

Three Dimensional Nonlinear Temperature and Structural Analysis of Roller compacted Concrete Dam

J. Noorzaei¹, K.H. Bayagoob², A.A. Abdulrazeg¹, M.S. Jaafar¹
T.A. Mohammed¹

Abstract: This paper focuses on the development, verification and application of a three-dimensional finite element code for coupled thermal and structural analysis of roller compacted concrete dams. The Kinta RCC gravity dam, which is the first roller compacted concrete dam in Malaysia, has been taken for the purpose of verification of the finite element code. The actual climatic conditions and thermal properties of the materials were considered in the analysis. The structural stress analysis was performed using the elasto-plastic stress analysis. The Mohr yield criterion which is widely used for concrete plasticity modeling was adopted in this study. The results have shown that, the elasto-plastic analysis can redistribute the state of stresses and produces a more realistic profile of stresses in the dam.

Keywords: Roller compacted concrete dams, Elasto- plastic Analysis; Finite element modeling.

1 Introduction

Research work on roller compacted concrete (RCC) dams started from 1960. From this date until now, many models have been proposed to predict realistic short and long term evaluations of the risk of the thermally induced cracking in these constructions. The proposed models range from low levels of the approximate methods to highly accurate levels using the two and three dimensional sophisticated finite element analysis.

Tarto and schrader (1985) discussed the necessary steps for performing a complete thermal study for a simple dam structure. The incremental construction concept is incorporated into the model by assigning material placement times relative to a common time of origin to each defined mode element. The environmental air temperature during the period of analysis was approximated in this work.

¹ University Putra Malaysia, UPM-Serdang, Malaysia

² Hadhramout University, Hadhramout, Yemen

Ishikawa (1991) discussed the procedure for applying the finite element software ADYNA to the thermal stress analysis of concrete structures. The birth and death of elements technique has been used in order to simulate the construction processes. In this study, only thermal analysis was carried out and variation of the elastic modulus with time is considered.

Saetta et al. (1995) presented a finite element procedure for the stress-strain analysis in concrete structures exposed to time-variable environmental conditions. In this study, the thermal analysis was taken into account. However, only linear elastic structural analysis was carried out where the variation of the elastic modulus with time is not taken into account.

Crichton et al. (1999) presented a simplified thermal and structural analysis of Kinta RCC dam. The analysis is 2-D linear and multi-linear elastic analysis and 3-D preliminary analysis in which the ambient air temperature is kept constant through the whole year. The effect of the reservoir water on the thermal response of the dam was approximated by assigning a temperature of 25 °C to upstream face.

Schrader and Rashed (2002) studied the effect of using the non-linear stress-strain properties in the analysis of RCC dam. The study results show that, when the strain softening and the true non-linear stress-strain behaviour of RCC is considered in stress analyses of RCC dams, the true stress condition will be obtained which leads finally to a reduction in the peak tensile stresses and uniform stress distribution at the foundation. The study ignored the thermal loads which are very dominant in the analysis of RCC dams.

In the previous work, the authors [Jaafar et al. (2004)] developed a finite element computer code for the determination of temperatures within the dam body. The finite element code was then applied to the actual full-scale problem to determine the impact of the placement schedule on the thermal response of RCC dam. Only thermal analysis was considered in this study.

Noorzaei et al. (2006) focused on the application and verification of a two-dimensional finite element code developed for the thermal and structural analysis of RCC dams. The predicted temperatures obtained from the finite element code were found to be in good agreement with actual temperatures measured in the field using thermocouples installed within the dam body. The linear stress strain relationship was adopted for the structural part.

Sethuraman and Rajesh.(2009) suggested that, in order to predicate the real behavior and expected damage during the life time of a structure, elastic plastic analysis is required.

The nonlinear phenomena in the structural response of RCC dams have not been addressed sufficiently, partly because of the complexity of the problem and the ex-

tensive computational effort required to carry out the coupled thermal and structural time increment analysis.

In this study, which is a continuation of the authors' previous work, the finite element code has been modified to three dimensional which is capable to perform nonlinear elasto-plastic analysis.

2 Computation of Thermal Field

The general partial differential equation governing heat flow in a three-dimensional solid medium is expressed as [Incropera and DeWitt (2002)]:

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial T}{\partial z} \right) + \dot{Q} = \rho c \frac{\partial T}{\partial t} \quad (1)$$

where T is the solid temperature ($^{\circ}\text{C}$); k_x , k_y , and k_z are the concrete conductivity coefficients in x , y and z directions respectively ($\text{W/m}^{\circ}\text{C}$); \dot{Q} is the rate of the heat introduced per volume (W/m^3); ρ is the material density (kg/m^3); and c is the solid specific heat ($\text{J/kg}^{\circ}\text{C}$).

Two main types of boundary conditions are Dirichlet and Cauchy boundary, which can be written respectively as [Sergerlind (1984)]:

$$T = T_p \quad (2a)$$

$$k_x \frac{\partial T}{\partial x} l_x + k_y \frac{\partial T}{\partial y} l_y + k_z \frac{\partial T}{\partial z} l_z + q + h(T_s - T_f) = 0 \quad (2b)$$

where T_p is the known values of the nodal temperatures on the boundaries; q is flowing heat from surface; h is the film coefficient; T_s is unknown temperatures at the boundary nodal points; T_f is the ambient temperature; l_x , l_y and l_z are the direction cosines of the outward normal to the surface under consideration [Noorzaei et al.(2006)].

3 Constitutive Modelling

The plastic behavior of a material is defined by an irreversible straining which can only sustain once a certain level of stress. This level of stress is determined by a suitable yield condition. Therefore two laws are necessary to predict the response in the elasto-plastic analysis, one before onset of the plastic yielding and the other after the yielding takes place. [S.Y. Long et al.(2008)]

Mohr-Coulomb criterion is widely used in the elasto-plastic analysis of concrete dams [Azmi and Paultre (2002)]. Thus this criterion is used in the present study to

define the yield surface. Meanwhile, perfect plasticity idealization is adopted, the equation of the yield surface of this criterion is given by [Zienkiewicz (1989)]:

$$F(\sigma) = \frac{1}{3}I_1 \sin \phi + \sqrt{J_2} \left[\sin \left(\theta + \frac{\pi}{3} \right) + \frac{1}{\sqrt{3}} \cos \left(\theta + \frac{\pi}{3} \right) \sin \phi \right] - c \cos \phi = 0 \quad (3)$$

Where c is the cohesion, ϕ is the angle of internal friction, I_1 is the first invariant of the stress tensor, J_2 is the second invariant of the deviatoric stress tensor, θ is the angle of similarity.

4 Computational Algorithm for Elasto-Plastic Analysis

After thermal analysis is performed for every stage of construction, the structural analysis of the RCC dam is preformed immediately [Noorzaei et al.(2006)]. The thermal strain due to temperature changes are converted into equivalent nodal force and added to the dam self weight and other external load acting on the dam body .The incremental-iterative procedure has been adopted for the nonlinear finite element elasto-plastic analysis of RCC dams. The computational procedures are outlined as below:

Step (i); the load is applied in several load steps as increments. The displacements increments are evaluated using the tangent stiffness matrix $[K]$ of the previous increment which updated after each iteration according to the stress and strain level:

$$[K]_{i-1} \{\Delta\delta\}_i = \{\Delta F\}_i \quad (4)$$

These displacement increments are accumulated to give the total displacement at any stage of loading:

$$\{\delta\}_i = \{\delta\}_0 + \sum_{j=1}^i \{\delta\}_j \quad (5)$$

Step (ii); using strain-displacement relationship, the incremental strains $\{\Delta\varepsilon\}_i$ can be calculated by the relation given below:

$$\{\Delta\varepsilon\}_i = [B] \{\Delta\delta\}_i \quad (6)$$

The total strain $\{\varepsilon\}_i$ after i^{th} load increment are then obtained as:

$$\{\varepsilon\}_i = \{\varepsilon\}_{i-1} + \{\Delta\varepsilon\}_i \quad (7)$$

where $\{\varepsilon\}_{i-1}$ are the strains vector at the end of $(i-1)^{th}$ load increment.

Step (iii); using the incremental strains, the increment of stresses $\{\sigma\}_i$ are determined as:

$$\{\Delta\sigma\}_i = [D]_{ep} \{\Delta\varepsilon\}_i \quad (8)$$

where $[D]_{ep}$ is the elasto-plastic material rigidity matrix evaluated according to the strain $\{\varepsilon\}_{i-1}$ and stress $\{\sigma\}_{i-1}$ levels calculated at the end of the previous iteration, taken into account the yielding, loading and unloading at the Gauss point under consideration in the case of conventional solid finite elements.

The total stresses $\{\sigma\}_i$ are determined as:

$$\{\sigma\}_i = \{\sigma\}_{i-1} + \{\Delta\sigma\}_i \quad (9)$$

Several iterations are needed to bring the stresses to the yield surface in the case of occurrence of yielding at the Gauss point under consideration. An outline of this algorithm for elasto-plastic analysis is presented in Fig. 1. A finite element program is written in Fortran language which can work under power station environment.

5 Simplified Crack Analysis

In order to estimate the safety of the dam against cracking, a simplified method has been used to predict the crack width which will be compared lately with the permissible crack width. In the simplified method, the mass gradient strain is calculated by the following equation [Tarto and schrader (1992)]:

$$\varepsilon = K_R K_f \alpha \Delta T \quad (10)$$

where ε is induced strain, K_R, K_f are structure and restraint factor respectively, α is coefficient of thermal expansion, and ΔT is Temperature difference with respect to interior temperature difference.

For a given dam block width (B_w), the crack width (W_{cr}) can be calculated as:

$$W_{cr} = B_w (\varepsilon - \varepsilon_c) \quad (11)$$

where ε_c is tensile strain capacity of the roller compacted concrete.

Substituting for the value of ε from Eq. (10) in Eq. (11), the crack width can be expressed as:

$$W_{cr} = (K_R K_f \alpha \Delta T - \varepsilon_c) B_w \quad (12)$$

To determine the crack width, the following parameters are adopted from RCC materials [Tarto and schrader (1992)]:

- i. K_R and K_f the restraints coefficients K_R and K_f are conservatively assumed equal to 1.0
- ii. The value of the coefficient of thermal expansion α is taken as 8×10^{-5} .
- iii. The value of the tensile strain capacity (ϵ_c) is assumed equal to $80\mu\text{m}$.
- iv. The temperature drop ΔT from the analysis is equal to 18.0°C .
- v. The permissible crack width is taken as 2.0 mm.

Furthermore, the guide line in term of crack index I_{cr} suggested by [Noorzaei et al.(2006)] has been used to assess the crack occurrence for linear analysis

$$I_{cr} = \frac{F_{cr}(t)}{\sigma(t)} \geq 1.0 \quad (13)$$

6 Kinta Dam Analysis

Kinta RCC is the first RCC gravity dam in Malaysia. The maximum height of the dam is 78 m and the crest length is 700 m. The construction of the dam started in September 2004 and finished in April 2006. The progress of the dam construction with respect to time is shown in Fig. 2. The block width is set equal to 20 m in the design of Kinta dam.

7 Material Properties and Site Conditions

The material properties for the RCC, the conventional concrete (CVC), and the rock foundation, are given in Table.1 [SUNGAI Kinta dam(2002)]. These properties, which are the actual properties supplied by the consulting company, are used in the analysis as an input data. The recorded hourly environmental temperatures at the site given in Fig.3 are used in the thermal analysis for the simulation of heat transfer by convection action. The cementitious content of the RCC mix used in the dam's construction are 100 kg/m³ of Ordinary Portland Cement and 100 kg/m³ of Fly Ash.

The effect of solar radiation during construction was incorporated by allowing an increase in ambient temperature of 1.0 °C to account for the solar radiation heating of the concrete surface.

8 Finite Element Modeling

The 3D finite element mesh model of the deepest dam block is shown in Fig.4. Twenty-noded isoparametric elements are used in the analysis. The mesh of the dam body is generated in such a way to simulate the construction phase.

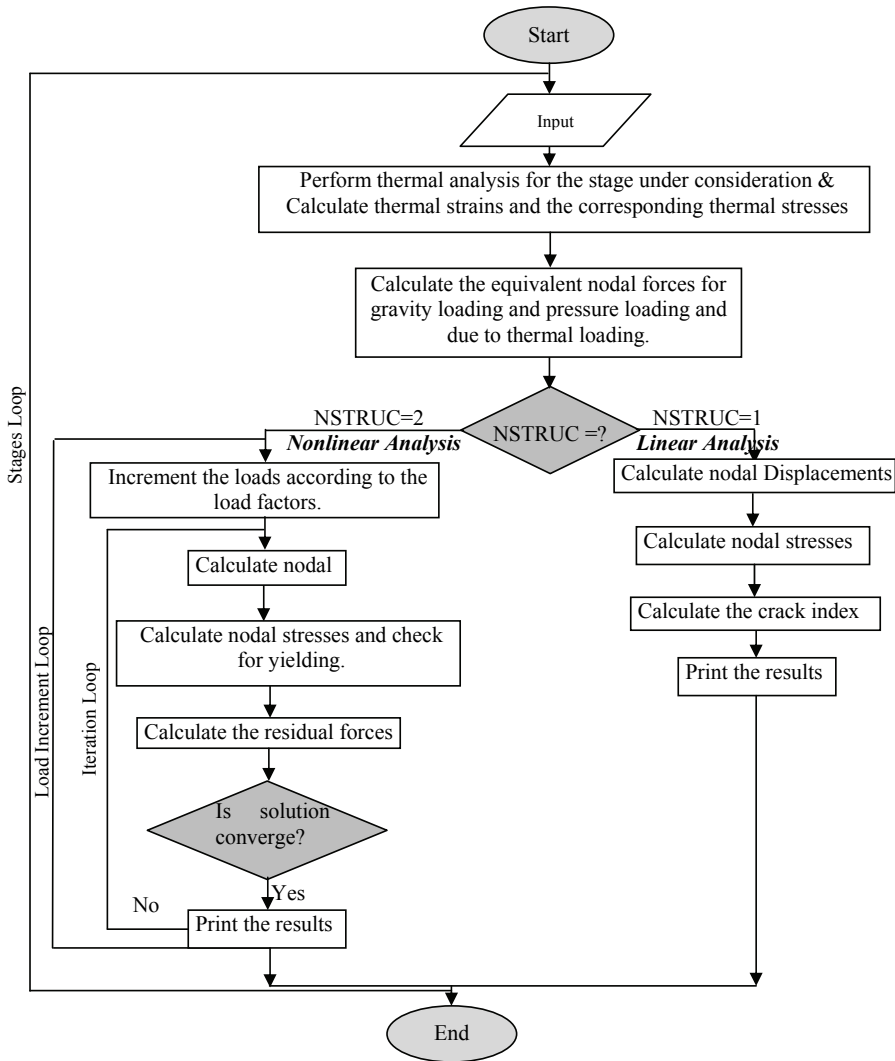


Figure 1: Flow chart of three dimensional linear and elasto-plastic structural analysis

9 Results and Discussion

9.1 Thermal Response

The 3D finite element code that was developed for the thermal and structural analysis of RCC dam has been verified by comparing the predicted temperatures with

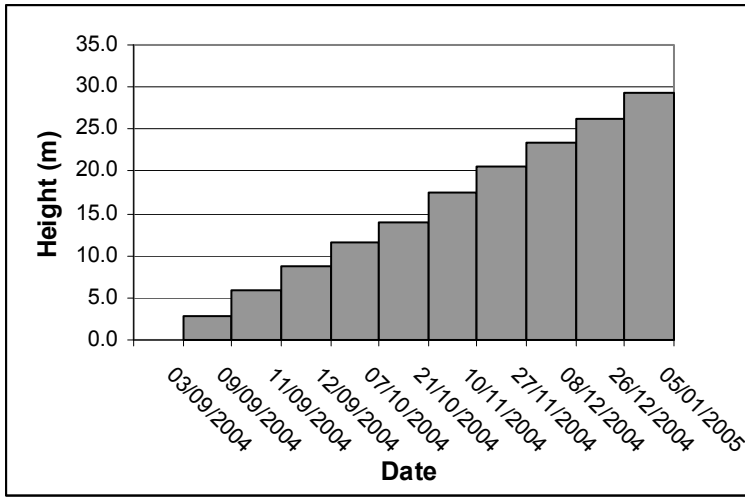


Figure 2: Kinta dam construction progress up to stage No. 10

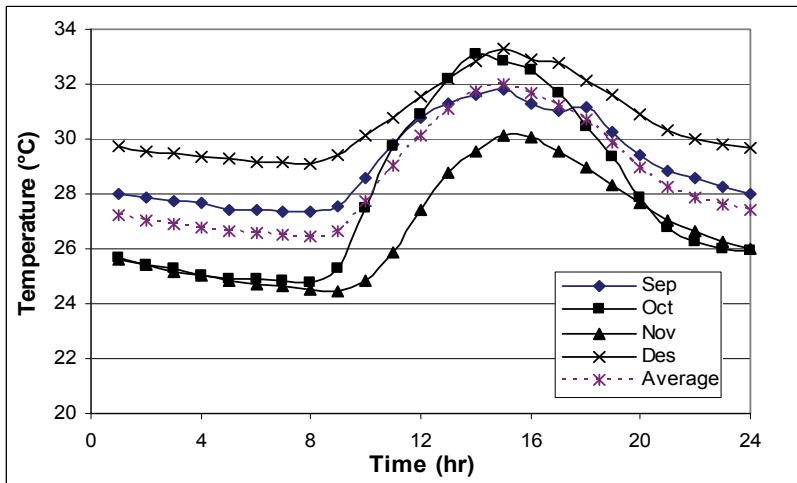


Figure 3: Monthly and average recorded daily temperatures at the Kinta dam Site

actual temperatures recorded by thermocouples installed in the dam’s body. The thermocouple locations which are installed at some selected levels in the deepest block of the dam are shown in Fig.5.

The comparison between the three dimensional finite element predicted temper-

Table 1: Thermal and structural properties of Kinta dam

Material	RCC	CVC	Rock	Water
Heat conduction coeff. K (W/m °C)	2.7	2.7	2.97	0.615
Heat convection coeff. h (W/m ² °C)	8.0	8.0	8.0	20.0
Specific heat c (J/kg °C)	1150	1150	800	4180
Density ρ (kg/ m ³)	2325	2325	2650	997
Elasticity modulus E (MPa)	18200	25700	24000	–
Poisson ratio ν	0.2	0.2	0.2	–

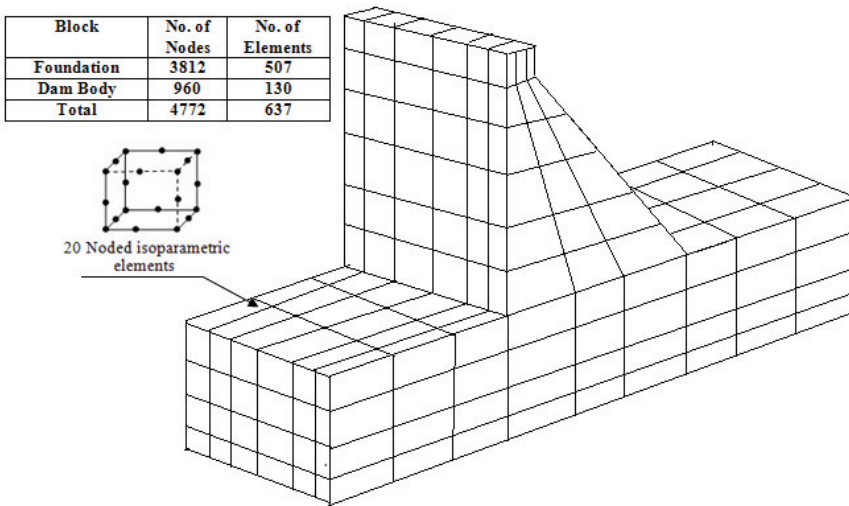


Figure 4: 3-D Finite Element mesh

atures and the monitoring temperatures from the thermocouples installed at the elevations 169 m and 179 m are shown via Figs. 6 and 7 respectively. It is clear from these plots that, the predicted temperatures obtained from developed code (3D analysis) are in good agreement with monitoring temperatures.

After verifying the developed code for the three dimensional thermal analysis, the thermal analysis is performed up to the last stage to be constructed using construction schedule shown in Fig. 5 and the average daily environmental temperature measured at the project site as shown in Fig. 3. The 3-D isothermal contour plot at the end of the dam construction is shown in Fig. 8. The plot shows that, the higher temperature zone is at the center of the dam body with maximum predicted

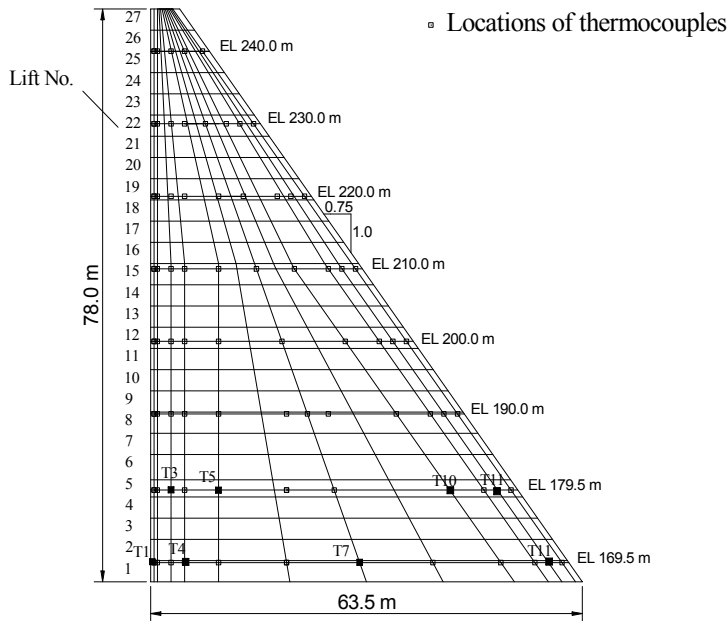


Figure 5: Thermocouples Locations of the Kinta dam deepest block

temperature of 42 °C, which gradually decreased to reach approximately the air temperature at the boundaries. In addition there is dissipation of the heat from the dam body to the rock foundation in the region lying just beneath the dam body.

9.2 Non-Linear Elasto- Plastic Structural Response of Kinta RCC Dam

After performing the 3-D thermal analysis, the structural stress analysis of the Kinta RCC dam is performed using the elasto-plastic stress analysis. The Mohr yield criterion which is widely used for concrete plasticity modeling is adopted in this study.

Table 2: Elasto-plastic material properties

Material	RCC	CVC	Rock
Cohesion <i>c</i> (MPa)	5.04	4.74	2.37
Friction Angle (deg.)	47.6	54.9	54.9

The elasto-plastic principal stress contours plots after a period of five years after finishing the dam construction are shown in Figs. 9. a-c.

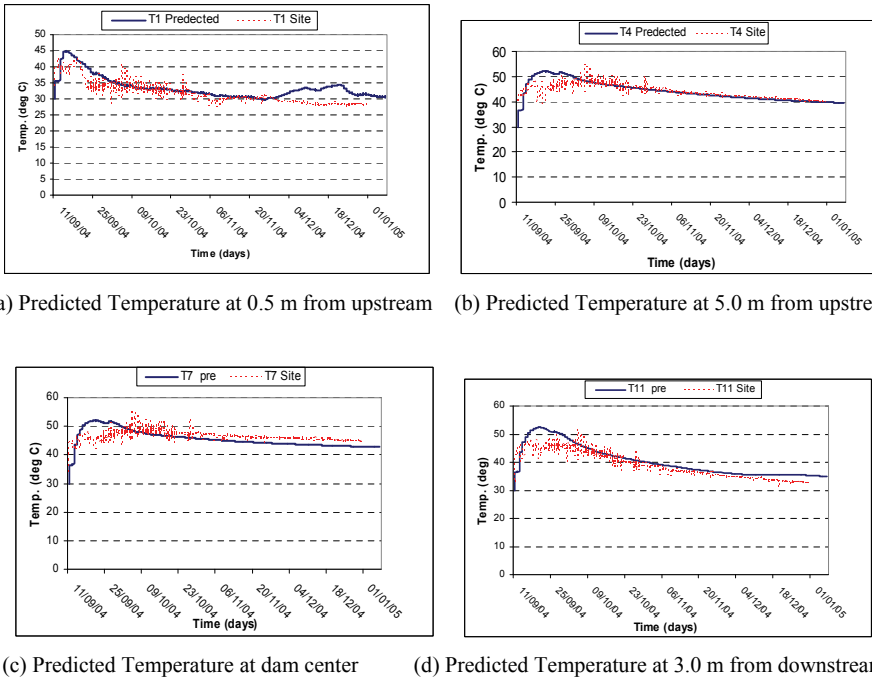


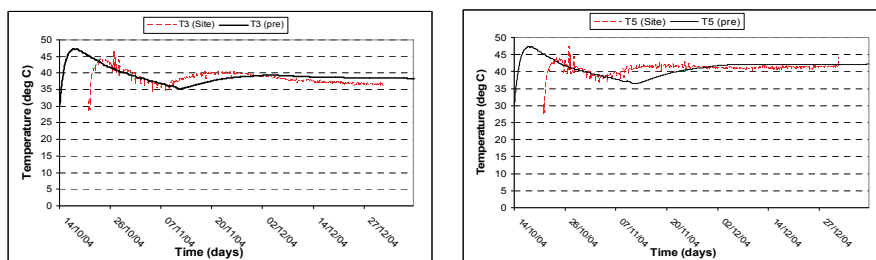
Figure 6: Comparisons between predicted and monitoring temperatures at level 169.5 m

The comparison between linear and elasto-plastic result are shown in Fig.10.a-b. It can be clearly observed from these plots that the affect the elasto-plastic analysis in reducing the final stresses compared to that obtained from the 3-D linear analysis. This is due to the redistribution of stresses in the elasto-plastic analysis. The comparison between the linear and the nonlinear elasto-plastic stresses are tabulated in Table 3.

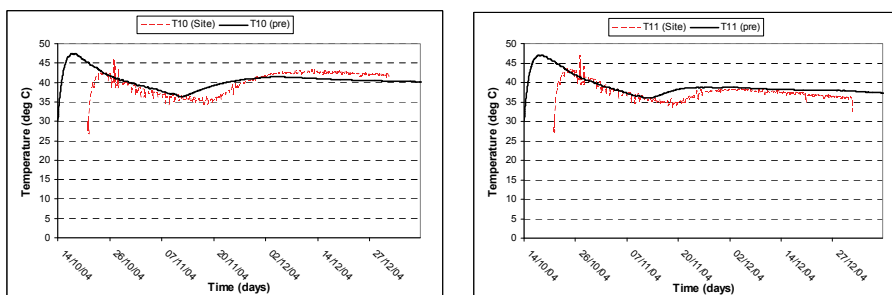
Table 3: Comparison of linear and elasto-plastic stresses

Stress (MPa)	Linear		Elasto-Plastic	
	Max.	Min.	Max.	Min.
σ_1	5.0	-2.0	3.0	-1.0
σ_2	2.0	-5.0	1	-3.0
σ_3	1.0	-8.0	0	-6.0

Fig. 11. shows the number yielded Gaussian points per the load increments. The



(a) Predicted Temperature at 0.5 m from upstream (b) Predicted Temperature at 5.0 m from upstream



(c) Predicted Temperature at 10.0 m from upstream (d) Predicted Temperature at 3.0 m from upstream

Figure 7: Comparisons between predicted and monitoring temperatures at level 179.5 m

yielding starts from the load increment number 8 with smoothly increasing manner then sudden increase occurs at the load increment number 18 where 165 points have been yielded and 345 points have yielded in the final load increment.

Fig.12 shows the yielded pattern in the final load increment which marked by ellipse. This yielded region located at the dam bottom (first lift) which may due to highly constraints from the rock foundation.

In order to assess the safety of the dam against cracking, the crack width has been predicted according to the simplified method presented in section 5.

Based on this method the predicted crack width (W_{cr}) (Eq.12) is equal to the permissible crack width, so the dam is consider safe against crack.

The crack index is determined at the end of every stage of thermal analysis, this parameter is time dependent and evaluated at the Gaussian points based on (Eq .13), which depends on the instantaneous RCC tensile strength, $f_{ct}(t)$.

The dam will be considered safe against cracking when the crack index is greater

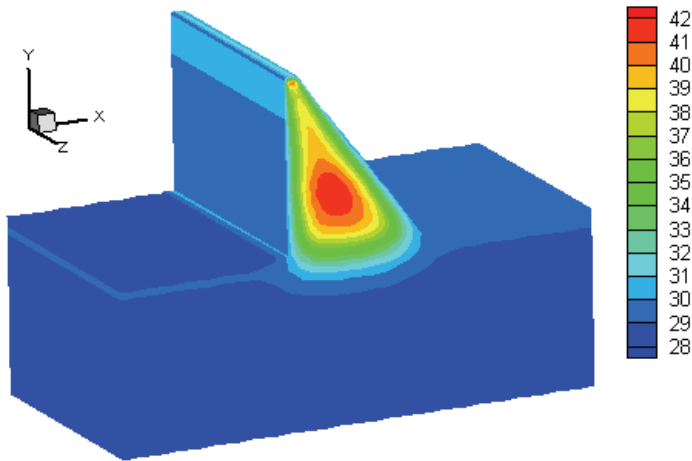


Figure 8: Temperature distribution after completing the dam construction

than 1.0. Fig.13. shows the variation in the crack index with time. It is clear from the plot, that, special attention must be paid to the zone located downstream, since the crack index drops below the allowable limit, where this zone is coincide with yielding region from the elasto- plastic analysis.

10 Conclusion

The present study was denoted in formulation, and development of thermal and structural analysis computer codification of three demission finite element program. The program code was validated against actual RCC dam.

Based on the limitations and assumptions used in the present study, the following points can be drawn

1. The developed finite element code is capable of simulating the thermal elasto-plastic response of RCC dams with reasonable accuracy.
2. The elasto-plastic can redistribute the state of stresses and produces a more realistic profile of stresses in the dam. Moreover, the elasto-plastic analysis could reduce significantly the high amount of overstressing noticed in the linear analysis.
3. The crack index variation can give a good indication of the probability of a crack occurring. This has clearly been observed from the compatibility to

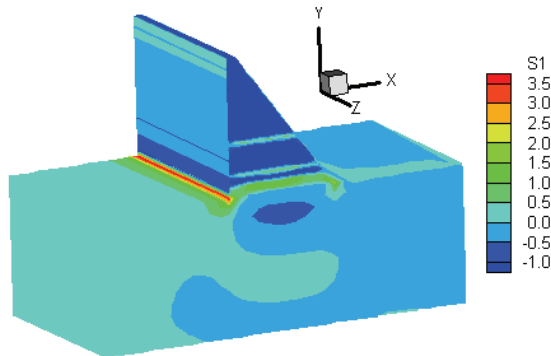
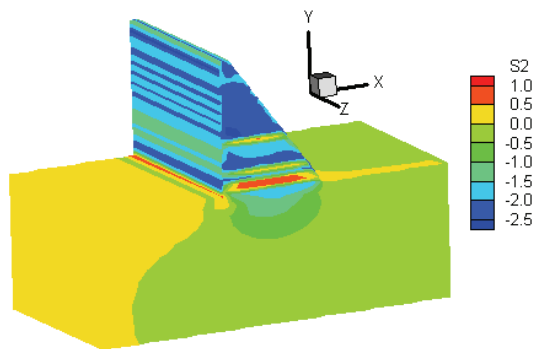
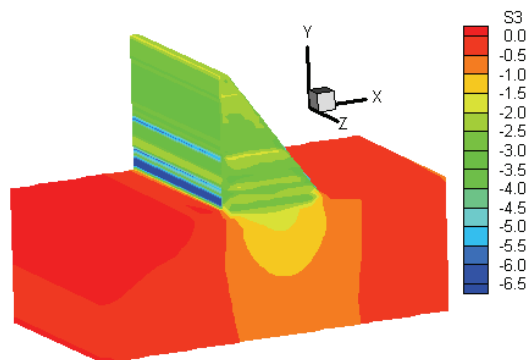
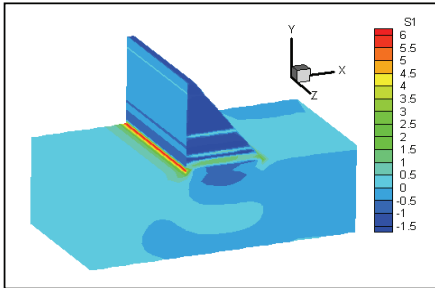
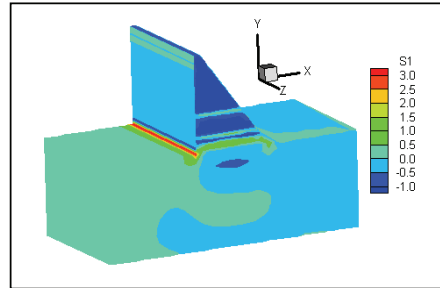
(a) Principal stresses σ_1 (MPa)(b) Principal stresses σ_2 (MPa)(c) Principal stresses σ_3 (MPa)

Figure 9: 3-D Elasto-Plastic Principal Stresses Distributions after 5-Years of Dam Construction Due to 1 Load Factor

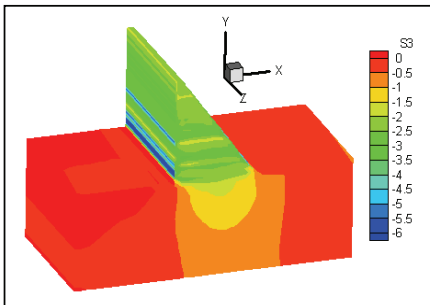


i. Linear Analysis

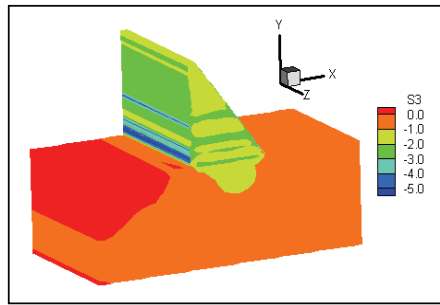


ii. Elasto-Plastic Analysis

(a) Principal stresses σ_1 (MPa)



i. Linear Analysis



ii. Elasto-Plastic Analysis

(a) Principal stresses σ_3 (MPa)

Figure 10: Comparison between linear and elasto-plastic stresses

elasto-plastic analysis where the probable cracked region from crack index coincides with yielding region from the elasto-plastic analysis.

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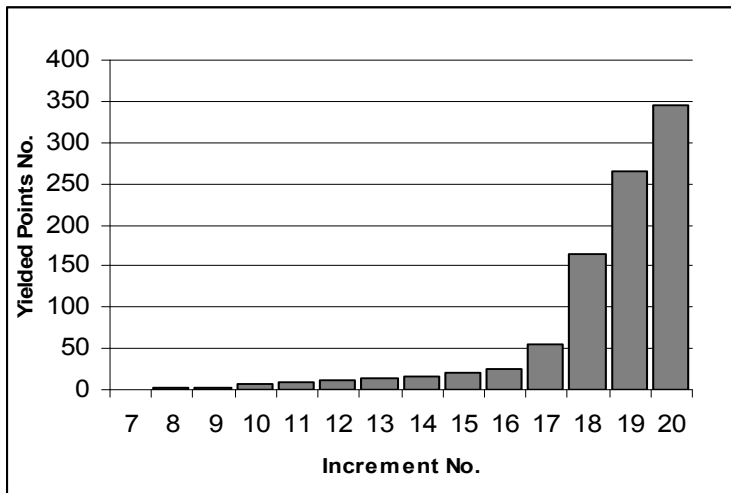


Figure 11: No. of Yielded Nodes per Load Increments due to Elasto-plastic Analysis

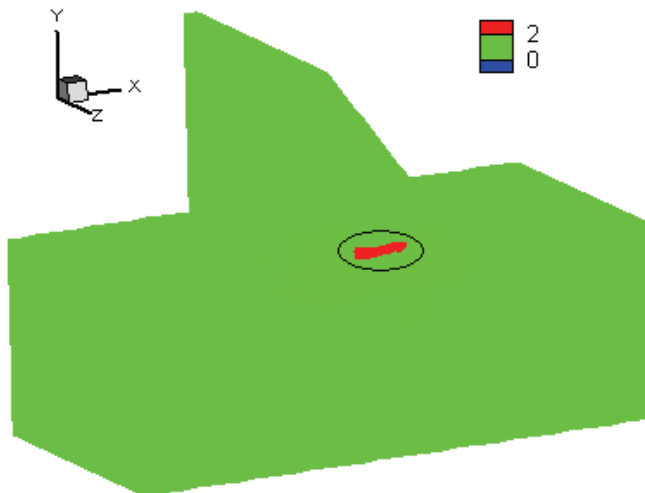


Figure 12: Elasto-plastic Yielded Contours

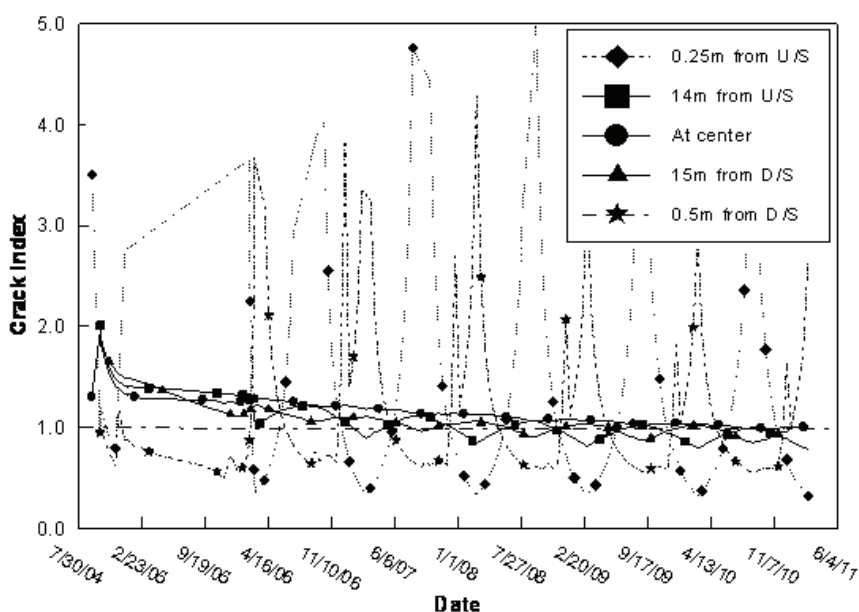


Figure 13: Variation of the Crack Index at the Dam Bottom using 3-D model

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