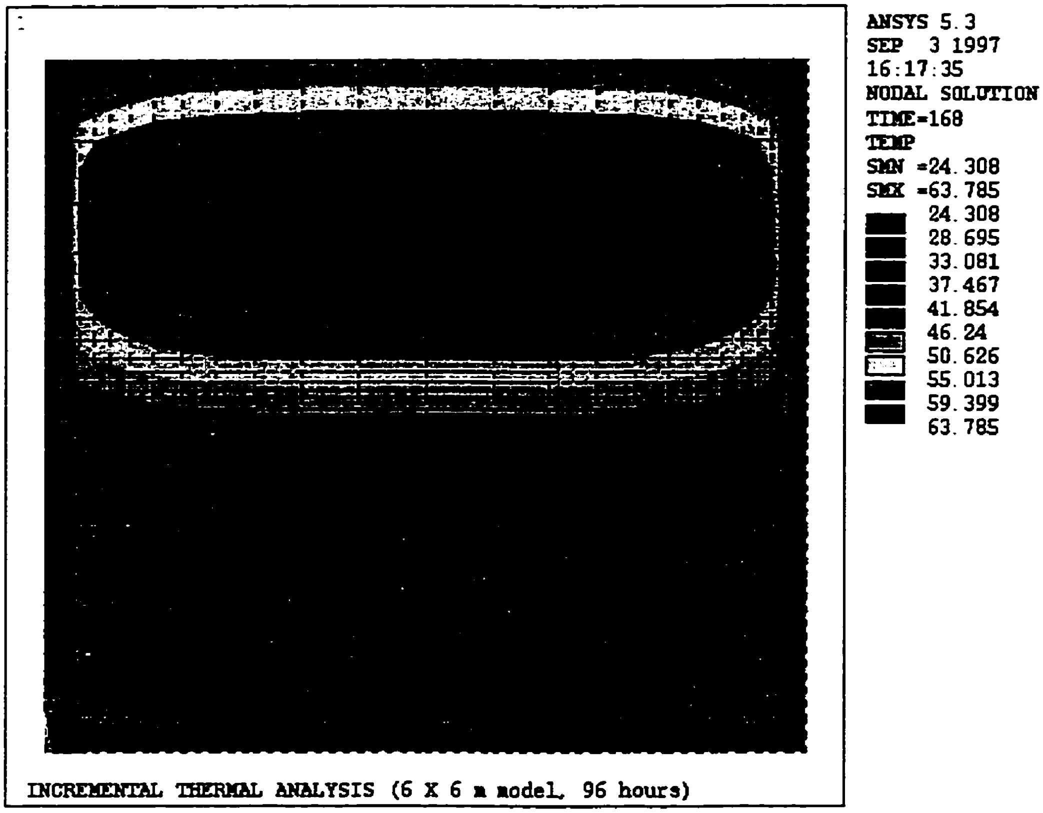


Figure 4.20 *Temperature Field of 6 X 6 m Model at Time 168 hours*

(upper block cast 96 hours after the first one)

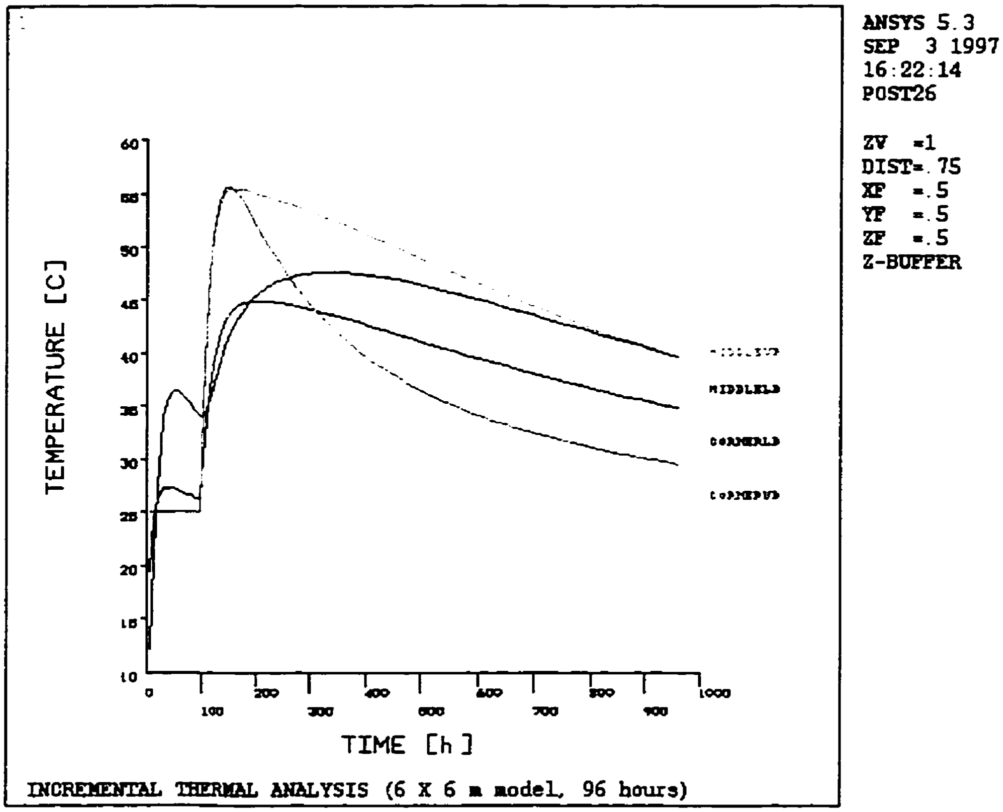


Figure 4.21 *Temperature-Time Diagram for Four Characteristic Nodes at Interface (upper block cast 96 hours after the first one)*

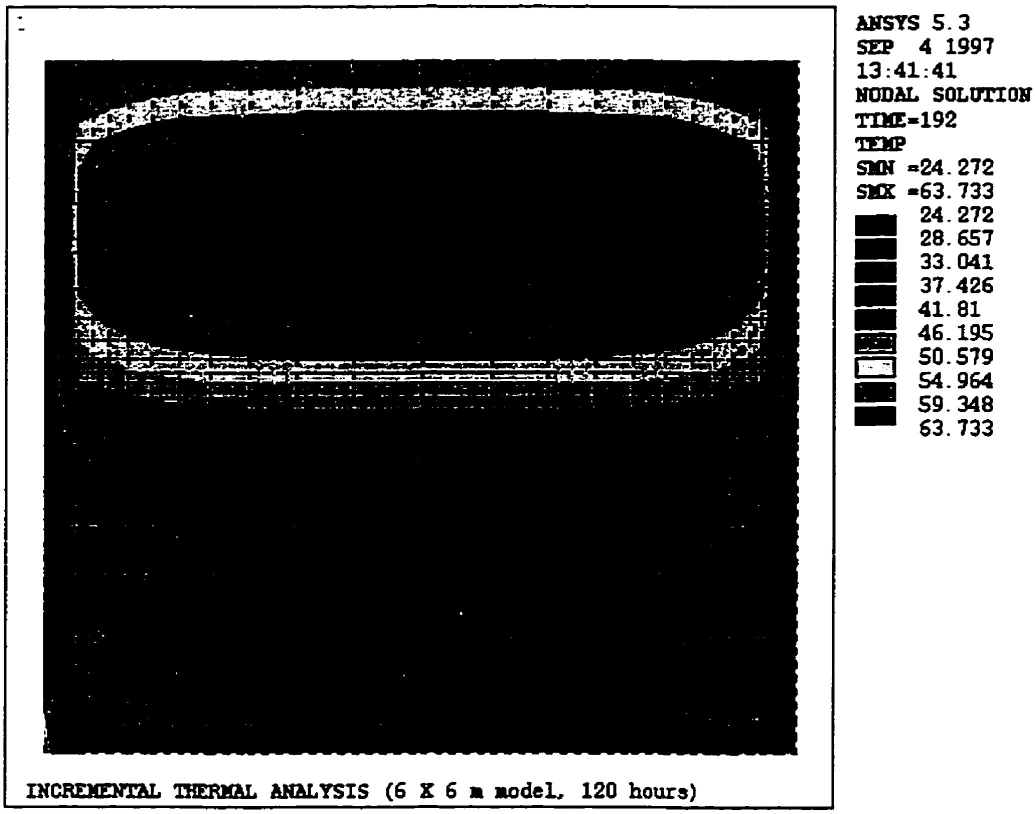


Figure 4.22 *Temperature Field of 6 X 6 m Model at Time 192 hours*

(upper block cast 120 hours after the first one)

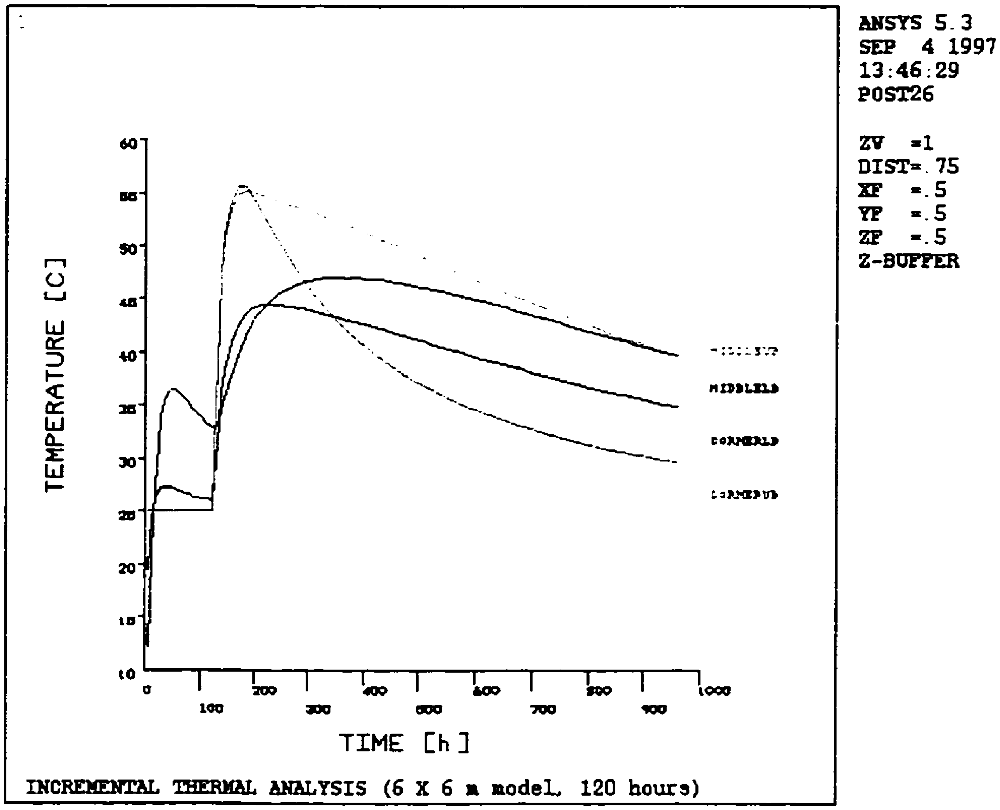


Figure 4.23 *Temperature-Time Diagram for Four Characteristic Nodes at Interface (upper block cast 120 hours after the first one)*

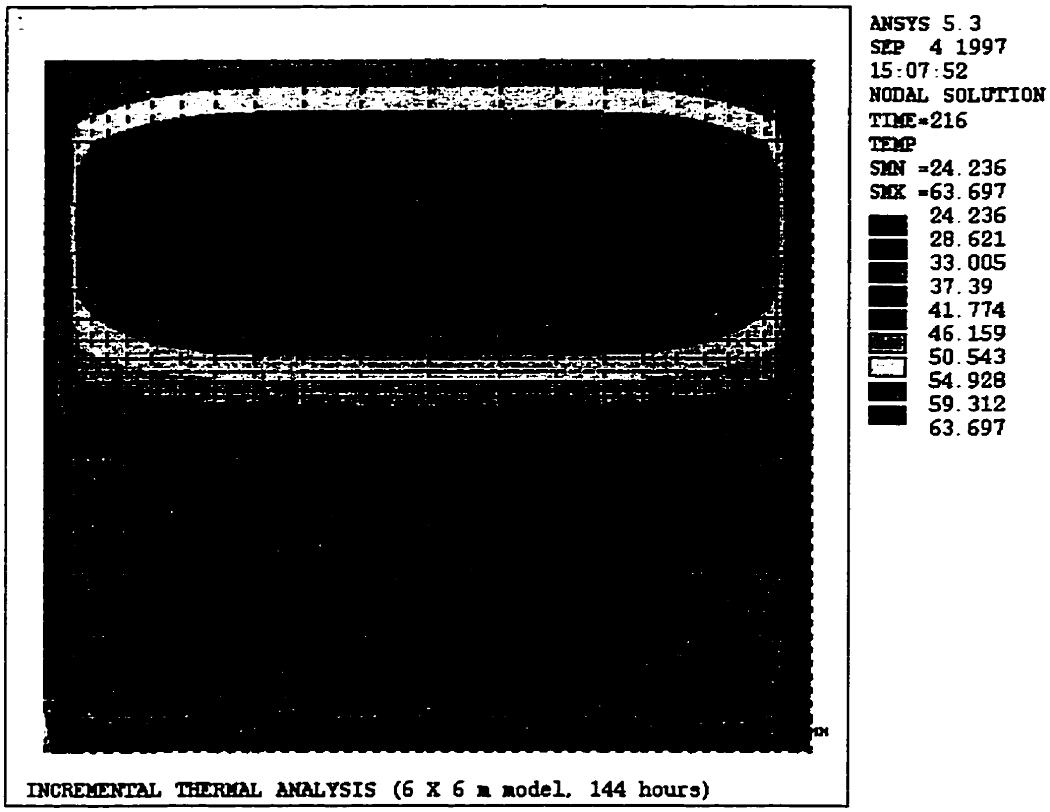


Figure 4.24 *Temperature Field of 6 X 6 m Model at Time 216 hours*

(upper block cast 144 hours after the first one)

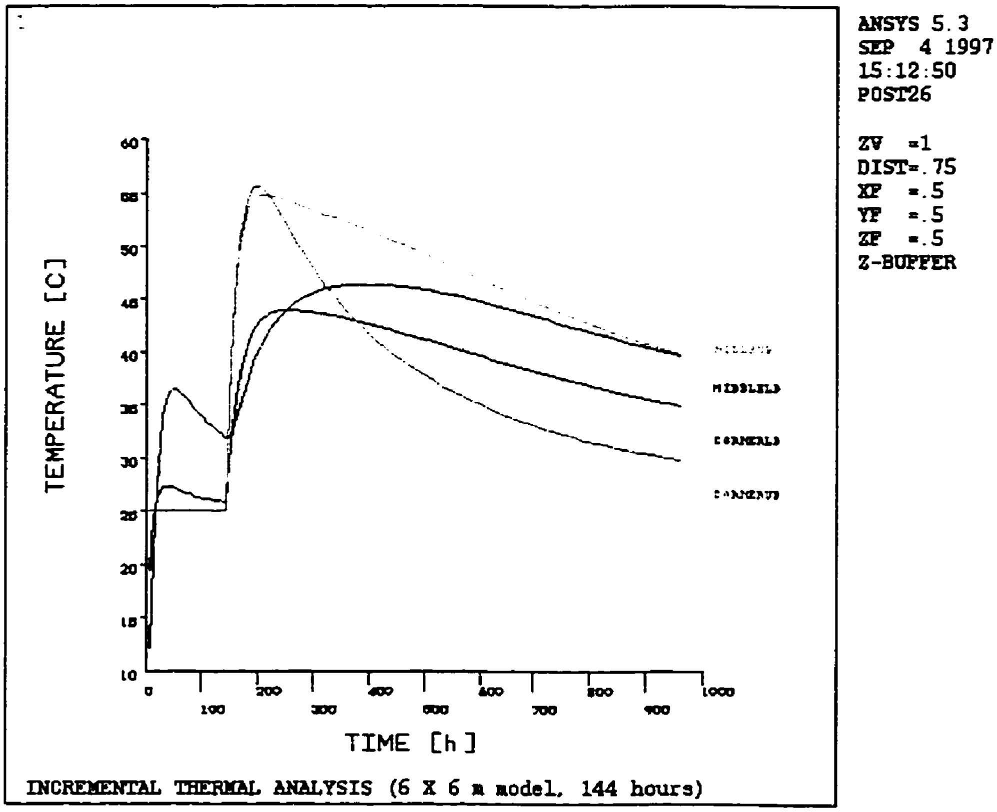


Figure 4.25 *Temperature-Time Diagram for Four Characteristic Nodes at Interface (upper block cast 144 hours after the first one)*

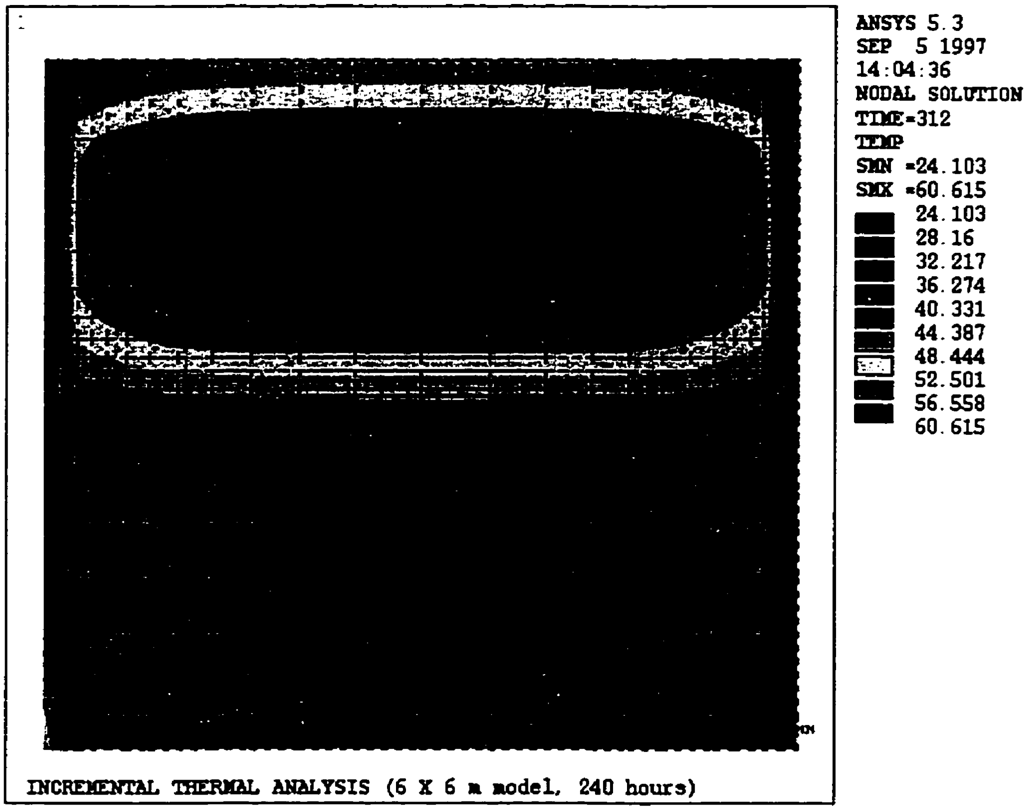


Figure 4.26 *Temperature Field of 6 X 6 m Model at time 312 hours*

(upper block cast 240 hours after the first one)

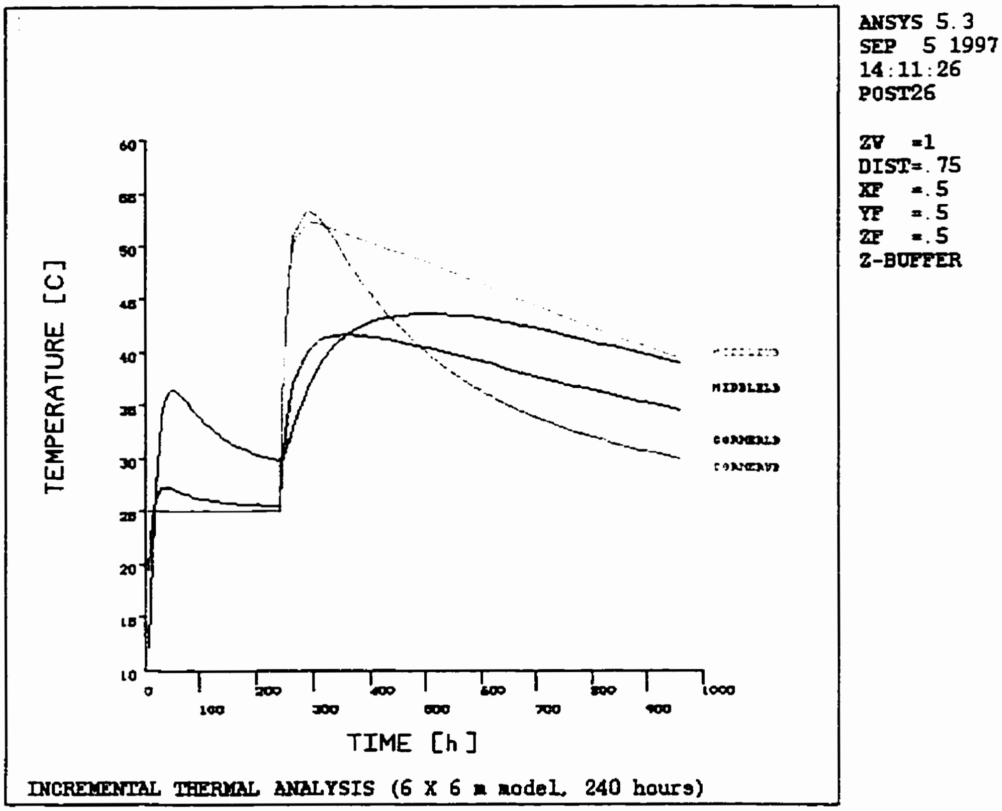


Figure 4.27 *Temperature-Time Diagram for Four Characteristic Nodes at Interface (upper block cast 240 hours after the first one)*

4.4.3 Temperature Field of Dam Model

In this part the dam model is analyzed. The whole dam is not observed because we need information local to the interface between two consequent lifts. The intersection between the two lofts is analyzed. The boundary condition is obtained from the field [6].

Figure 4.20 presents the temperature field with the maximum temperature developed at time 156 hours of around 50℃. Temperature of laboratory specimen measured on the field was around 38℃. When we enlarged this model temperature developed was much higher than dam specimen. The reason for this is that the specimen is done in the laboratory, where outside temperature is the room temperature, while those two blocks of concrete are poured in September, when the outside temperature is much lower. In addition, the sizes of the two blocks of the dam are different from the size of concrete blocks used for the model. The initial temperature is also a big reason for the difference in the results. In the dam model iced water was used. Except for these major differences, there are also some minor differences, such as different coefficients and concrete properties.

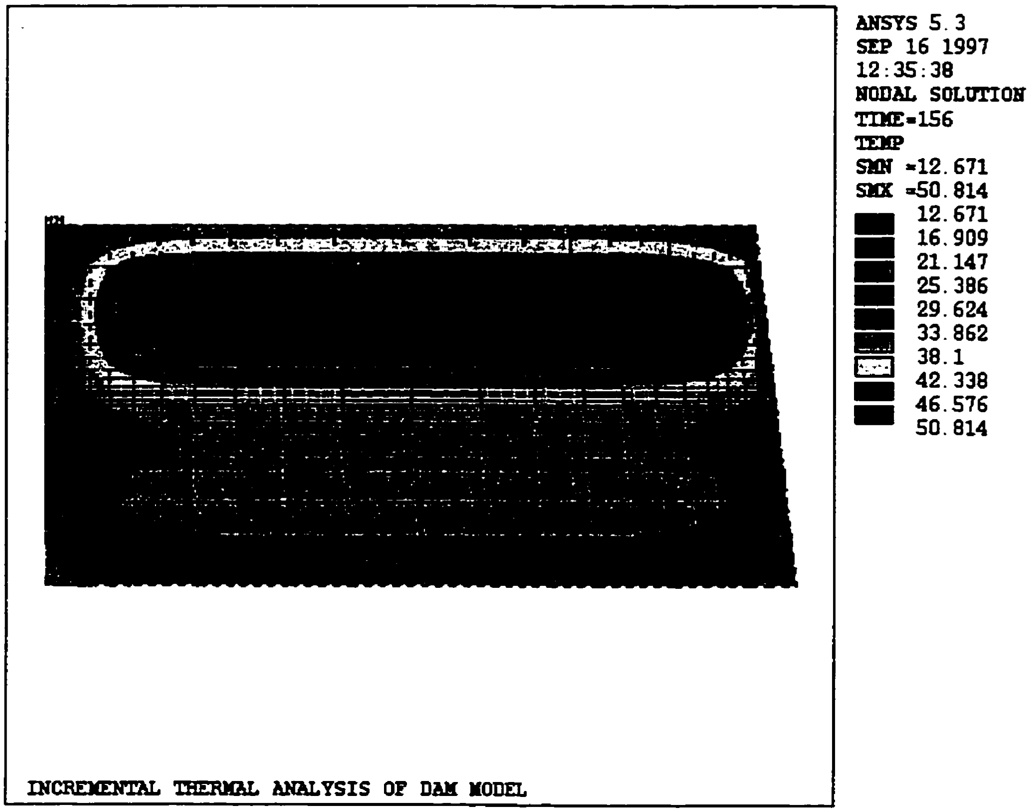


Figure 4.28 *Temperature Field of Dam Blocks at Time 156 hours (time when maximum temperature is developed)*

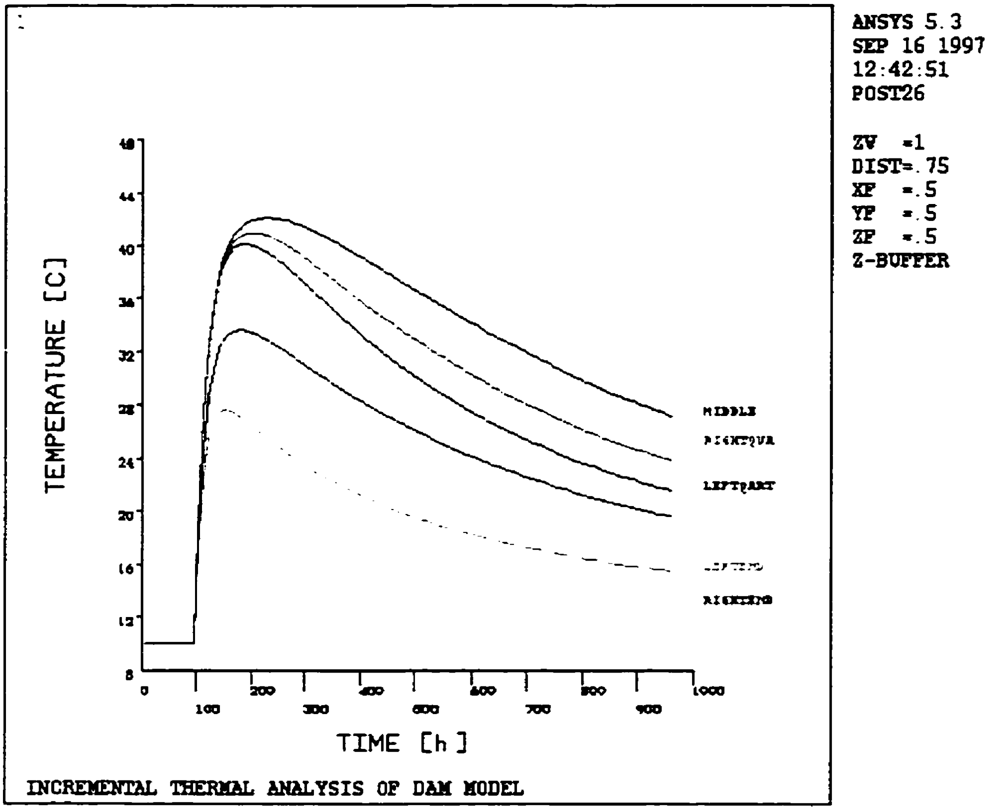


Figure 4.29 *Time – Temperature Diagram for Five Nodes on the Interface (left end, left quarter, middle, right quarter, right end)*

4.5 DISCUSSION

From this chapter, it can be concluded that the analysis algorithm can be used to reliably predict thermal behaviour of concrete specimens and dam in the early stage. Temperature is measured in laboratory specimen in the field and this value is 38°*C*. Temperature obtained using this algorithm is 37.78°*C*, which is pretty close and accurate enough. This can confirm the validation of the algorithm. We can say that most of the factors that influence thermal behaviour of the specimens and the dam are very close to the real situation in the field. It means the boundary conditions, heat generation rates, material properties, and the time steps are accurate enough.

This work will be extended to perform structural analysis. In structural analysis, the temperature field obtained as result of this analysis should be used as a load. In this way, we can see how much stress is produced by temperature before the concrete enters the working stage.

In addition, in order to reduce temperature in mass concrete some improvements in construction scheduling, size of blocks, time of casting, materials preparation can be done if an accurate plan is established ahead of time.

5 STRESS EVALUATION ON THE INTERFACE

5.1 INTRODUCTION

Crack formation and growth causes failure of concrete structures. To prevent this process, investigation of the stress field is necessary. Stress evaluation is one of the major tasks in concrete structures. Due to heat of hydration of cement in early age mass concrete, stresses are not negligible. Mathematically, these stresses will disappear after some time, but this is not the case in reality. Before the structure enters in service, it is already pre-stressed. Stresses stay captured in the structure and are self-equilibrating. What is the magnitude of these stresses? Are they hard to determine? That is why we have to go with assumptions.

Tensile stresses caused by various types of loads are the most dangerous with respect cracking. Cracks occur in the weakest place in the concrete structures. When we are dealing with mass concrete for dam structures, the weakest locations are at the interface between lifts of concrete. This interface represents non-homogeneity in the structure and even a small crack can be an important source of stress concentration. When the concrete is exposed to tensile stress, especially concrete close to the interface, it behaves as an elastic-brittle material.

A number of previous studies predict thermal behaviour of young concrete, but few papers talk about residual stress in young concrete. Residual stresses are hard to predict without many assumptions. We do not know when those stresses will stop dropping down by the curve predicted mathematically. That is the main reason why we choose maximum stress as residual stress in a structure. In this way, we will have the model with the worst distribution of stress.

In order to obtain the magnitude of residual stresses in the dam structure, we investigate different models. First, the finite element modeling is started with a specimen made in the laboratory. To capture the size effect, this small specimen is enlarged two, five, and ten times. Analysis with different times of pouring of upper block is carried in order to obtain optimum time for casting upper block of concrete. Finally, the dam model was simulated using the finite element method. Concrete characteristics, boundary conditions, and influence of the lower blocks, are all included in this study and the model simulates the field conditions as accurately as possible.

5.2 THERMAL LOADS

Different types of thermal loads exist in massive concrete structures such as dams. Thermal load that first appear in massive concrete structures are loads due to heat of hydration of cement. Cement in contact with water produces heat. More heat develops in concrete that contains more cement. Mass concrete has low cement content concrete. Still, due to the huge amount of concrete cast at one time, high temperatures develops.

The reduction of thermal stresses is one of the main engineering tasks during construction of gravity dams. Not only dams, but also other structures, where massive concrete is used are in danger to be exposed to high stress development from heat of cement hydration. To reduce these stresses, different methods are established. Some of them reduce temperature by using ice water in the process of making concrete or precooled aggregate. The other methods heat the lower block in order to get smaller difference of temperature between blocks. They are all good methods but after some time a crack between blocks is still unavoidable.

In this research, the Long Spruce generation station is investigated. The Long Spruce is located in the North part of Manitoba where temperature in summer time reach almost 40°C and in the winter can be as low as -40°C. This severe conditions produce thermal load that can destroy the structure. The cracks or leaking joints do not appear on each interface in the dam, they are usually on the most loaded interface. In the case of the Long Spruce dam, they appear on the blocks that are closest to the border between water and air. This is the worst place with respect to outside load conditions. The water level is changed during the year and large ice formations occur in the wintertime. All those and other loads are main reason for crack appearance.

The thermal loads that are specifically investigated in this thesis are those produced by cement hydration. The thermal load gives rise to thermal deformation of a new block and the rigidity of the new block is not constant which means that the stress field is affected by this varying rigidity. Thermal loads remain in the dam structure until the time the cement is stabilized thermally.

5.3 FINITE ELEMENT ANALYSIS

The behaviour of concrete has been investigated for a long time using different methods. Classical analytical procedure was applied first but this procedure is almost impossible for complex structures. This is why empirical methods were used based on a large amount of experimental data. Today, the finite element method is a very powerful method for analytical calculation of different factors in concrete such as stress and thermal field in two or three dimensions, cracking parameters, interface problems, and others. Some of those effects and parameters are ignored or treated approximately in the past and this is why problems were not modeled rationally. However, experimental research did not stop with finite element development, it is still very important for comparison of finite element results with experimental results.

Finite element method is based on a finite number of elements connected at a finite number of joints. The following parameters must be defined for the structural analysis: structure geometry, material properties, boundary conditions and loading. From the results, we should be able to read displacements at grid points and stresses.

In our problem, we are dealing with two-dimensional analysis. The shapes of elements can be triangular, rectangular, or general quadrilateral. For this particular problem, rectangular shapes were used.

5.3.1 Structural Analysis Algorithm

In order to get a better understanding of thermally induced stresses on structure behaviour of concrete model this algorithm is made. A similar algorithm is presented for thermal analysis in Chapter 4. The main parts of the program are the pre-processing phase, solution phase and post-processing phase.

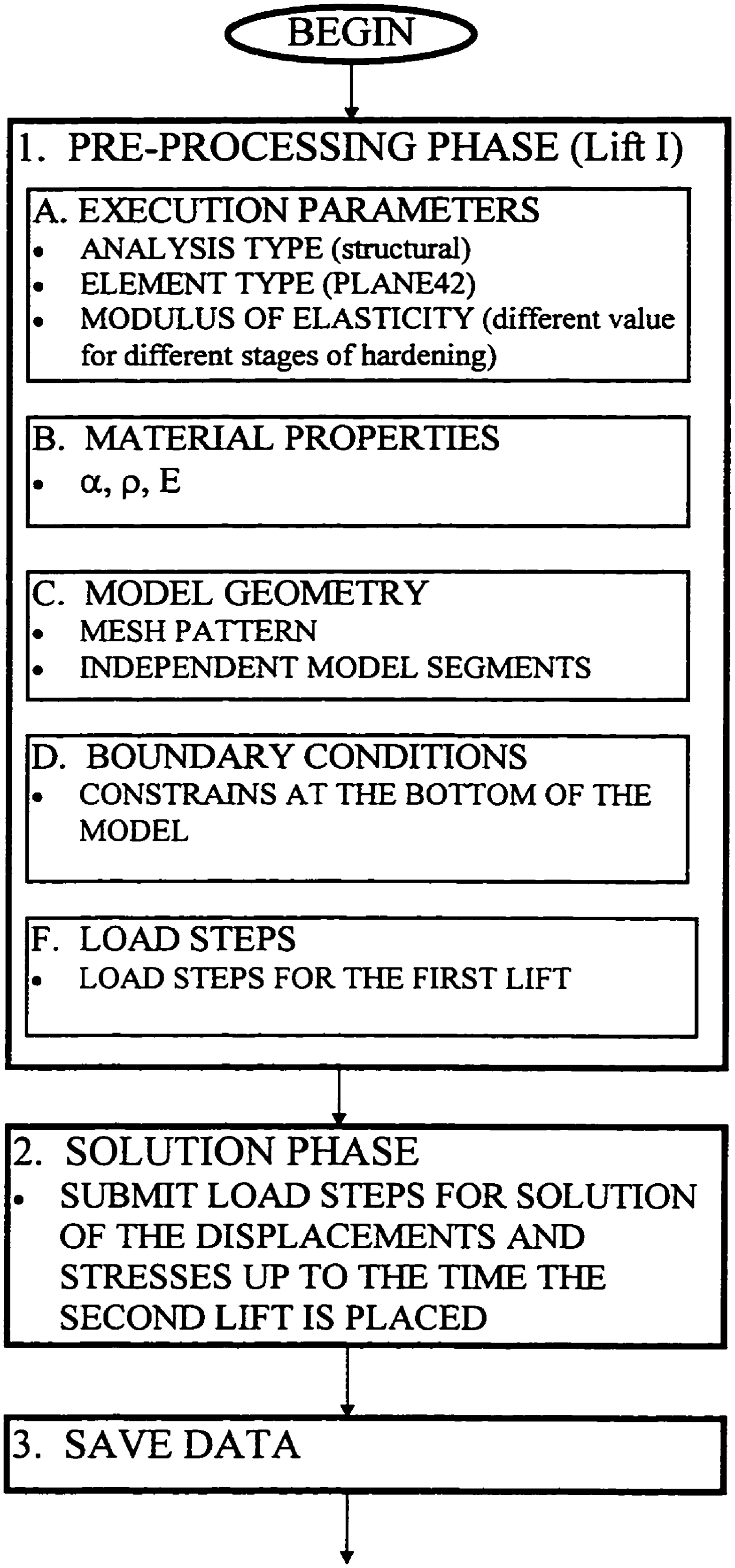


Figure 5.1 *Finite Element Modeling Algorithm for Structural Analysis (page 1 of 2)*

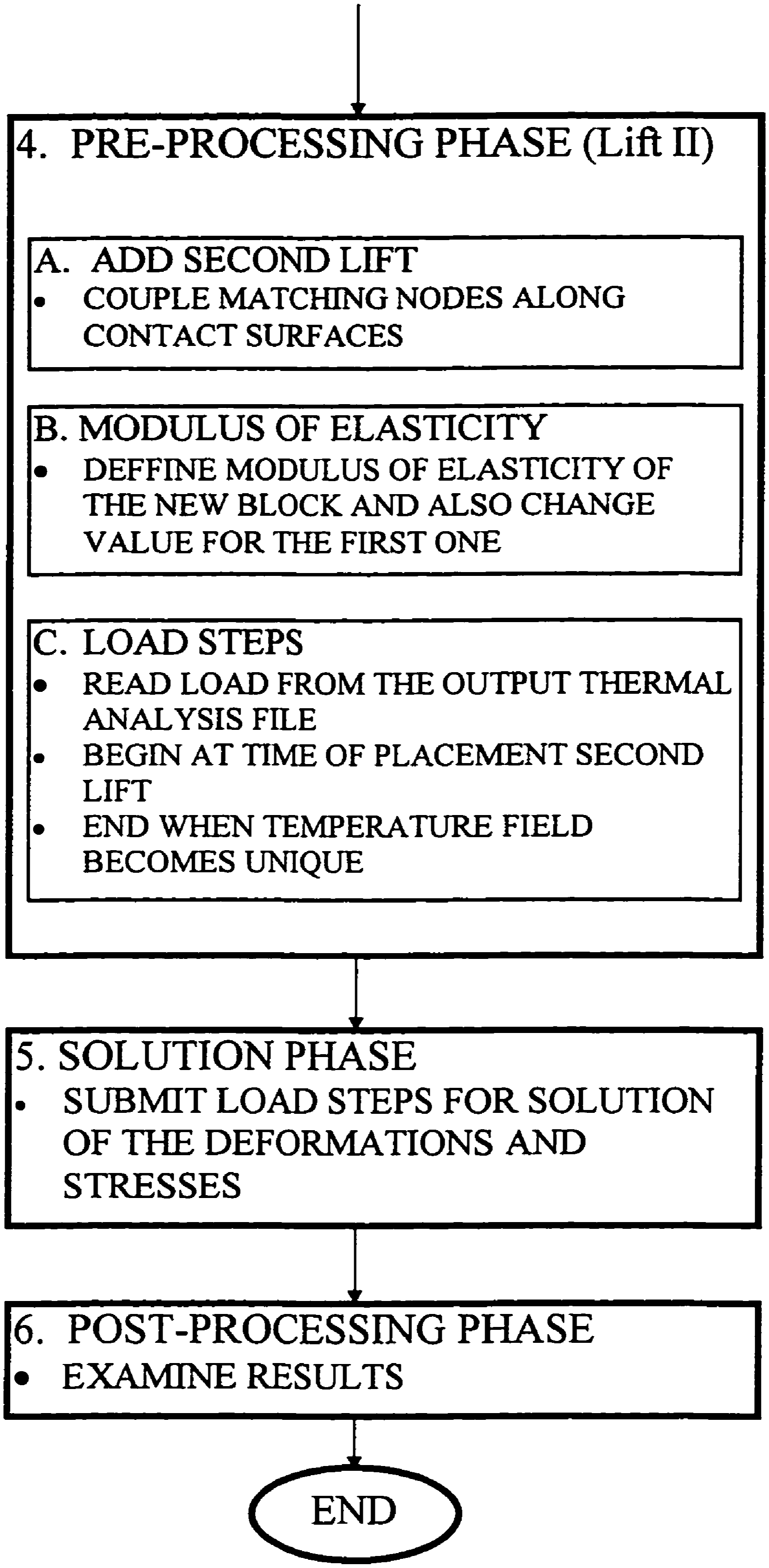


Figure 5.1 *Finite Element Modeling Algorithm for Structural Analysis (page 2 of 2)*

5.3.2 Stress-Strain Relationship

The stress-strain relationship for linear materials can be expressed by:

$$\{\sigma\} = [D]\left(\{\varepsilon\} - \{\varepsilon^{th}\}\right) \tag{5.1}$$

Where,

$\{\sigma\}$ is stress vector = $[\ \sigma_x\ \sigma_y\ \sigma_z\ \sigma_{xy}\ \sigma_{yz}\ \sigma_{xz}\ ]^T$

[D] is elasticity matrix depend on material properties such as modulus of elasticity, Poisson's ratio and shear modulus.

$\{\varepsilon\}$ is strain vector = $[\ \varepsilon_x\ \varepsilon_y\ \varepsilon_z\ \varepsilon_{xy}\ \varepsilon_{yz}\ \varepsilon_{xz}\ ]^T$

$\{\varepsilon^{th}\}$ is thermal strain vector

The sign convention used for stress and strains is that the tension is positive and compression is negative. For the shears, positive sign is when two positive axes rotate toward each other.

To express strains, above equation can be written in the following form:

$$\{\varepsilon\} = \{\varepsilon^{th}\} + [D]^{-1}\{\sigma\} \tag{5.2}$$

$\{\varepsilon^{th}\} = \Delta T\ [\ \alpha_x\ \alpha_y\ \alpha_z\ 0\ 0\ 0\ ]$ is the thermal strain vector

α_x is coefficient of thermal expansion in the x direction

ΔT is difference between current temperature and reference (strain-free) temperature

5.3.3 Derivation of Structural Matrices

The element stiffness matrix can be derived using an energy principle, such as the principle of virtual work. The principle of virtual work is based on equality of internal strain energy and change in external work due to applied loads. It can be presented in the following form:

$$\delta U = \delta V \tag{5.3}$$

Where,

U is strain energy (internal work) = $U_1 + U_2$

V is external work = $V_1 + V_2 + V_3$

δ is variation operator

The virtual strain energy for two-dimensional problems can be presented as follows:

$$\delta U = \int_V \{\delta\varepsilon\}^T \{\sigma\} dV \tag{5.4}$$

Where,

{ε} is strain vector

{σ} is stress vector

A is area of element

Assuming linear material properties and geometry, evaluation of equation (5.4) gives:

$$\delta U = \int_V \left(\{\delta\varepsilon\}^T [D] \{\varepsilon\} - \{\delta\varepsilon\}^T [D] \{\varepsilon^{th}\} \right) dV \quad (5.5)$$

The relation between strain and nodal displacement can be presented as:

$$\{\sigma\} = [D] \left(\{\varepsilon\} - \{\varepsilon^{th}\} \right) \quad (5.6)$$

Combining those two equations we get:

$$\delta U = \{\delta u\}^T \int_V [B]^T [D][B] dV \{u\} - \{\delta u\}^T \int_V [B]^T [D] [\varepsilon^{th}] dV \quad (5.7)$$

where,

[B] is strain-displacement matrix, based on the element shape functions

{u} is nodal displacement vector

The vector of nodal displacement {u} does not depend on the volume.

In order to get element stiffness matrix, we should know external virtual work. External virtual work caused by forces applied on the nodes can be written as:

$$\delta V = \{\delta u\}^T \{F_e^{nd}\} \quad (5.8)$$

Where,

$\{F_e^{nd}\}$ is generalized nodal point forces

As we mentioned in the beginning, the internal virtual work and external virtual work must be equal. Equating equations (5.7) and (5.8) and after cancellation of $\{\delta u\}^T$ term from both sides, we can write the equation in the following form:

$$[K_e]\{u\}-\{F_e^{th}\}=\{F_e^{nd}\} \tag{5.9}$$

Where,

$[K_e]=\int_V [B]^T[D]\,[B]dV$ is element stiffness matrix

$\{F_e^{th}\}=\int_V [B]^T[D]\{\varepsilon^{th}\}dV$ is element thermal load vector

Equation (5.9) represents the equilibrium equation for one element. Integration of the element stiffness matrix must be carried numerically. After formation of element stiffness matrix, the stiffness matrix should be formed by the systematic addition of element stiffnesses.

$$\{F\}=[K]\{u\} \tag{5.10}$$

Where,

{F} is external nodal point load (known)

{u} is the unknown nodal point displacements which should be solved

Now, when nodal point displacement is known, the element stresses within each element should be found using the following equation:

$$\{\sigma\}=[D]\,[B]\{u\} \tag{5.11}$$

5.4 SIZE EFFECT IN STRESS ANALYSIS

After thermal analysis a structural analysis was done. Load for structural analysis is a temperature field obtained in thermal analysis. Each load step has a different temperature field and it has been systematically applied to structural analysis.

The small laboratory specimen used as a first model for structural analysis does not capture exact behaviour of mass concrete. Different sizes of specimens are investigated in order to capture this behaviour.

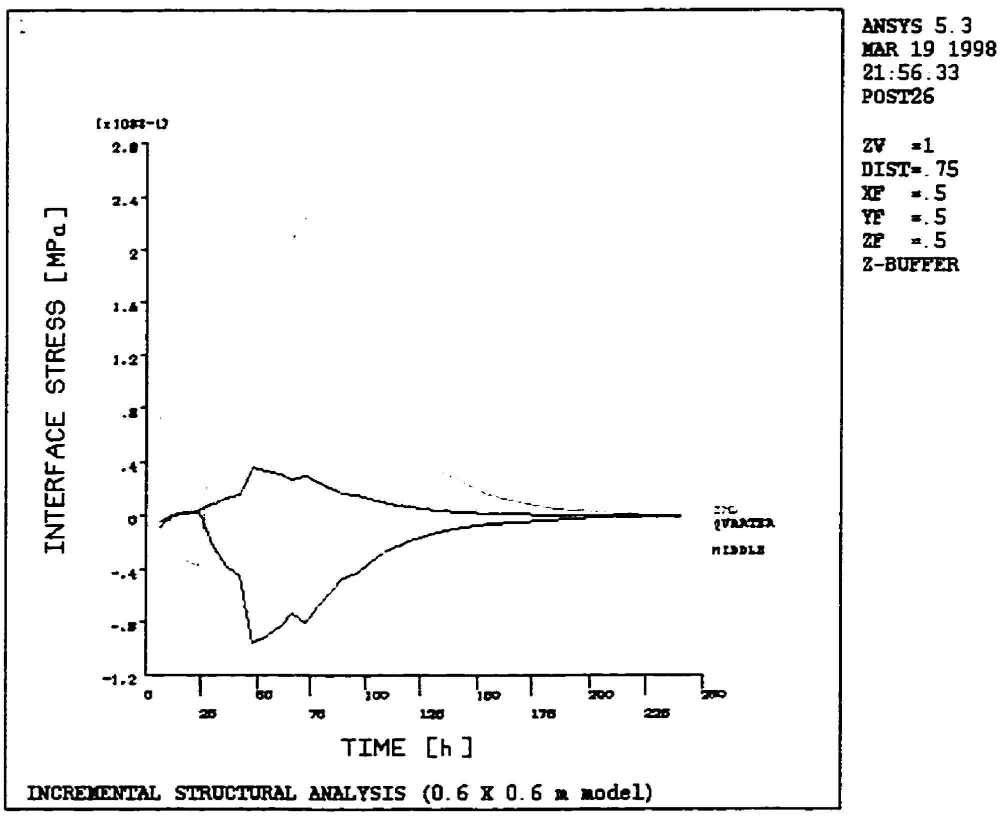


Figure 5.2 *Time – Interface Stress Diagram for 0.6 X 0.6 m Model*

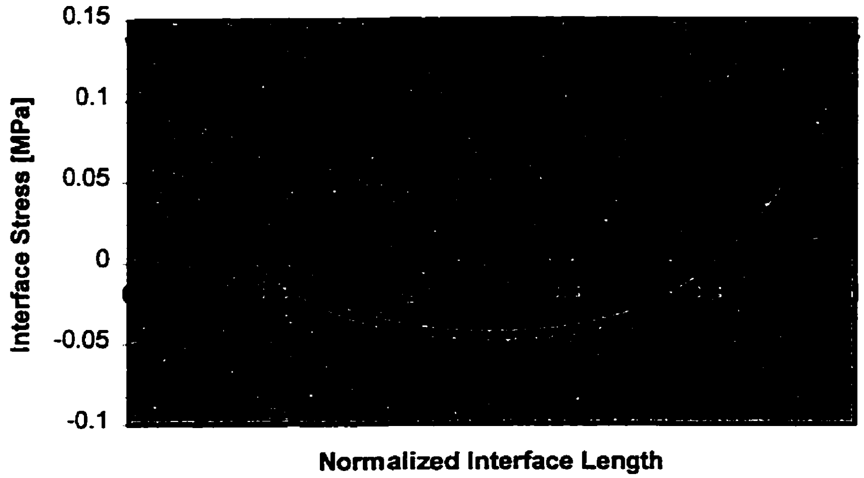


Figure 5.3 *Length – Interface Stress Diagram at Time 42 hours (0.6 X 0.6 model)*

First, structural analysis of laboratory specimen 0.6 X 0.6 *m* is prepared and it is found that the residual stress does not exceed 0.28 *MPa.*

After this analysis, the model was doubled. It means the 1.2 X 1.2 *m* model was analyzed. Normal stresses are more than doubled, now it is 0.812 MPa. In the 3 X 3 *m* model, stresses reach value of almost 2.4 *MPa.* In the 6 X 6 *m* model, stresses are over 3.5 *MPa.* This is how stress directly depends on the size of the model. This amount of stress should not be neglected. These large models are not made in practice because the upper block of concrete can not be poured 24 hours after casting the lower one.

Temperature of 6 X 6 *m* specimen is very high in the middle of the upper block. It reaches 66 ℃, which is by almost 10 ℃ higher than in the smallest specimen.

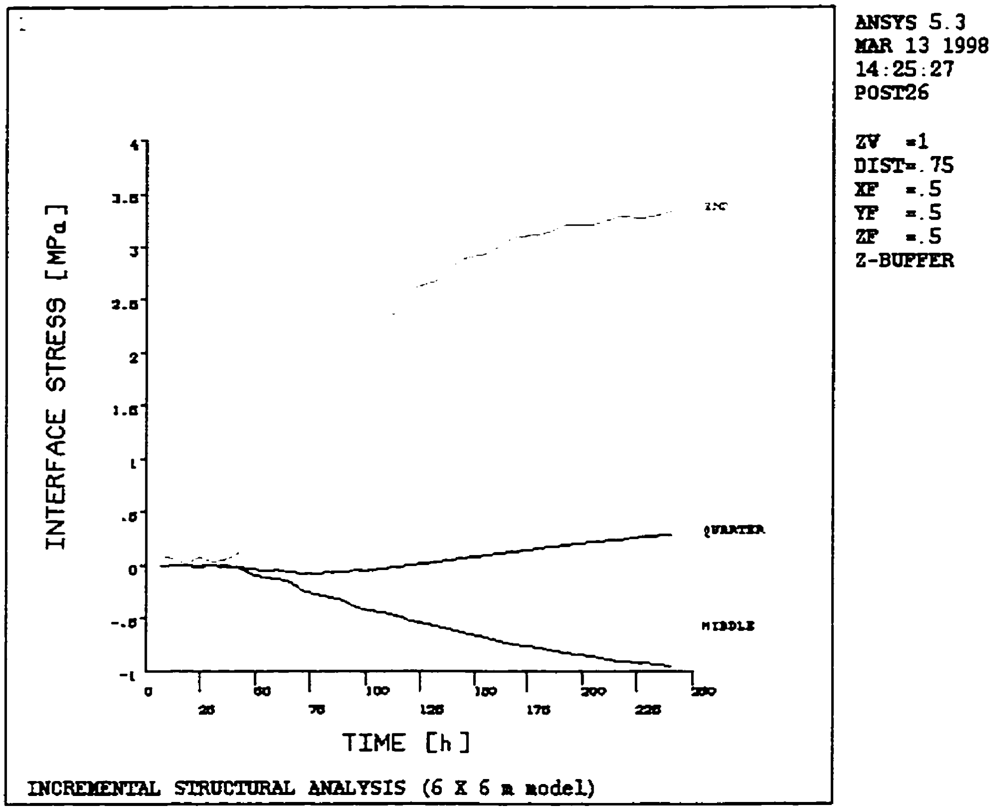


Figure 5.4 *Time – Normal Stress on the Interface Diagram for the 6x6 m Model*

Figure 5.5 presents influence of specimen size on maximum stress on the interface. It is obvious that stresses increase a lot with increase in the size of the specimen. For the largest specimen analyzed in this thesis, which is the most similar to concrete block of the dam, stresses are so high that casting without temperature control may not be done. Although, this analysis is not very realiable this kind of analysis is necessary to capture influence of specimen size on temperature development in the early stage of concrete.

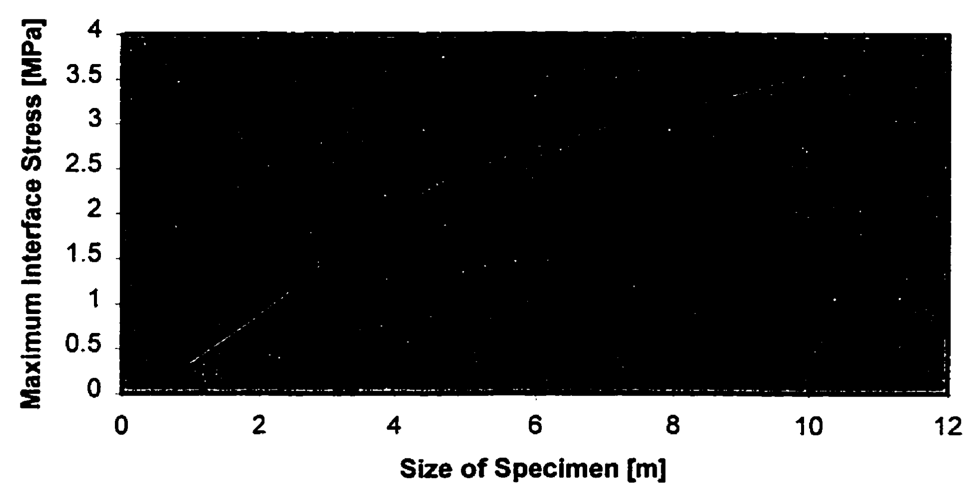


Figure 5.5 *Size of the Specimen – Maximum Stress on the Interface*

5.4.1 Different Time of Pouring Upper Block of Concrete

After analysis concentrated on the size effect, the 6 X 6 *m* concrete block with different time of pouring upper block of concrete is analyzed. Concrete block 6 X 6 *m* is investigated because that size of block is the best simulation of concrete used for massive structures as dams. One block of concrete is poured in 6 X 3 *m* size, then the other one is poured on the top of the first one in the same size.

In the first model, the stress field is analyzed when the upper block of concrete is poured 24 hours after the lower block is cast. From temperature field diagram (Chapter 4) we can see that the temperature goes very high, around 66°C. This temperature causes stresses at the end of the interface close to 2.3 *Mpa*, too much for concrete this old and in this stage. This is not case in the reality. In practice, the temperature field in the concrete is observed. When temperature passes the maximum value, then the upper block of concrete is poured. Now, the question is what is the best time for pouring the upper block. Our approach is slightly different. Actually, we observe stresses on the interface. The upper concrete block is poured at 24, 48, 72, 96, 120, 144, and 240 hours after the lower one is cast. The best results are obtained after 240 hours.

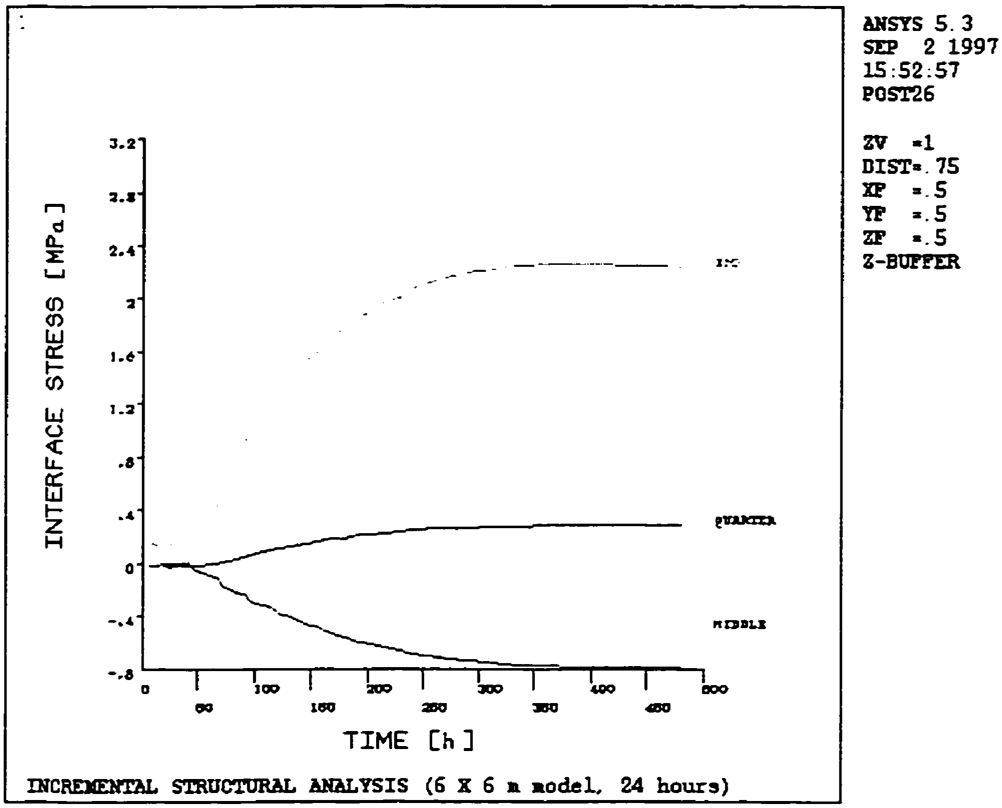


Figure 5.6 *Time - Interface Stress Diagram for Three Characteristic Nodes (upper block of concrete is poured 24 hours after the first one)*

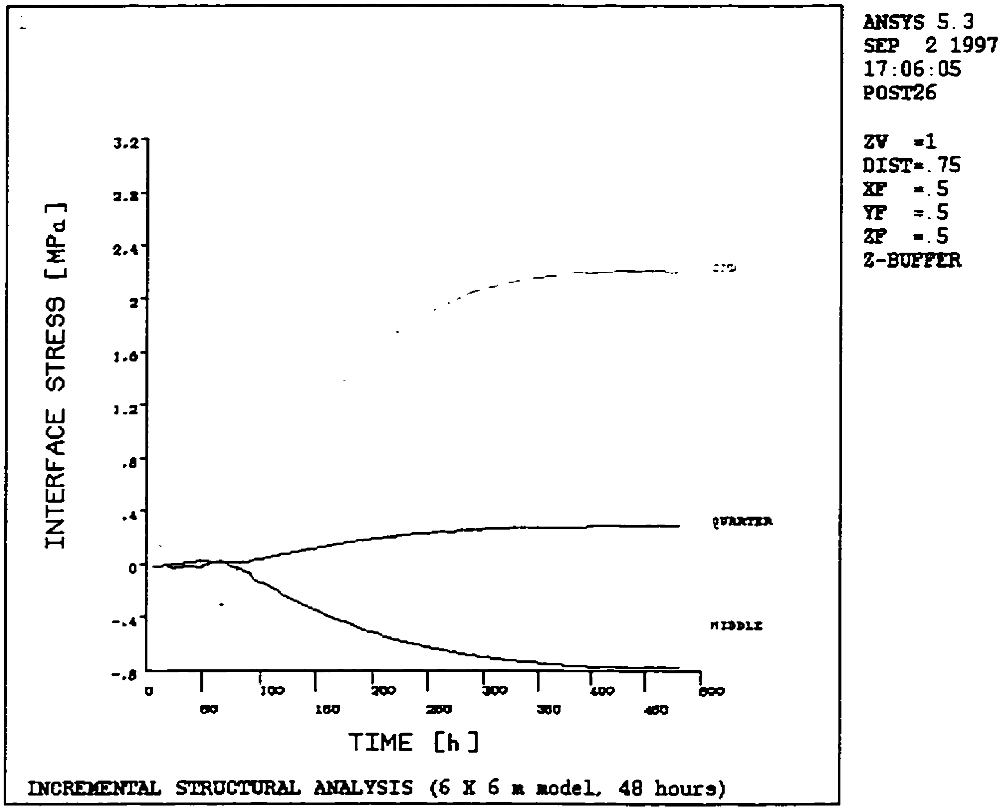


Figure 5.7 *Time - Interface Stress Diagram for Three Characteristic Nodes (upper block of concrete is poured 48 hours after the first one)*

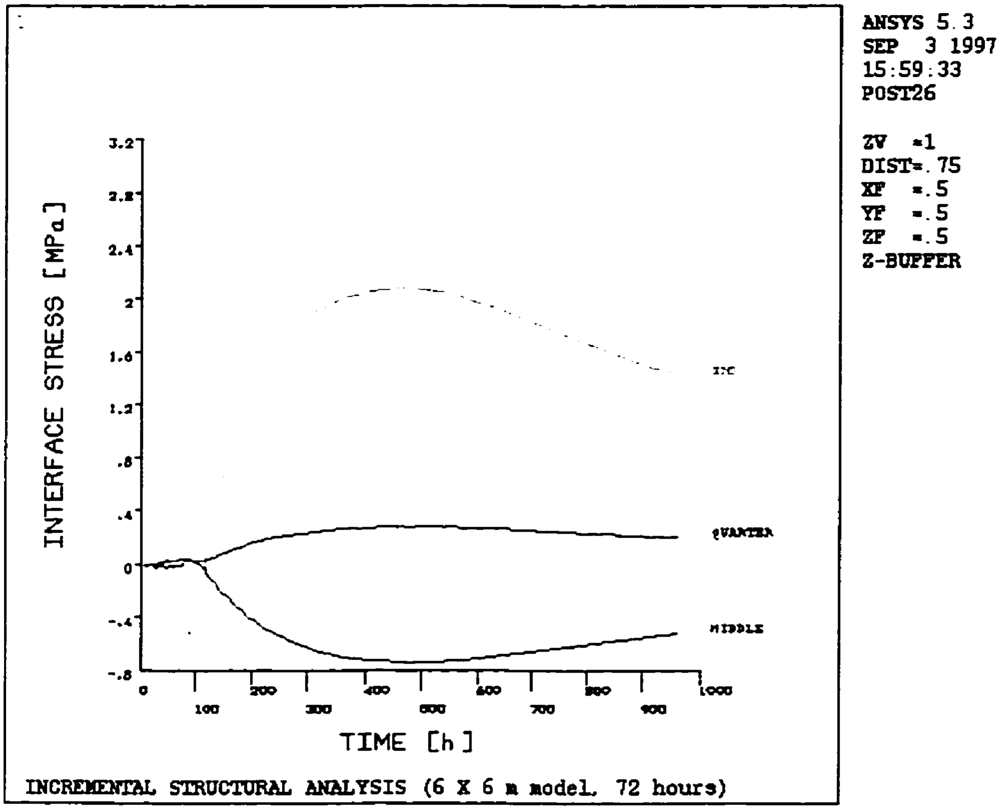


Figure 5.8 *Time - Interface Stress Diagram for Three Characteristic Nodes (upper block of concrete is poured 72 hours after the first one)*

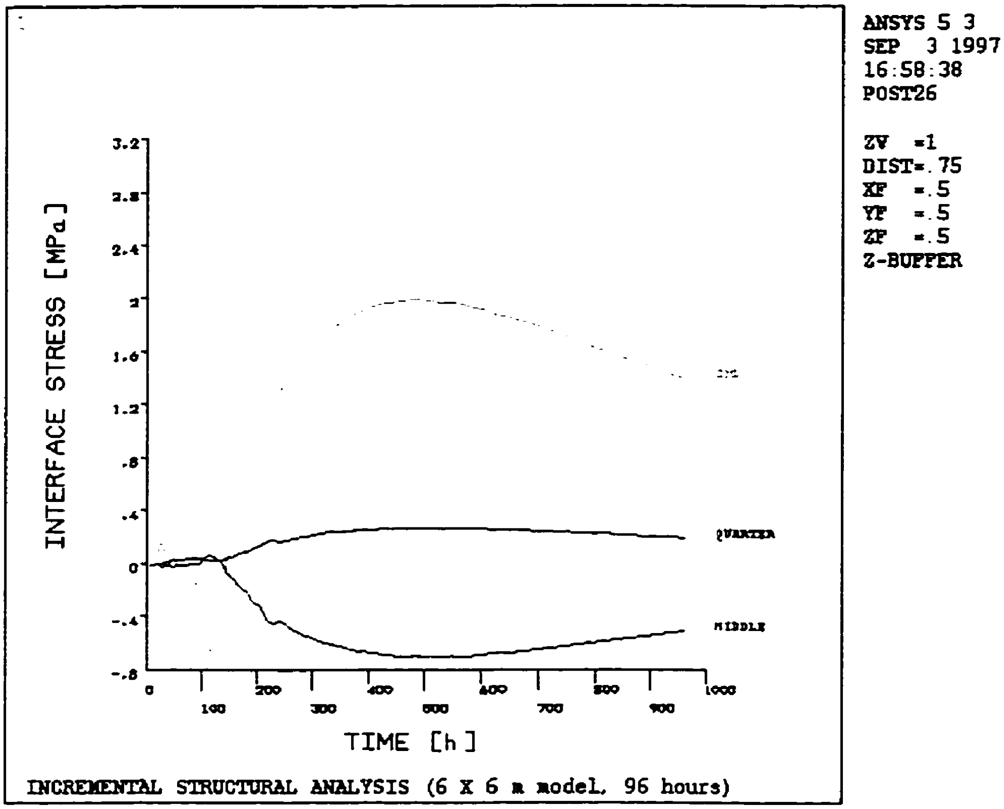


Figure 5.9 *Time - Interface Stress Diagram for Three Characteristic Nodes (upper block of concrete is poured 96 hours after the first one)*

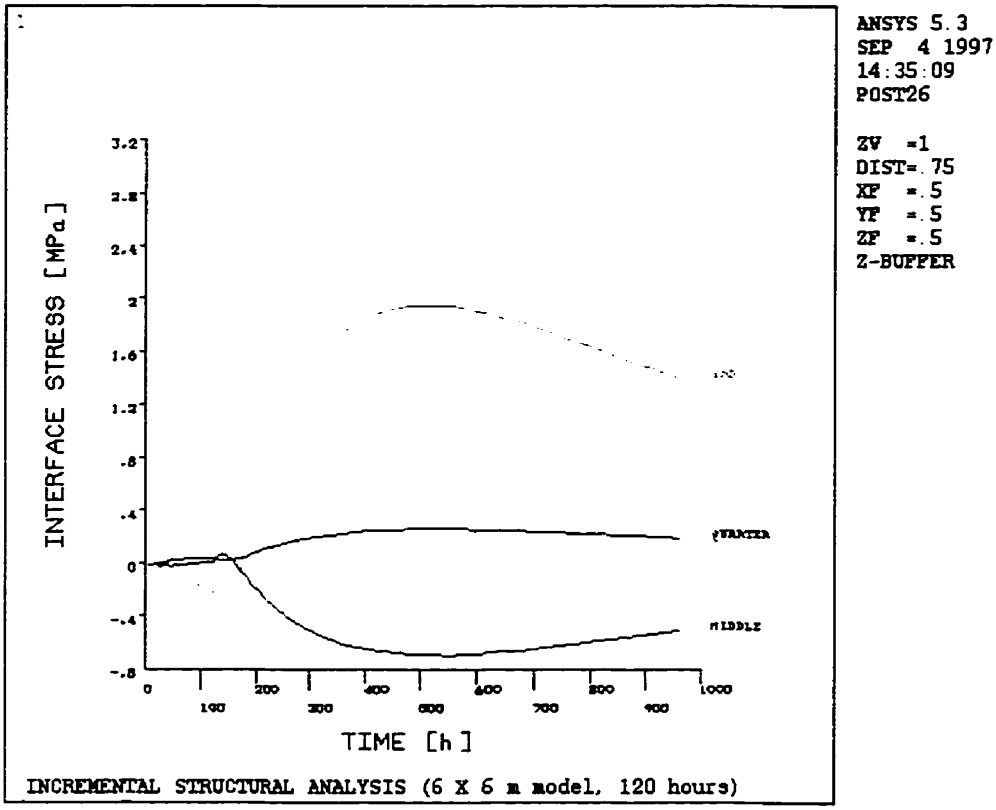


Figure 5.10 *Time - Interface Stress Diagram for Three Characteristic Nodes (upper block of concrete is poured 120 hours after the first one)*

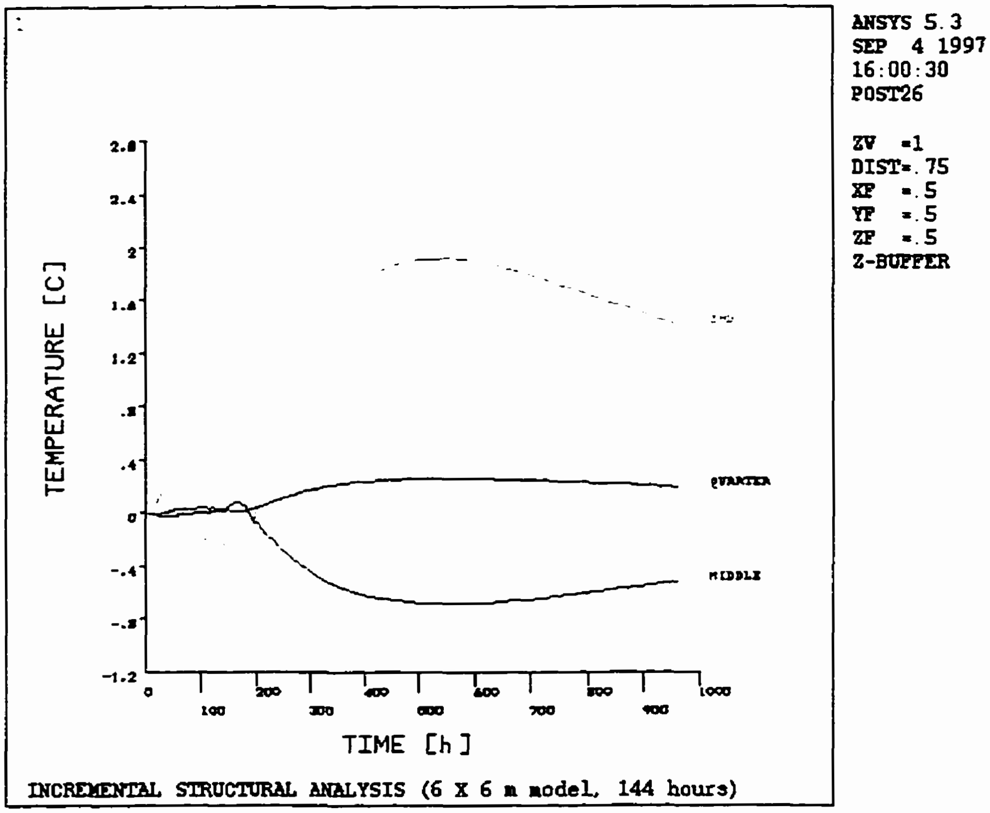


Figure 5.11 *Time - Interface Stress Diagram for Three Characteristic Nodes (upper block of concrete is poured 144 hours after the first one)*

Now we can see that the maximum temperature went from 66°C down to 60°C. Automatically, stresses are expected to drop. From Figure 5.11, it is obvious that stresses really dropped a lot. They are now around 1.7 MPa, which is much less than before.

This means that the longer we wait, we will get smaller stresses. However, this is not possible in reality. From the Figure 5.12 we can see that it is not necessary to wait longer than 130 hours because stresses did not dropp a lot after some time. Waiting longer will be waist of time.

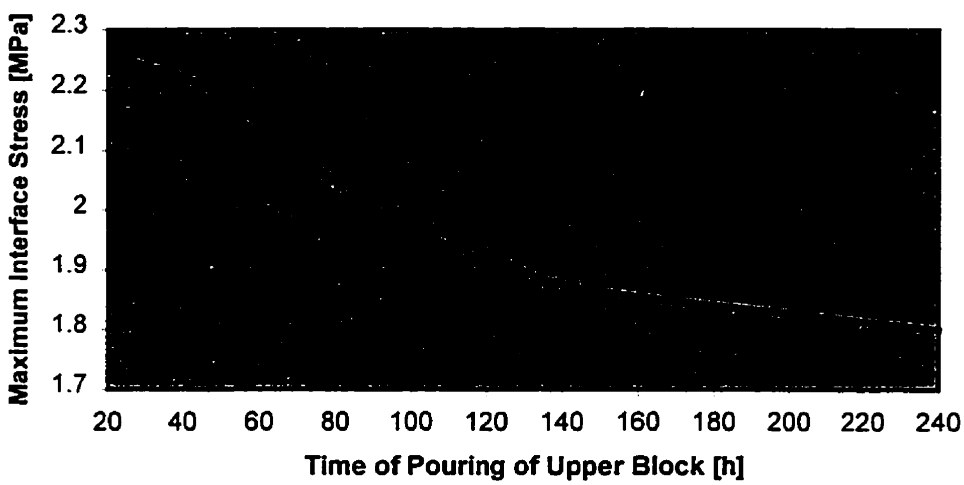


Figure 5.12 *Dependence between Time of Pouring and Maximum Interface Stresses*

5.4.2 Stress Analysis of the Dam Model

In addition to the laboratory specimens, the Long Spruce dam situation is simulated. The whole dam is not modeled because we do not need that kind of extra information. The intersection between the two blocks is analyzed. The boundary conditions are obtained from the field as well as from [6].

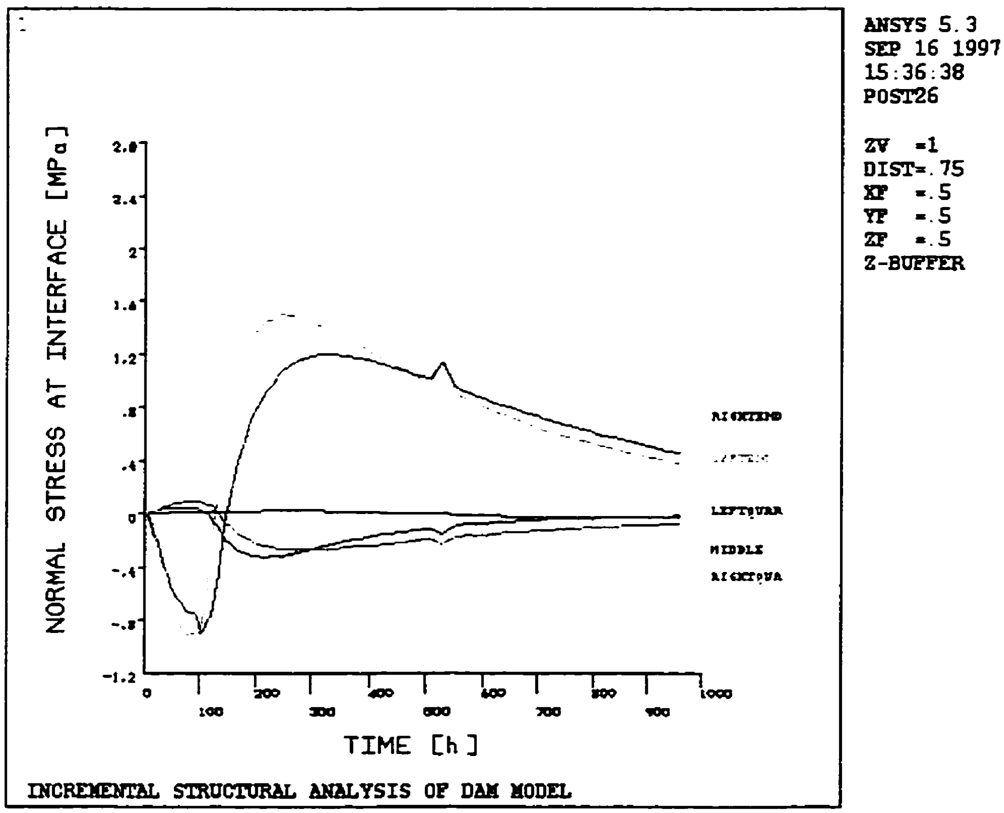


Figure 5.13 *Time – Normal Stress at Interface Diagram for the Dam Model*

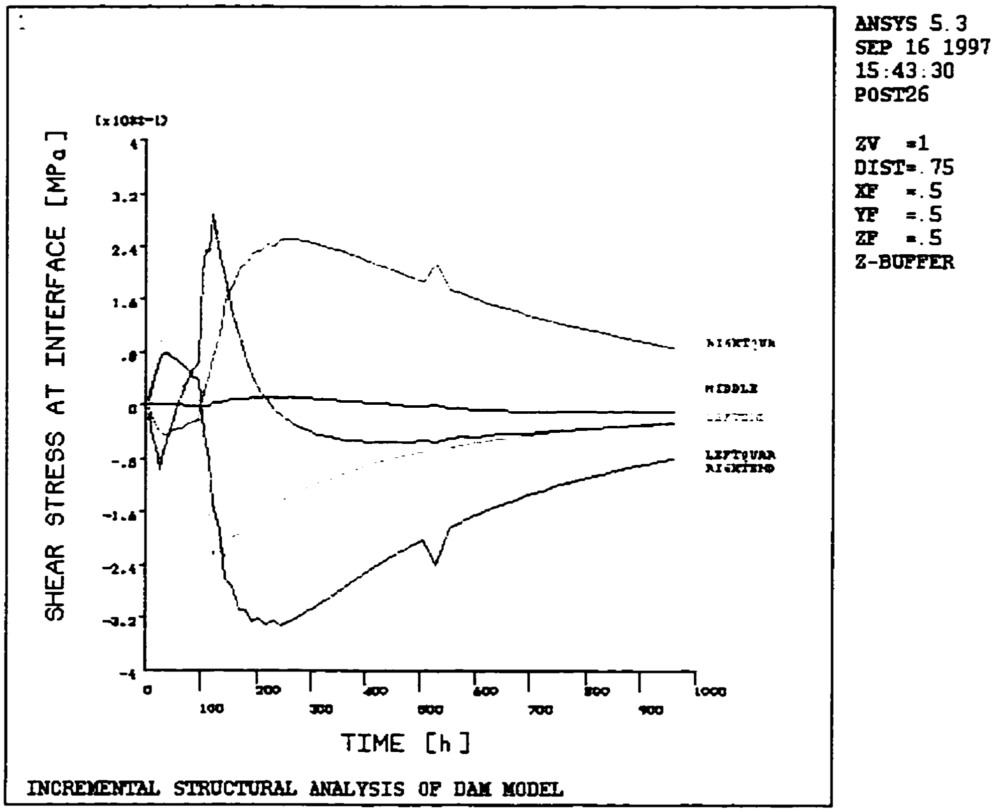


Figure 5.14 *Time – Shear Stress at Interface Diagram*

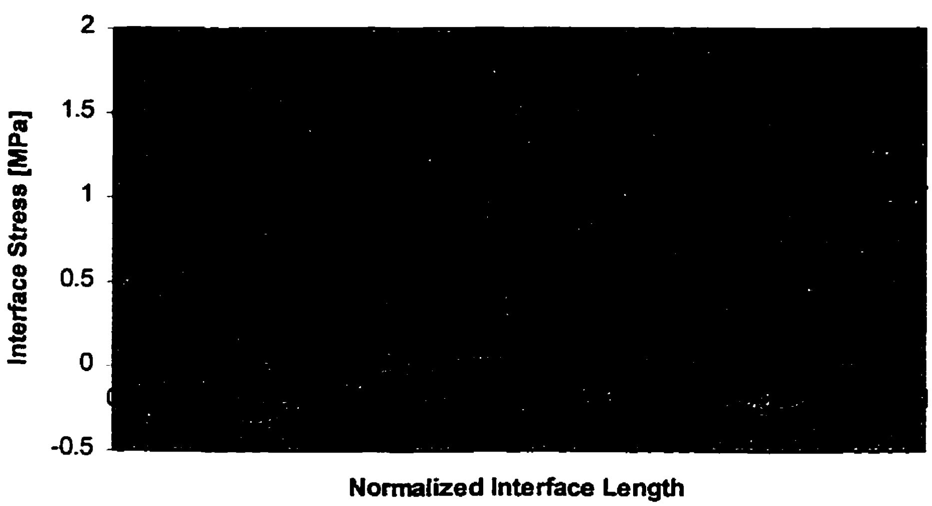


Figure 5.15 *Maximum Stresses on the Interface for Dam Model*

Normal stresses at interface shown in Figure 5.13 are still very high and these stresses must be taken into account when we analyze the stress field in the dam. The maximum stress is on the left side of the model. The differences between the left and right side stresses exist since this model is not symmetrical.

If Figure 5.15 and 5.5 are compared the stress curve in the interface are not the same shapes. The reason for this is length of interface. In the case of first figure we are dealing with small specimen and in the other case specimen is almost 15 times larger. There are two characteristic areas to the stress curve. One part of the stress distribution is positive and the other one is negative. The areas under the curves are equal, i.e. the total algebraic surface is null. This can be a proof that finite element algorithm for structural analysis works properly as the internal stress must be self equilibrating.

5.5 DISCUSSION

Stresses from the early stage of concrete are usually neglected when stress analysis of a dam is carried out. From the results of this investigation it is obvious that residual stresses from this early stage must be added to the analysis of mass concrete.

Different models are used for this research. First, we wanted to capture size effect. Four different models are used. It is shown from the analysis when size of specimen increases stresses become larger. In practice, the casting of upper block does not occur after 24 hours, it is usually done a couple of days later. This is the reason why simulating the dam was carried out. It is also shown that it is possible to find an optimum time for pouring a subsequent block. Stress analysis is one of the most important analyses of concrete structures.

The upper block is poured at different times and results show that as we pour later the stresses became smaller. Technical and economical reasons do not permit a long wait for subsequent pour and the reduction in slows after some time. Probably stresses will increase again because the difference in temperature between the blocks becomes large.

Finally, the dam model was analyzed. The stress field is smaller for this model because the concrete is different, ice water is used in the concrete and outside conditions are better.

6 CONCLUSIONS AND RECOMENDATIONS

To better understand the behaviour of massive concrete structures in its early stage thermal and stress analyses were carried out. The thermal analysis captures the thermal behaviour of an incrementally constructed massive concrete structure. The structural or stress analysis captures structural behaviour using temperature field from the thermal analysis as a load. Both algorithms, we can say, reliably predict the behaviour of massive concrete structures.

Maximum temperature obtained from thermal analysis algorithm is almost the same as one obtained from the field. Material constants, influence of framework, time dependent loads from heat of hydration of cement and incremental structural effect are properly incorporated in the algorithm. Algorithm can be used for different sizes of specimens and for different times of casting the upper block of concrete.

Stress analysis shows that stresses formed in early age of mass concrete is not negligible. These stresses form first cracks. In the model, the process of hardening is considered using modulus of elasticity dependable on time. Incremental temperature load and gravity are two loads applied on the structure and they closely predict the real situation.

In the analysis of the dam model, only two blocks are analyzed. The rest of the structure is approximated. This work should be extended to the whole structure and results should be more accurate. Time and software limitations did not allow us to carry out this kind of analysis.

The algorithm will give better prediction if we include radiation from the surfaces as well as more accurate formwork characteristics for dam model. Smaller time step, more frequent change of heat of hydration load and modulus of elasticity would also give better approximation of actual behaviour of structure. In addition, investigation on lift thickness, construction schedule, restraints on parts of structure can be carried in the future.

The analysis of cracked models should be examined. Finding the time when crack starts and its growth to full length would be very useful information for better understanding of massive concrete. In this period of early stage of concrete, cracks are initiated. Development of cracks depends also on outside conditions. Dams that preform in severe conditions, as it is the case with the Long Spruce dam, have a high predisposition for large crack development.

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APPENDIX A

HEAT TRACED DRAINAGE SYSTEM

A.1 INTRODUCTION

Detailed calculation of energy estimation needed for tunnel heating on the downstream side of the Long Spruce dam is given in this appendix. Except calculation of radius of the tunnel and heat necessary to keep temperature in the tunnel above zero, the other parameters such as type of heaters, thermostat control, contactors are chosen. The tunnel was built by Manitoba Hydro summer 1996.

A.2 ENERGY LOSS

Energy needed for heating the tunnel can be presented by following formula,

$$q = q_1 + q_2 + q_3 \tag{A. 1}$$

The heat loss through the wall of the dam by convection:

$$q_1 = Ah_c(T_c - T_\infty) \tag{A. 2}$$

Where,

h_c = 11.6 $W/(m^2 K)$ - the convective coefficient between air in the tunnel and concrete

T_∞ = 283 K (10°C) - the air temperature in the tunnel

T_c = 268 K (-5°C) - the concrete temperature

The heat loss per unit length through the insulation by conduction:

$$q_2 = \frac{[3.82Lk(T_\infty - T_0)]}{\ln\left(\frac{r_1}{r_2}\right)} \quad \text{(A. 3)}$$

Where,

k = 0.02405 *W/(m K)* - thermal conductivity for insulation thickness 1"

T_0 = 233 *K* (-40°C) - the outside temperature

r_1 = 0.3175 *m* - the radius of the pipe

r_2 = 0.3429 *m* - the radius of the insulation

The heat loss with water:

$$q_3 = q_a + q_b + q_c \quad \text{(A. 4)}$$

The energy needed for increase temperature of ice from 263 *K* to 273 *K*:

$$q_a = m' c_{ice}(T_1 - T_2) \quad \text{(A. 5)}$$

Where,

m' *[kg/s]* - the mass of ice

c_{ice} = 2.1 *kJ/(kg K)* - the specific heat of ice

The energy needed for melting ice (changing phase):

$$q_b = m' h_{sf} = m'(h_f - h_s) \quad \text{(A. 6)}$$

Where,

h_{sf} *[kJ/kg]* the latent heat of melting

The energy needed for increase temperature of water from 273 *K* to 280 *K*:

$$q_c = m' c_w (T_3 - T_4) \tag{A. 7}$$

Where,

c_w = 4.17 *kJ/(kg K)* is the specific heat of water

A.3 THE DRAINAGE PIPE

The amount of water from the crack is maximum **V' = 100** *l/min*. This is the base for determination of diameter for the drainage pipe. The slope of the tunnel is 1/2 %.

The mass flow rate is:

$$m' = \rho V' = 1.655 \; kg/s \tag{A. 8}$$

The velocity of water through the tunnel should be estimated. This velocity is needed to determine the radios of the drainage pipe.

Using second Newton's low, we can write:

$$\Sigma F = ma \tag{A. 9}$$

$$mg \sin \alpha = ma \qquad \alpha = 0.286^0$$

$$v^2 = v^2 + 2a(x\text{-}x_0) \tag{A. 10}$$

$$v = 2.11 \; m/s$$

$$v = \frac{m'}{\rho A} = \frac{m}{\rho r^2 \pi} \tag{A. 11}$$

From the equation (A.11) the radius of the pipe can be calculated:

$$r = 0.0158\ m$$

A.4 TOTAL ENERGY

The insulation material which we are using has the "***R*** - value/inch" $6\,\frac{\frac{ft^2 hF}{Btu}}{inch}$.

This is property of a material and is related directly to the thermal conductivity ***k***. After the transformation we got the value for ***k*** for the thickness of insulation of *1 inch*.

$$k = 0.02405\ W/m\ K$$

Substituting these parameters in the equation (1) and (2) we will get:

$$q_1 = 3.549\ kW$$

$q_2 = 2.720\ kW$ - for thickness of the insulation of 25.4 *mm*

$q_2 = 0.706\ kW$ - for thickness of the insulation of 50.8 *mm*

To calculate q_3 we need to know water flow rate during winter period. The exact value is impossible to know and we can approximate that water flow rate is *1l/min*. For this value q_3 is calculated by equation (A.4):

$$q_a = 0.348\ kW$$

$$q_b = 5.33\ kW$$

$$q_c = 0.20\ kW$$

$$q_3 = 0.348 + 5.33 + 0.20 = 5.878\ kW$$

Using equation (A.1) the total amount of heat which is lost in the tunnel is:

q = 12.147 kW - for thickness of insulation of 1 inch

q = 10.130 kW - for thickness of insulation of 2 inches

A.5 HEATERS

For the extreme low outside temperature the amount of heat, needed to maintain the temperature in the tunnel above freezing point (around 10^0C), is $q = 10\ kW$. To approach this value in the tunnel we will use *3 20QTV2* heat traces. Temperature can be monitored and heat reduced if necessary.

The QTV family of Chemelex Auto-Trace self-regulating heaters maintains temperatures up to 110^{0}C. These heaters can also be used for basic freeze protection in high heat loss systems. The QTV heaters can be used in hazardous areas and corrosive areas.

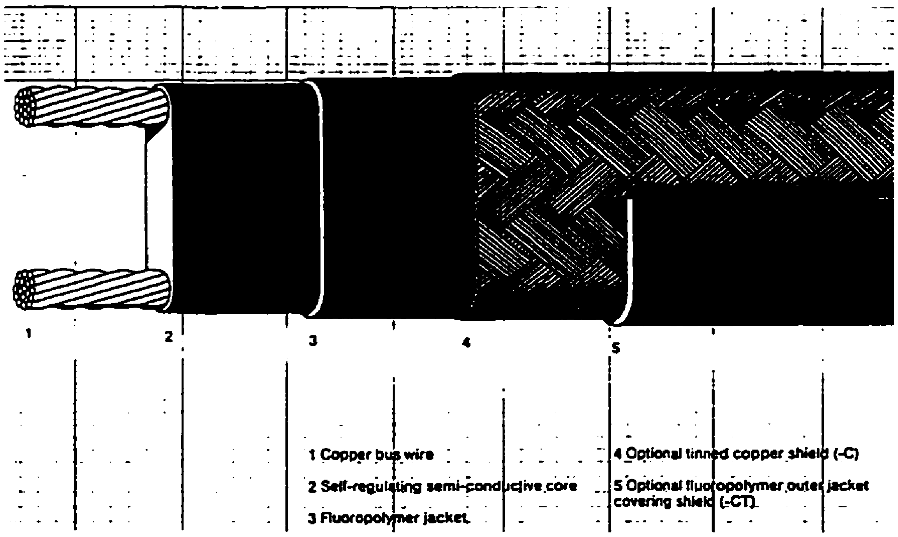


Figure A.1 *Chemelex Auto-Trace Self-Regulating Heater*

Properties of heaters *20QTV* are:

Service Voltage	240 VAC
Circuit Breaker Section	20QTV2
Circuit breaker size vs.	30A
Maximum circuit length	
If started at: 10^0C	240 feet
-18^0C	195 feet
-29^0C	180 feet

A.6 THERMOSTAT CONTROL

The AMC-F5 thermostat is designed for use on outdoor heat traced water lines. The enclosure is waterproof (NEMA 4X) and corrosion resistant. The temperature on which sensor works should not be above 60^0C.

Properties	
Enclosure	NEMA 4X
	Glass field nylon
	waterproof, gasketed lid
Setpoint	5^0C
Sensor Exposure Limits	-35^0C to 60^0C
Switch	SP-ST UL Listed and CSA
Certified	

More information about ANC-F5 thermostat can be found in the catalog number AMC-F5.

A.7 CONTACTORS

The 304 is a three pole contactor with contacts that can be replaced in the field. The contactor is in thermoplastic enclosure that is light weight, dust tight, water tight, and corrosion resistant.

More about contactor 304 can be found in the catalog number E304.

APPENDIX B

HEAT OF HYDRATION OF CEMENT

B.1 HEAT OF HYDRATION OF CEMENT

Heat of hydration of cement used for the concrete models is presented below in two ways, table and diagram.

Table B.1 contains five columns. The meaning of symbols in the table is explained below:

- t time in days where different values of heat from hydration of cement are applied
- T(t) general expression for adiabatic temperature rise due to cement hydration heat
- Q(t) total amount of heat generated per unit volume
- R(t) the rate of heat generation

Calculation of all these parameters with formulas is given in Chapter 4.

Time [day]	T(t) [°C]	Q(t) [kJ/m³]	R(t) [kJ/m³day]	R(t) [kJ/m³hr]
0	0	0	0	0
0.25	12	28018	96,099	4004
0.5	21	48773	71,192	2966
0.75	28	64150	52,740	2198
1	33	75541	39,071	1628
1.25	37	83980	28,944	1206
1.5	39	90231	21,443	893
1.75	41	94862	15,885	662
2	43	98293	11,768	490
2.25	44	100835	8,718	363
2.5	45	102718	6,458	269
2.75	45	104113	4,784	199
3	46	105146	3,544	148
3.25	46	105912	2,626	109
3.5	46	106479	1,945	81
3.75	46	106899	1,441	60
4	47	107210	1,068	44
4.25	47	107441	791	33
4.5	47	107612	586	24
4.75	47	107738	434	18
5	47	107832	322	13
5.5	47	107953	176	7
6	47	108019	97	4
6.5	47	108056	53	2
7	47	108076	29	1
7.5	47	108087	16	1
8	47	108093	9	0
8.5	47	108096	5	0
9	47	108098	3	0
9.5	47	108099	1	0
10	47	108099	1	0
11	47	108100	0	0
12	47	108100	0	0
13	47	108100	0	0
14	47	108100	0	0
15	47	108100	0	0
16	47	108100	0	0
17	47	108100	0	0
18	47	108100	0	0
19	47	108100	0	0
20	47	108100	0	0

Table B.1 *Dependence between time, adiabatic temperature rise, total amount of heat an heat generation*

This table presents exact values that are applied for dam model, even times for time steps are exactly what is applied in the algorithm. Different values of these loads are applied for the other models. The size of model determines time step. For larger model time step is smaller in order to get stable conditions faster. In addition, amount of cement in concrete block determines coefficients necessary for calculation of heat (load).

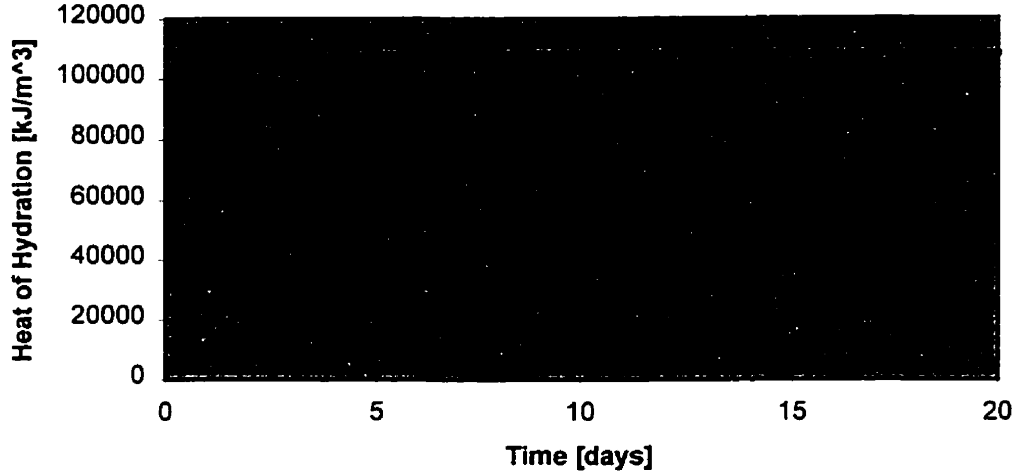


Figure B.1 *Heat of Hydration versus Time for Dam Model*

Figure B.1 presents dependence of heat of hydration of cement from time. In the beginning heat developed from hydration of cement is fast, in short period of time cement developed lot of heat. Later on the heat is almost constant. In massive concrete structures this heat stays captured in concrete for a long period of time.

APPENDIX C

DEPENDANCE OF MODULUS OF ELASTICITY WITH TIME

C.1 DEPENDANCE OF MODULUS OF ELASTICITY WITH TIME

The modulus of elasticity for fresh concrete is very low. Its value increases with time, actually with hardening of concrete. After 28 days modulus of elasticity is considered constant.

Exact values of modulus of elasticity used in dam model are presented in the following table and diagram.

Table contains four columns and they present following:

- T *[h]* – time
- β - coefficient presented in Figure 4.4 at Chapter 4
- E_{28} *[MPa]* – modulus of elasticity at 28 days of concrete casting
- E *[MPa]* – modulus of elasticity applied in the model

Figure C.1 present dependence of modulus of elasticity from time. It is obvious that increase of modulus of elasticity is highest in the first few days. That is the most important time for our analysis.

T [h]	β	E28 [MPa]	E [MPa]
6	0.16	26000	4160
12	0.16	26000	4160
18	0.16	26000	4160
24	0.42	26000	10920
30	0.42	26000	10920
36	0.42	26000	10920
42	0.42	26000	10920
48	0.59	26000	15340
54	0.59	26000	15340
60	0.59	26000	15340
66	0.59	26000	15340
72	0.67	26000	17420
78	0.67	26000	17420
84	0.67	26000	17420
90	0.67	26000	17420
96	0.72	26000	18720
102	0.72	26000	18720
108	0.72	26000	18720
114	0.72	26000	18720
120	0.76	26000	19760
132	0.76	26000	19760
144	0.8	26000	20800
156	0.8	26000	20800
168	0.82	26000	21320
180	0.82	26000	21320
192	0.84	26000	21840
204	0.84	26000	21840
216	0.86	26000	22360
228	0.86	26000	22360
240	0.88	26000	22880
264	0.89	26000	23140
288	0.9	26000	23400
312	0.91	26000	23660
336	0.92	26000	23920
360	0.93	26000	24180
384	0.94	26000	24440
408	0.95	26000	24700
432	0.96	26000	24960
456	0.97	26000	25220
480	0.98	26000	25480
504	0.98	26000	25480
528	0.98	26000	25480
552	0.99	26000	25740
576	0.99	26000	25740
600	0.99	26000	25740
624	0.99	26000	25740
648	0.99	26000	25740
672	1	26000	26000
696	1	26000	26000
720	1	26000	26000
744	1	26000	26000
768	1	26000	26000
792	1	26000	26000
816	1	26000	26000
840	1	26000	26000
864	1	26000	26000
888	1	26000	26000
912	1	26000	26000
936	1	26000	26000
960	1	26000	26000

Table C.1 *Calculation of Modulus of Elasticity for the Stress Analysis Algorithm*

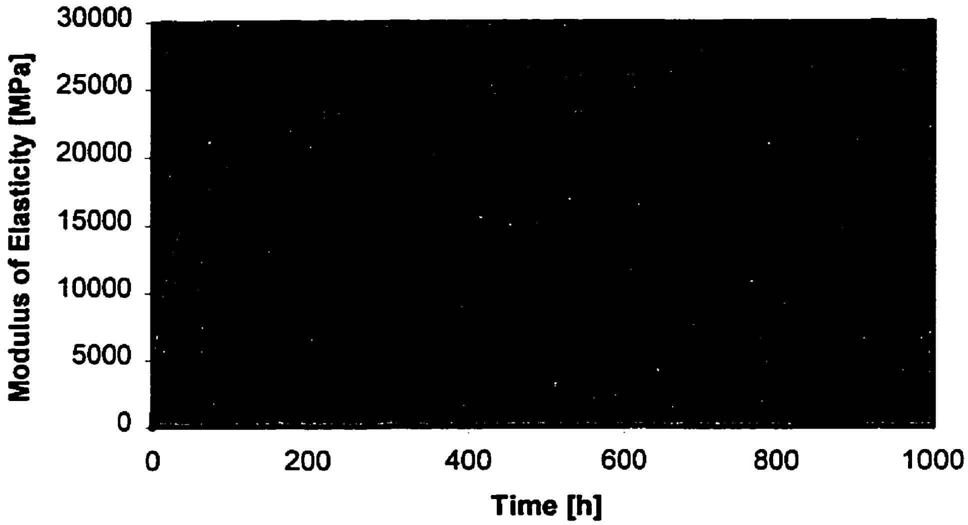


Figure C.1 *Dependence between Modulus of Elasticity and Time*

APPENDIX D

INCREMENTAL THERMAL ANALYSIS OF DAM MODEL

PROGRAM LISTING

```
!------------------------------------------------------------------------------------!
!                                                                                    !
!            INCREMENTAL THERMAL ANALYSIS OF DAM MODEL                               !
!                                                                                    !
!       - thermal analysis of Long Spruce Generating Station -                      !
!                                                                                    !
!       Thermal loads:                                                               !
!                    - heat of hydration of cement                                   !
!                    - ambient temperature on outside surfaces                       !
!                    - bottom of the block at temperature 25°C                       !
!                                                                                    !
!       Base Units: length [m], temperature [C], energy [kJ], time [hr]             !
!                                                                                    !
!------------------------------------------------------------------------------------!
/clear
    !
    ! BUILD THE MODEL
    !
/filnam, thermal
/title, INCREMENTAL THERMAL ANALYSIS OF DAM MODEL
/prep7
et,1,55  $csys,0  $type,1
    !
    ! Material properties
    !
mp,kxx,1,9.2    $mp,c,1,0.85  $mp,dens,1,2294   ! concrete
mp,kxx,2,1.04   $mp,c,2,1.16  $mp,dens,2,550    ! framework
    !
    ! Define keypoints
    !
k,1,0,0              $k,2,0.2,0              $k,3,0,2.7432        $k,4,0.2,2.7432
k,5,0,5.1816         $k,6,0.2,5.1816         $k,7,10.2335,0       $k,8,10.4335,0
k,9,9.9245,2.7432    $k,10,10.1245,2.7432    $k,11,9.65,5.1816    $k,12,9.85,5.1816
k,13,0.2,0           $k,14,10.2335,0         $k,15,0.2,2.7432     $k,16,9.9245,2.7432
k,17,0.2,2.7432      $k,18,9.9245,2.7432     $k,19,0.2,5.1816     $k,20,9.65,5.1816
    !
    ! Define and divide lines
    !
l,1,2   $l,3,4    $l,5,6
l,7,8   $l,9,10   $l,11,12
    !
l,1,3   $l,2,4    $l,13,15  $l,14,16  $l,7,9    $l,8,10
l,3,5   $l,4,6    $l,17,19  $l,18,20  $l,9,11   $l,10,12
    !
l,13,14  $l,15,16  $l,17,18  $l,19,20
    !
lsel,s,,,1,6     $lesize,all,,,1,1
lsel,s,,,7,12    $lesize,all,,,10,0.1
lsel,s,,,13,18   $lesize,all,,,10,10
lsel,s,,,19,22   $lesize,all,,,20,-5
lsel,all
```

```
        !
        ! Define and mesh areas
        !
eshape,2
        !
mat,2
al,1,2,7,8 $al,2,3,13,14 $al,4,5,11,12 $al,5,6,17,18
amesh,1,4
        !
mat,1
al,9,10,19,20 $al,15,16,21,22
amesh,5,6
        !
        ! Connect the first part
        !
cp,1,temp,85,2     $cp,2,temp,87,4    $cp,3,temp,88,5    $cp,4,temp,89,6
cp,5,temp,90,7     $cp,6,temp,91,8    $cp,7,temp,92,9    $cp,8,temp,93,10
cp,9,temp,94,11    $cp,10,temp,95,12
        !
cp,11,temp,116,43  $cp,12,temp,117,56 $cp,13,temp,118,57 $cp,14,temp,119,58
cp,15,temp,120,59  $cp,16,temp,121,60 $cp,17,temp,122,61 $cp,18,temp,123,62
cp,19,temp,124,63  $cp,20,temp,125,64
        !
        ! Connect the second part
        !
cp,21,temp,318,24  $cp,22,temp,319,25 $cp,23,temp,320,26  $cp,24,temp,321,27
cp,25,temp,322,28  $cp,26,temp,323,29 $cp,27,temp,324,30  $cp,28,temp,325,31
cp,29,temp,326,32  $cp,30,temp,317,23
        !
cp,31,temp,316,86   $cp,32,temp,357,97  $cp,33,temp,358,98  $cp,34,temp,359,99
cp,35,temp,360,100 $cp,36,temp,361,101 $cp,37,temp,362,102 $cp,38,temp,363,103
cp,39,temp,364,104 $cp,40,temp,365,105 $cp,41,temp,366,106 $cp,42,temp,367,107
cp,43,temp,368,108 $cp,44,temp,369,109 $cp,45,temp,370,110 $cp,46,temp,371,111
cp,47,temp,372,112 $cp,48,temp,373,113 $cp,49,temp,374,114 $cp,50,temp,375,115
cp,51,temp,347,96
        !
cp,52,temp,348,76  $cp,53,temp,349,77  $cp,54,temp,350,78  $cp,55,temp,351,79
cp,56,temp,352,80  $cp,57,temp,353,81  $cp,58,temp,354,82  $cp,59,temp,355,83
cp,60,temp,356,84  $cp,61,temp,327,75
        !
save
finish
        !
        ! APPLY LOADS AND OBTAIN THE SOLUTION
        !
/solution
antype,transient
tintpr,,,,1.0
        !
nropt,1
cnvtol,heat,,,,1.0e-10
```

```
        !
        !  Initial conditions
        !
timint,off
        !
time,0.1
nsel,s,node,,1,84       $d,all,temp,25          ! initial temperture for framework,
nsel,s,node,,85,315     $d,all,temp,10          ! block 1 of concrete and block 2
nsel,s,node,,316,546    $d,all,temp,10          ! of concrete
nsel,all  $esel,all
        !
ealive,all
esel,s,,,316,546   $nsle
ekill,all                          ! deactivate elements from upper block
nsel,all    $esel,all              ! of concrete
save
        !
        !  Transient portion
        !
timint,on  $kbc,1
nsel,s,node,,1,84       $ddele,all,temp         ! delete initial temperatures from
nsel,s,node,,85,315     $ddele,all,temp         ! framework and lower block of concrete
        !
nsel,s,node,,1,1        $d,all,temp,25          ! constrain the bottom of the lower
nsel,s,node,,126,144    $d,all,temp,25          ! block of framework whih is in touch
nsel,s,node,,44,44      $d,all,temp,25          ! with ground
nsel,all
        !
sfl,7,conv,15,,10   $sfl,13,conv,15,,10  $sfl,3,conv,15,,10
sfl,14,conv,15,,10  $sfl,20,conv,15,,10  $sfl,17,conv,15,.10
sfl,6,conv,15,,23   $sfl,18,conv,15,,23  $sfl,12,conv,15,,23        ! surface load
        !
time,6
esel,s,elem,,41,240   $bfe,all,hgen,,4004      ! heat generation by cement
nsel,all  $esel,all                            ! in concrete
solve
        !
time,12
esel,s,elem,,41,240   $bfe,all,hgen,,2966
nsel,all  $esel,all
solve
        !
time,18
esel,s,elem,,41,240   $bfe,all,hgen,,2197
nsel,all  $esel,all
solve
        !
time,24
esel,s,elem,,41,240   $bfe,all,hgen,,1627
nsel,all  $esel,all
        !
```

```
solve
          !
time,30
esel,s,elem,,41,240   $bfe,all,hgen,,1206
nsel,all   $esel,all
solve
          !
time,36
esel,s,elem,,41,240   $bfe,all,hgen,,893
nsel,all   $esel,all
solve
          !
time,42
esel,s,elem,,41,240   $bfe,all,hgen,,661
nsel,all   $esel,all
solve
          !
time,48
esel,s,elem,,41,240   $bfe,all,hgen,,490
nsel,all   $esel,all
solve
          !
time,54
esel,s,elem,,41,240   $bfe,all,hgen,,363
nsel,all   $esel,all
solve
          !
time,60
esel,s,elem,,41,240   $bfe,all,hgen,,269
nsel,all   $esel,all
solve
          !
time,66
esel,s,elem,,41,240   $bfe,all,hgen,,199
nsel,all   $esel,all
solve
          !
time,72
esel,s,elem,,41,240   $bfe,all,hgen,,147
nsel,all   $esel,all
solve
          !
time,78
esel,s,elem,,41,240   $bfe,all,hgen,,109
nsel,all   $esel,all
solve
          !
time,84
esel,s,elem,,41,240   $bfe,all,hgen,,81
nsel,all   $esel,all
solve
```

```
        !
time,90
esel,s,elem,,41,240   $bfe,all,hgen,,60
nsel,all  $esel,all
solve
        !
time,96
esel,s,elem,,41,240   $bfe,all,hgen,,44
nsel,all  $esel,all
solve
        !
time,96.1  $kbc,1
        !
esel,s,,,241,440    $nsle                    ! activate elements from the upper
ealive,all                                   ! block of concrete
nsel,all   $esel,all
        !
sfldele,214,conv  $sfldele,20,conv  $sfldele,17,conv      ! delete load from the
                                                          ! surfaces which are in
                                                          ! contact with upper block
        !
sfl,7,conv,15,,10  $sfl,13,conv,15,,10  $sfl,3,conv,15,,10       ! new loaded
sfl,22,conv,15,,10  $sfl,6,conv,15,,10  $sfl,18,conv,15,,10      ! surfaces
sfl,12,conv,15,,10
        !
esel,s,elem,,41,240   $bfe,all,hgen,,44
nsel,all  $esel,all
solve
        !
time,102
nsel,s,node,,316,546   $ddele,all,temp           ! delete initial temperature from
                                                 ! the upper block
esel,s,elem,,41,240   $bfe,all,hgen,,32
esel,s,elem,,241,440   $bfe,all,hgen,,4004
nsel,all  $esel,all
solve
        !
time,108
esel,s,elem,,41,240   $bfe,all,hgen,,24
esel,s,elem,,241,440   $bfe,all,hgen,,2966
nsel,all  $esel,all
solve
        !
time,114
esel,s,elem,,41,240   $bfe,all,hgen,,18
esel,s,elem,,241,440   $bfe,all,hgen,,2197
nsel,all  $esel,all
solve
        !
time,120
esel,s,elem,,41,240   $bfe,all,hgen,,13
```

```
esel,s,elem,,241,440   $bfe,all,hgen,,1627
nsel,all   $esel,all
solve
        !
time,132
esel,s,elem,,41,240   $bfe,all,hgen,,7
esel,s,elem,,241,440   $bfe,all,hgen,,893
nsel,all   $esel,all
solve
        !
time,144
esel,s,elem,,41,240   $bfe,all,hgen,,4
esel,s,elem,,241,440   $bfe,all,hgen,,490
nsel,all   $esel,all
solve
        !
time,156
esel,s,elem,,41,240   $bfe,all,hgen,,2
esel,s,elem,,241,440  $bfe,all,hgen,,269
nsel,all   $esel,all
solve
        !
time,168
esel,s,elem,,41,240   $bfe,all,hgen,,1
esel,s,elem,,241,440   $bfe,all,hgen,,147
nsel,all   $esel,all
solve
        !
time,180
esel,s,elem,,41,240   $bfe,all,hgen,,0.6
esel,s,elem,,241,440 $bfe,all,hgen,,81
nsel,all   $esel,all
solve
        !
time,192
esel,s,elem,,41,240   $bfe,all,hgen,,0.3
esel,s,elem,,241,440   $bfe,all,hgen,,44
nsel,all   $esel,all
solve
        !
time,204
esel,s,elem,,41,240   $bfe,all,hgen,,0.2
esel,s,elem,,241,440   $bfe,all,hgen,,24
nsel,all   $esel,all
solve
        !
time,216
esel,s,elem,,41,240   $bfe,all,hgen,,0.1
esel,s,elem,,241,440   $bfe,all,hgen,,13
nsel,all   $esel,all
solve
```

```
          !
time,228
esel,s,elem,,41,240   $bfe,all,hgen,,0.06
esel,s,elem,,241,440   $bfe,all,hgen,,7
nsel,all   $esel,all
solve
          !
time,240
esel,s,elem,,41,240   $bfe,all,hgen,,0.03
esel,s,elem,,241,440   $bfe,all,hgen,,4
nsel,all   $esel,all
solve
          !
time,264
esel,s,elem,,41,240   $bfe,all,hgen,,0.01
esel,s,elem,,241,440   $bfe,all,hgen,,1
nsel,all   $esel,all
solve
          !
time,288
esel,s,elem,,241,440   $bfe,all,hgen,,0.37
nsel,all   $esel,all
solve
          !
time,312
esel,s,elem,,241,440   $bfe,all,hgen,,0.11
nsel,all   $esel,all
solve
          !
time,336
esel,s,elem,,241,440  $bfe,all,hgen,,0.03
nsel,all   $esel,all
solve
          !
time,360
esel,s,elem,,241,440  $bfe,all,hgen,,0.01
nsel,all   $esel,all
solve
          !
time,384
solve
          !
time,408
solve
          !
time,432
solve
          !
time,456
solve
          !
```

```
time,480
solve
          !
time,504
solve
          !
time,528
solve
          !
time,552
solve
          !
time,576
solve
          !
time,600
solve
          !
time,624
solve
          !
time,648
solve
          !
time,672
solve
          !
time,696
solve
          !
time,720
solve
          !
time,744
solve
          !
time,768
solve
          !
time,792
solve
          !
time,816
solve
          !
time,840
solve
          !
time,864
solve
          !
```

```
time,888
solve
          !
time,912
solve
          !
time,936
solve
          !
time,960
solve
          !
save
finish
```

APPENDIX E

INCREMENTAL STRUCTURAL ANALYSIS OF DAM MODEL

PROGRAM LISTING

```
!-------------------------------------------------------------------------------!
!                                                                               !
!           INCREMENTAL STRUCTURAL ANALYSIS OF DAM MODEL                        !
!                                                                               !
!       - stress analysis of Long Spruce Generating Station -                   !
!                                                                               !
!       Loads:                                                                  !
!               - gravity                                                       !
!               - loads from temperature field                                  !
!                                                                               !
!       Note: the temperature load is input from thermal.rht file               !
!             this file is result file from the thermal analysis                !
!                                                                               !
!       Base Units: length [m], temperature [C], time [hr], stress [MPa]        !
!                                                                               !
!-------------------------------------------------------------------------------!
/clear
        !
        !  BUILD THE MODEL
        !
/filnam, stress
/title, INCREMENTAL STRUCTURAL ANALYSIS OF DAM MODEL
/prep7
et,1,42  $csys,0  $type,1
        !
        !  Material properties
        !
mp,alpx,1,9.5e-6     $mp,dens,1,2500     $mp,ex,1,4160       ! material properties
mp,alpx,2,9.5e-6     $mp,dens,2,2500     $mp,ex,2,10920      ! for concrete ( the
mp,alpx,3,9.5e-6     $mp,dens,3,2500     $mp,ex,3,15340      ! modulus of elasticity is
mp,alpx,4,9.5e-6     $mp,dens,4,2500     $mp,ex,4,17420      ! changing with time)
mp,alpx,5,9.5e-6     $mp,dens,5,2500     $mp,ex,5,18720
mp,alpx,6,9.5e-6     $mp,dens,6,2500     $mp,ex,6,19760
mp,alpx,7,9.5e-6     $mp,dens,7,2500     $mp,ex,7,20800
mp,alpx,8,9.5e-6     $mp,dens,8,2500     $mp,ex,8,21350
mp,alpx,9,9.5e-6     $mp,dens,9,2500     $mp,ex,9,21840
mp,alpx,10,9.5e-6    $mp,dens,10,2500    $mp,ex,10,22360
mp,alpx,11,9.5e-6    $mp,dens,11,2500    $mp,ex,11,22880
mp,alpx,12,9.5e-6    $mp,dens,12,2500    $mp,ex,12,23140
mp,alpx,13,9.5e-6    $mp,dens,13,2500    $mp,ex,13,23400
mp,alpx,14,9.5e-6    $mp,dens,14,2500    $mp,ex,14,23660
mp,alpx,15,9.5e-6    $mp,dens,15,2500    $mp,ex,15,23920
mp,alpx,16,9.5e-6    $mp,dens,16,2500    $mp,ex,16,24180
mp,alpx,17,9.5e-6    $mp,dens,17,2500    $mp,ex,17,24440
mp,alpx,18,9.5e-6    $mp,dens,18,2500    $mp,ex,18,24700
mp,alpx,19,9.5e-6    $mp,dens,19,2500    $mp,ex,19,24960
mp,alpx,20,9.5e-6    $mp,dens,20,2500    $mp,ex,20,25220
mp,alpx,21,9.5e-6    $mp,dens,21,2500    $mp,ex,21,25480
mp,alpx,22,9.5e-6    $mp,dens,22,2500    $mp,ex,22,25740
mp,alpx,23,9.5e-6    $mp,dens,23,2500    $mp,ex,23,26000
        !
```

```
mp,alpx,24,9.5e-6    $mp,dens,24,2500    $mp,ex,24,4160
mp,alpx,25,9.5e-6    $mp,dens,25,2500    $mp,ex,25,10920
mp,alpx,26,9.5e-6    $mp,dens,26,2500    $mp,ex,26,15340
mp,alpx,27,9.5e-6    $mp,dens,27,2500    $mp,ex,27,17420
mp,alpx,28,9.5e-6    $mp,dens,28,2500    $mp,ex,28,18720
mp,alpx,29,9.5e-6    $mp,dens,29,2500    $mp,ex,29,19760
mp,alpx,30,9.5e-6    $mp,dens,30,2500    $mp,ex,30,20800
mp,alpx,31,9.5e-6    $mp,dens,31,2500    $mp,ex,31,21350
mp,alpx,32,9.5e-6    $mp,dens,32,2500    $mp,ex,32,21840
mp,alpx,33,9.5e-6    $mp,dens,33,2500    $mp,ex,33,22360
mp,alpx,34,9.5e-6    $mp,dens,34,2500    $mp,ex,34,22880
mp,alpx,35,9.5e-6    $mp,dens,35,2500    $mp,ex,35,23140
mp,alpx,36,9.5e-6    $mp,dens,36,2500    $mp,ex,36,23400
mp,alpx,37,9.5e-6    $mp,dens,37,2500    $mp,ex,37,23660
mp,alpx,38,9.5e-6    $mp,dens,38,2500    $mp,ex,38,23920
mp,alpx,39,9.5e-6    $mp,dens,39,2500    $mp,ex,39,24180
mp,alpx,40,9.5e-6    $mp,dens,40,2500    $mp,ex,40,24440
mp,alpx,41,9.5e-6    $mp,dens,41,2500    $mp,ex,41,24700
mp,alpx,42,9.5e-6    $mp,dens,42,2500    $mp,ex,42,24960
mp,alpx,43,9.5e-6    $mp,dens,43,2500    $mp,ex,43,25220
mp,alpx,44,9.5e-6    $mp,dens,44,2500    $mp,ex,44,25480
mp,alpx,45,9.5e-6    $mp,dens,45,2500    $mp,ex,45,25740
mp,alpx,46,9.5e-6    $mp,dens,46,2500    $mp,ex,46,26000
        !
mp,alpx,47,3.5e-6    $mp,dens,47,550     $mp,ex,47,10000
        !
        ! Define keypoints
        !
k,1,0,0              $k,2,0.2,0              $k,3,0,2.7432        $k,4,0.2,2.7432
k,5,0,5.1816         $k,6,0.2,5.1816         $k,7,10.2335,0       $k,8,10.4335,0
k,9,9.9245,2.7432    $k,10,10.1245,2.7432    $k,11,9.65,5.1816    $k,12,9.85,5.1816
k,13,0.2,0           $k,14,10.2335,0         $k,15,0.2,2.7432     $k,16,9.9245,2.7432
k,17,0.2,2.7432      $k,18,9.9245,2.7432     $k,19,0.2,5.1816     $k,20,9.65,5.1816
        !
        ! Define and devide lines
        !
l,1,2  $l,3,4   $l,5,6
l,7,8  $l,9,10  $l,11,12
        !
l,1,3  $l,2,4   $l,13,15  $l,14,16  $l,7,9   $l,8,10
l,3,5  $l,4,6   $l,17,19  $l,18,20  $l,9,11  $l,10,12
        !
l,13,14  $l,15,16  $l,17,18  $l,19,20
        !
lsel,s,,,1,6     $lesize,all,,,1,1
lsel,s,,,7,12    $lesize,all,,,10,0.1
lsel,s,,,13,18   $lesize,all,,,10,10
lsel,s,,,19,22   $lesize,all,,,20,-5
lsel,all
        !
        ! Define and mesh areas
```

```
        !
eshape,2
        !
mat,47
al,1,2,7,8  $al,2,3,13,14  $al,4,5,11,12  $al,5,6,17,18
amesh,1,4
        !
mat,1
al,9,10,19,20
amesh,5
        !
mat,24
al,15,16,21,22
amesh,6
        !
        ! Connect the first part
        !
cp,1,ux,85,2    $cp,2,ux,87,4    $cp,3,ux,88,5    $cp,4,ux,89,6
cp,5,ux,90,7    $cp,6,ux,91,8    $cp,7,ux,92,9    $cp,8,ux,93,10
cp,9,ux,94,11   $cp,10,ux,95,12
        !
cp,11,ux,116,43  $cp,12,ux,117,56  $cp,13,ux,118,57  $cp,14,ux,119,58
cp,15,ux,120,59  $cp,16,ux,121,60  $cp,17,ux,122,61  $cp,18,ux,123,62
cp,19,ux,124,63  $cp,20,ux,125,64
        !
cp,21,uy,85,2    $cp,22,uy,87,4    $cp,23,uy,88,5    $cp,24,uy,89,6
cp,25,uy,90,7    $cp,26,uy,91,8    $cp,27,uy,92,9    $cp,28,uy,93,10
cp,29,uy,94,11   $cp,30,uy,95,12
        !
cp,31,uy,116,43  $cp,32,uy,117,56  $cp,33,uy,118,57  $cp,34,uy,119,58
cp,35,uy,120,59  $cp,36,uy,121,60  $cp,37,uy,122,61  $cp,38,uy,123,62
cp,39,uy,124,63  $cp,40,uy,125,64
        !
        ! Connect the second part
        !
cp,41,ux,318,24  $cp,42,ux,319,25  $cp,43,ux,320,26  $cp,44,ux,321,27
cp,45,ux,322,28  $cp,46,ux,323,29  $cp,47,ux,324,30  $cp,48,ux,325,31
cp,49,ux,326,32  $cp,50,ux,317,23
        !
cp,51,ux,316,86   $cp,52,ux,357,97   $cp,53,ux,358,98   $cp,54,ux,359,99
cp,55,ux,360,100  $cp,56,ux,361,101  $cp,57,ux,362,102  $cp,58,ux,363,103
cp,59,ux,364,104  $cp,60,ux,365,105  $cp,61,ux,366,106  $cp,62,ux,367,107
cp,63,ux,368,108  $cp,64,ux,369,109  $cp,65,ux,370,110  $cp,66,ux,371,111
cp,67,ux,372,112  $cp,68,ux,373,113  $cp,69,ux,374,114  $cp,70,ux,375,115
cp,71,ux,347,96
        !
cp,72,ux,348,76  $cp,73,ux,349,77  $cp,74,ux,350,78  $cp,75,ux,351,79
cp,76,ux,352,80  $cp,77,ux,353,81  $cp,78,ux,354,82  $cp,79,ux,355,83
cp,80,ux,356,84  $cp,81,ux,327,75
        !
cp,82,uy,318,24  $cp,83,uy,319,25  $cp,84,uy,320,26  $cp,85,uy,321,27
```

```
cp,86,uy,322,28  $cp,87,uy,323,29  $cp,88,uy,324,30   $cp,89,uy,325,31
cp,90,uy,326,32  $cp,91,uy,317,23
        !
cp,92,uy,316,86     $cp,93,uy,357,97     $cp,94,uy,358,98     $cp,95,uy,359,99
cp,96,uy,360,100    $cp,97,uy,361,101    $cp,98,uy,362,102    $cp,99,uy,363,103
cp,100,uy,364,104 $cp,101,uy,365,105 $cp,102,uy,366,106 $cp,103,uy,367,107
cp,104,uy,368,108 $cp,105,uy,369,109 $cp,106,uy,370,110 $cp,107,uy,371,111
cp,108,uy,372,112 $cp,109,uy,373,113 $cp,110,uy,374,114 $cp,111,uy,375,115
cp,112,uy,347,96
        !
cp,113,uy,348,76 $cp,114,uy,349,77  $cp,115,uy,350,78  $cp,116,uy,351,79
cp,117,uy,352,80 $cp,118,uy,353,81  $cp,119,uy,354,82  $cp,120,uy,355,83
cp,121,uy,356,84 $cp,122,uy,327,75
        !
save
finish
        !
        !   APPLY LOADS AND OBTAIN THE SOLUTION
        !
/solution
antype, static
        !
nropt,3
cnvtol,u,,,,0.0
ealive,all
esel,s,,,316,546     $nsle
esel,s,,,1,84        $nsle
        !
ekill,all
nsel,all    $esel,all
        !
        !   Constrain the bottom of the lower block
        !
d,1,ux,uy,0    $d,2,uy,0      $d,85,uy,0    $d,126,uy,0
d,127,uy,0     $d,128,uy,0  $d,129,uy,0  $d,130,uy,0
d,131,uy,0     $d,132,uy,0  $d,133,uy,0  $d,134,uy,0
d,135,uy,0     $d,136,uy,0  $d,137,uy,0  $d,138,uy,0
d,139,uy,0     $d,140,uy,0  $d,141,uy,0  $d,142,uy,0
d,143,uy,0     $d,144,uy,0  $d,116,uy,0
d,43,uy,0      $d,44,uy,ux,0
        !
time,6
ldread,temp,,,6,,thermal.rth
solve
        !
time,12
ldread,temp,,,12,,thermal.rth
solve
        !
time,18
ldread,temp,,,18,,thermal.rth
```

```
solve
      !
time,24
esel,s,,,41,240 $mpdele,ex,1  $mpchg,2,all
esel,all
ldread,temp,,,24,,thermal.rth
solve
      !
time,30
ldread,temp,,,30,,thermal.rth
solve
      !
time,36
ldread,temp,,,36,,thermal.rth
solve
      !
time,42
ldread,temp,,,42,,thermal.rth
solve
      !
time,48
esel,s,,,41,240 $mpdele,ex,2  $mpchg,3,all
esel,all
ldread,temp,,,48,,thermal.rth
solve
      !
time,54
ldread,temp,,,54,,thermal.rth
solve
      !
time,60
ldread,temp,,,60,,thermal.rth
solve
      !
time,66
ldread,temp,,,66,,thermal.rth
solve
      !
time,72
esel,s,,,41,240 $mpdele,ex,3  $mpchg,4,all
esel,all
ldread,temp,,,72,,thermal.rth
solve
      !
time,78
ldread,temp,,,78,,thermal.rth
solve
      !
time,84
ldread,temp,,,84,,thermal.rth
solve
```

```
        !
time,90
ldread,temp,,,90,,thermal.rth
solve
        !
time,96
esel,s,,,41,240 $mpdele,ex,4  $mpchg,5,all
esel,all
ldread,temp,,,96,,thermal.rth
solve
        !
        !  Second part placed
        !
time,96.1
        !
esel,s,,,241,440    $nsle
ealive,all
nsel,all    $esel,all
        !
ldread,temp,,,96.1,,thermal.rth
solve
        !
time,102
ldread,temp,,,102,,thermal.rth
solve
        !
time,108
ldread,temp,,,108,,thermal.rth
solve
        !
time,114
ldread,temp,,,114,,thermal.rth
solve
        !
time,120
esel,s,,,41,240 $mpdele,ex,5  $mpchg,6,all
esel,all
esel,s,,,241,440 $mpdele,ex,24  $mpchg,25,all
esel,all
ldread,temp,,,120,,thermal.rth
solve
        !
time,132
ldread,temp,,,132,,thermal.rth
solve
        !
time,144
esel,s,,,41,240 $mpdele,ex,6  $mpchg,7,all
esel,all
esel,s,,,241,440 $mpdele,ex,25  $mpchg,26,all
esel,all
```

```
ldread,temp,,,144,,thermal.rth
solve
    !
time,156
ldread,temp,,,156,,thermal.rth
solve
    !
time,168
esel,s,,,41,240 $mpdele,ex,7  $mpchg,8,all
esel,all
esel,s,,,241,440 $mpdele,ex,26  $mpchg,27,all
esel,all
ldread,temp,,,168,,thermal.rth
solve
    !
time,180
ldread,temp,,,180,,thermal.rth
solve
    !
time,192
esel,s,,,41,240 $mpdele,ex,8  $mpchg,9,all
esel,all
esel,s,,,241,440 $mpdele,ex,27  $mpchg,28,all
esel,all
ldread,temp,,,192,,thermal.rth
solve
    !
time,204
ldread,temp,,,204,,thermal.rth
solve
    !
time,216
esel,s,,,41,240 $mpdele,ex,9  $mpchg,10,all
esel,all
esel,s,,,241,440 $mpdele,ex,28  $mpchg,29,all
esel,all
ldread,temp,,,216,,thermal.rth
solve
    !
time,228
ldread,temp,,,228,,thermal.rth
solve
    !
time,240
esel,s,,,41,240 $mpdele,ex,10  $mpchg,11,all
esel,all
esel,s,,,241,440 $mpdele,ex,29  $mpchg,30,all
esel,all
ldread,temp,,,240,,thermal.rth
solve
    !
```

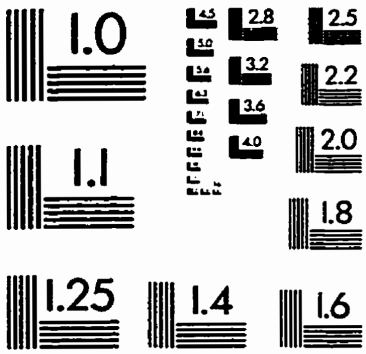
```
time,264
esel,s,,,41,240 $mpdele,ex,11  $mpchg,12,all
esel,all
esel,s,,,241,440 $mpdele,ex,30  $mpchg,31,all
esel,all
ldread,temp,,,264,,thermal.rth
solve
        !
time,288
esel,s,,,41,240 $mpdele,ex,12  $mpchg,13,all
esel,all
esel,s,,,241,440 $mpdele,ex,31  $mpchg,32,all
esel,all
ldread,temp,,,288,,thermal.rth
solve
        !
time,312
esel,s,,,41,240 $mpdele,ex,13  $mpchg,14,all
esel,all
esel,s,,,241,440 $mpdele,ex,32  $mpchg,33,all
esel,all
ldread,temp,,,312,,thermal.rth
solve
        !
time,336
esel,s,,,41,240 $mpdele,ex,14  $mpchg,15,all
esel,all
esel,s,,,241,440 $mpdele,ex,33  $mpchg,34,all
esel,all
ldread,temp,,,336,,thermal.rth
solve
        !
time,360
esel,s,,,41,240 $mpdele,ex,15  $mpchg,16,all
esel,all
esel,s,,,241,440 $mpdele,ex,34  $mpchg,35,all
esel,all
ldread,temp,,,360,,thermal.rth
solve
        !
time,384
esel,s,,,41,240 $mpdele,ex,16  $mpchg,17,all
esel,all
esel,s,,,241,440 $mpdele,ex,35  $mpchg,36,all
esel,all
ldread,temp,,,384,,thermal.rth
solve
        !
time,408
esel,s,,,41,240 $mpdele,ex,17  $mpchg,18,all
esel,all
```

```
esel,s,,,241,440 $mpdele,ex,36  $mpchg,37,all
esel,all
ldread,temp,,,408,,thermal.rth
solve
         !
time,432
esel,s,,,41,240 $mpdele,ex,18  $mpchg,19,all
esel,all
esel,s,,,241,440 $mpdele,ex,37  $mpchg,38,all
esel,all
ldread,temp,,,432,,thermal.rth
solve
         !
time,456
esel,s,,,41,240 $mpdele,ex,19  $mpchg,20,all
esel,all
esel,s,,,241,440 $mpdele,ex,38  $mpchg,39,all
esel,all
ldread,temp,,,456,,thermal.rth
solve
         !
time,480
esel,s,,,41,240 $mpdele,ex,20  $mpchg,21,all
esel,all
esel,s,,,241,440 $mpdele,ex,39  $mpchg,40,all
esel,all
ldread,temp,,,480,,thermal.rth
solve
         !
time,504
esel,s,,,241,440 $mpdele,ex,40  $mpchg,41,all
esel,all
ldread,temp,,,504,,thermal.rth
solve
         !
time,528
esel,s,,,241,440 $mpdele,ex,41  $mpchg,42,all
esel,all
ldread,temp,,,440,,thermal.rth
solve
         !
time,552
esel,s,,,41,240 $mpdele,ex,21  $mpchg,22,all
esel,all
esel,s,,,241,440 $mpdele,ex,42  $mpchg,43,all
esel,all
ldread,temp,,,552,,thermal.rth
solve
         !
time,576
esel,s,,,241,440 $mpdele,ex,43  $mpchg,44,all
```

```
esel,all
ldread,temp,,,576,,thermal.rth
solve
    !
time,600
ldread,temp,,,600,,thermal.rth
solve
    !
time,624
ldread,temp,,,624,,thermal.rth
solve
    !
time,648
esel,s,,,241,440 $mpdele,ex,44  $mpchg,45,all
esel,all
ldread,temp,,,648,,thermal.rth
solve
    !
time,672
esel,s,,,41,240 $mpdele,ex,22  $mpchg,23,all
esel,all
ldread,temp,,,672,,thermal.rth
solve
    !
time,696
ldread,temp,,,696,,thermal.rth
solve
    !
time,720
ldread,temp,,,720,,thermal.rth
solve
    !
time,744
ldread,temp,,,744,,thermal.rth
solve
    !
time,768
esel,s,,,241,440 $mpdele,ex,45  $mpchg,46,all
esel,all
ldread,temp,,,768,,thermal.rth
solve
    !
time,792
ldread,temp,,,792,,thermal.rth
solve
    !
time,816
ldread,temp,,,816,,thermal.rth
solve
    !
time,840
```

```
ldread,temp,,,840,,thermal.rth
solve
          !
time,864
ldread,temp,,,864,,thermal.rth
solve
          !
time,888
ldread,temp,,,888,,thermal.rth
solve
          !
time,912
ldread,temp,,,912,,thermal.rth
solve
          !
time,936
ldread,temp,,,936,,thermal.rth
solve
          !
time,960
ldread,temp,,,960,,thermal.rth
solve
          !
save
finish
```

IMAGE EVALUATION TEST TARGET (QA-3)



150mm

6"

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