Ain Shams University
Faculty of Engineering
Department of Structural Engineering

Development of Finite Element Analysis for Coupled Thermal and Stress Analysis for Conventional Gravity Concrete Dams

A THESIS

Submitted in Partial Fulfillment for the Requirements of the Degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

Submitted by

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June 2014

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STATEMENT

This dissertation is submitted to Ain Shams University for the Degree of Master of Science in Civil Engineering (Structural Engineering.)

The work included in this thesis was carried out by the author in the Department of Structural Engineering, Faculty of Engineering, Ain Shams University, Cairo, Egypt.

No part of this thesis has been submitted for a degree or a qualification at any other university or institution.

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ACKNOWLEDGEMENT

I would like to thank my dear supervisor **Prof. EzzeldinYazeed** for his help and advice.

I am grateful to **Prof. Amr Ali Abdelrahman** for his support.
I would like to extend my gratefulness to my **Professor and dear father Prof. Ayman Embaby** for his valuable advices and encouragement**.**

Finally, I want to express my regards and thanks to my mother for her continuous encouragement and advice all over my life since my first steps in school until now.

Abstract

Development of Finite Element Aanalysis for Coupled Thermal and Stress Analysis for Conventional Gravity Concrete Dams.

Rana Ayman Abo-El Fetuoh Embaby

Master of Science Thesis

Structural Engineering Departement

Ain Shams University

During the process of setting out and hardening of concrete, the temperature profile shows a gradual nonlinear distribution due to development of heat of hydration. At early ages of concrete structures, this non-linear distribution has a large influence on crack evolution.

It is thus important to study the factors affecting the amount of heat generated in the hydration heat process to minimize it as much as possible in order to prevent the generation of undesired cracks through the dam's body. Finite element analysis has been performed on a real full scale dam to determine the impact of changing the time intervals of concrete placing schedule on the thermal/stress response of dam. Many other factors have also been investigated such as the concrete construction schedule, the cement content which also affects the maximum adiabatic temperature and the effect of the ambient temperature. A mass gradient temperature analysis via ACI guidelines is adopted as a first step to specify adequate construction joints. Then, the finite element coupled thermal-stress is performed using thermal and static boundary conditions to investigate the temperature emission and the generated stress within the dam. The most effective factors that govern the emission of heat due to hydration which should be considered by the designers are specified to decrease the tensile stresses generated due to heat of hydration.

Finally, recommendations based on this numerical investigation is generated which would benefit both the researcher and the practicing engineer.

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Chapter 1 Introduction

1.1 General

Basically, gravity dams are solid concrete structures that maintain their stability against design loads from their geometric shape, mass and strength of concrete. They are normally constructed on a straight axis, but may be slightly curved or angled to accommodate specific site conditions. The two general concrete construction methods for concrete gravity dams are conventional placed mass concrete and Roller Compacted Concrete (RCC). The most important characteristics of mass concrete that differentiate its behavior from that of structural concrete is its thermal behavior. The large size of mass concrete structures creates the potential for large temperature changes in the structure and significant temperature differentials between the inner and the outer surfaces of the structure. The accompanying volume-change differentials and restraints result in tensile strain and stresses that may cause cracking detrimental to structure design, the serviceability and appearance of the dam.

All concrete elements and structures experience volume change in varying degrees depending on the construction, configuration and environment of the concrete. Uniform volume change will not produce cracking if the element or the structure is relatively free to change volume in all directions. This is rarely the case of concrete gravity dams because size alone usually causes non uniform change, and there is often sufficient restraint either internally or externally to produce cracking.

Thus, the rate and amount of heat generation are the most important aspects to be studied as they can have adverse effects on the strength, the durability and permeability of the dam. Stresses due to heat of hydration are classified as internal constraining stress and external constraining stress. The internal constraining stress results from the restraining effect of volumetric changes due to different temperature distribution as a result of the primary damage mechanism which is delayed ettrengite formation (DEF). DEF can cause internal expansion and cracking of concrete, which may not be evident for several years after placement. For instance, at the initial state of hydration, temperature differences between the surface and inner parts results in surface tension. Where at later stages, contracting deformations in the inner parts are greater than those at the surface, thereby resulting in tension stresses in the inner parts. Eventually the magnitude of internal constraining stress is proportional to the temperature difference between the surface and inner parts.

On the other hand, external constraining stress is caused by restraining the volumetric change of fresh concrete in contact with subsoil or the substrate of previously cast concrete. The change in concrete heat results in the change of volume, and the restraining effect is dependent on the contact area and the stiffness of the external constrains objects.

In order to maintain the serviceability and the strength conditions in concrete gravity dams, cracks should be minimized in number and width. The costs of achieving this goal should be considered. The change in volume can be minimized or controlled by such measures as reducing cement content by introducing some pozzolanic materials, fly ashes or additives, or precooling, post cooling, insulating to control the rate of heat absorbed or lost, and/or by other temperature control measures.

By appropriate consideration of the preceding measures it is possible to control cracking or at least minimize the crack widths via pre-specified contraction joints that reduce the number of uncontrolled cracks.

The contraction joints spacing can be obtained conceptually depending on a mass gradient analysis taking into consideration the material properties, the placing temperature of concrete, the adiabatic temperature, the geometry of dam and the ambient temperature.

Relatively, the optimization of the contraction joints' spacing and the maximum placing temperature depends upon a considerable number of factors which should not be treated in isolation; among these factors:

- Method of construction.
- Concrete placement schedule
- Components /mix properties.
- Maximum concrete placing temperature.
- Environmental (ambient) conditions at the site.
- Concrete adiabatic temperature.
- Dam geometry and size.

In mass concrete, thermal strains and stresses develop by a change in mass concrete volume. The volume change that leads to thermal cracking is due to the temperature difference between the peak temperature of the concrete attained during early hydration (normally within the first week following placement) and the minimum temperature to which the element will be subjected under service conditions. Thus, the maximum allowable concrete temperatures and temperature differences are often specified to ensure that proper planning occurs prior to concrete placement. In many cases, the specified limits are seemingly arbitrary and do not consider project specifications. As an example of this certain project specifications is limiting the maximum concrete temperature difference to 135°F (57°C), and the maximum concrete temperature difference to 35°F(19°C). In many situations, limiting the temperature difference to 35°F (19°C) is overly restrictive; thermal cracking may not occur even at higher temperature differences. In other cases, significant thermal cracking may still occur even when the temperature difference is less than 35°F (19°C). The maximum allowable temperature difference is a function of concrete mechanical properties such as thermal expansion, tensile strength and elastic modulus, as well as the size and restraints of the concrete element. (ACI 207.2R-95) provides guidance on calculating the maximum allowable temperature difference to prevent thermal cracking based on the properties of the concrete and for specific structure. Other restrictions are often included, such as limits on the maximum and minimum temperatures of delivered concrete. At early stages of concrete, the modulus of elasticity of concrete is so small thus the compressive stresses induced due to rise in temperature are insignificant even in zones of full restraint (base of dam/foundation), a realistic analysis assumption can be assumed for a condition of no initial stresses.

The tensile stress and cracking can be reduced to zero if the initial temperature of the concrete is set below the final stable temperature of the structure by the amount of potential temperature rise, theoretically this is possible; however it is not practical except in hot climates.

In this thesis, a numerical investigation on the effect of heat generated mainly from hydration of cement and ambient temperature regarding conventional concrete gravity dams.

1.2 Objectives of the Present Investigation

The objectives of this investigation can be summarized as follow:

- Evaluation of the internal thermal stresses and temperature of concrete gravity dams using a numerical model and performing a numerical analysis on sample concrete dams in order to scrutinize the internal thermal stresses and temperature. The main criteria adopted in estimating the joint spacing and the construction sequence