Thermal Stress Analysis of a Dam Wall by Finite Element Model

First L. K. Gudukeya and Second C. Mbohwa

***Abstract* - Arch dams are designed for the same loads as other dams with the exception of the temperature load, which has a significant influence in arch dam design as compared to gravity dam design. In concrete arch dams, because of the particular geometry, solar radiation shares of exposed surfaces vary spatially through downstream face. In this case, three-dimensional temperature distribution analysis is unavoidable. When a transient heat transfer analysis is performed in a dam safety evaluation, it would be convenient to identify the most critical time to carry out a complete stress analysis. To investigate the seismic safety of concrete dams, it is essential to quantify the static state of stress and strain that exist at the time the earthquake occurs, which may vary significantly from winter to summer conditions. In this paper, a three dimensional finite element model implemented in ABAQUS is used for simulating the temperature behavior in operational phase of typical arch dam. Then an elastic analysis is carried out and the associated thermal stresses are calculated and combined with other static loadings (self-weight and hydrostatic) and dynamic one. For dynamic analysis, a coupled system of dam and reservoir is considered. The static loads are compared and combined with earthquake load. Results show significant thermally induced tensile stresses in the crest region and at the downstream face of the dam, which is the most vulnerable zone for seismic induced damage. At the upstream face, due to the effect of reservoir water, the thermal tensile stresses have small magnitude while dynamic stresses are excessively increased.**

***Index Terms* - Concrete Arc bridges, Finite Element Analysis, Thermal Analysis, ABAQUS**

I. INTRODUCTION

Concrete arch dams in operation are permanently subjected to thermal action due to seasonal temperature variation [2].

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L K Gudukeya D.Eng Candidate, University of Johannesburg, Faculty of Engineering and the Built Environment, Auckland Park Campus, Auckland Park 2006, P.O Box 524, Johannesburg, South Africa.

Lecturer; University of Zimbabwe, Department of Mechanical Engineering, P.O Box MP167, Mt Pleasant, Harare, Zimbabwe loicekmg@gmail.com

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C Mbohwa Professor and Supervisor, Quality and Operations Management Department, University of Johannesburg, Auckland Park Bunting Road Campus, P. O. Box 524, Auckland Park 2006, Room C Green 5, Johannesburg, South Africa. cmbohwa@uj.ac.za

The variation in seasonal temperatures and climatic conditions has significant influence in temperature field patterns that are observed within arch dams. Most deterioration in arch dams has been observed to be a result of temperature loading [4].The temperature loads are modelled in finite element computational software which comes in various packages. Temperature modelling largely depends on the thermal conductivity of concrete, coefficient of thermal expansion, diffusivity and specific heat. To study the performance of operational concrete arch dams, static and dynamic analyses are both considered. In static analysis, the focus is on temperature field patterns, stresses and displacements. In dynamic analysis, the focus is to obtain the dynamic properties if the dam and responses of the dam to dynamic forces such as seismic action.

This research is aimed at formulating a finite element model, taking into consideration the non-homogeneity of heat generation within concrete, to accurately predict the distribution of temperature in a hydrating concrete mass, the resulting thermal gradients and associated thermal stresses and strains. Knowledge of these phenomena will allow for a reasonably accurate prediction of the location and potential for cracking of concrete.

Finite element modelling techniques have been used efficiently in previous research to carry out temperature assessment of concrete dams. However, no much study has been carried out in assessing the effect of seasonal temperature variation on the static and dynamic properties of concrete arch dams in operation, by using a three dimensional finite element model.

Furthermore, the effect of temperature gradient on the static and dynamic performance of concrete dams has not been studied. Examples of previous research that include temperature related analysis are cited below. Abdullah et al. [1] used a 3D finite element model to perform coupled thermo-structural analysis on gravity dams. Agullo et al. [2] used a one dimensional finite element difference system to model the thermal behaviour of different dam sections with variable thickness at selected elevation. Adrian et al [8] created a finite element model for the prediction of thermal stress in mass concrete. The modelling involved thermal parameters of concrete, geometry and site topology.

Fig1: Kariba concrete arch dam

Kariba Dam, shown in Fig 1, constructed in the period 1955–59, is one of the largest dams in the world. The dam was constructed on the Zambezi River, at grid reference 28.74778oE and 16.51222o S, along the border between the countries of Zambia and Zimbabwe (called respectively Northern and Southern Rhodesia during the colonial times) and is jointly owned by the two countries. Kariba was designed as a single purpose hydropower project, but as it turned out both fishery and tourism became important benefits.

The main technical characteristics are as follows:

Type of Dam	Double Curvature Concrete Arch dam
Height	617m
Spillway Gates	6 gates, 8.8m wide and 9m high
Discharge Capacity of Spillway	9500m3/s
Length of Reservoir	280km
Minimum Retention Level	488.50m
Minimum Operating Level	475.50m
Total Storage	180.6km3
Live Storage	64.8km3
Maximum Surface Area	5577m2
Depth of Stilling Pool	78m
Volume of Stilling Pool	410 x 106 m3
Kariba South Bank Power Cavern	6 x 117.5MW = 705MW max capacity
Kariba North Bank Power Cavern	4 x 153.5MW = 615MW max capacity
Total Generation Capacity	1320MW

In double curvature arch dams, the temperature loading is essentially influenced by the shading effect due to the curved geometry. The shape of the valley including the surrounding topography also has an effect in the temperature field in the arch dam. The thermal static and dynamic results from the FE model are verified to validate it. This is done by comparing crest displacements from the FE model with experimental results for the combined action of thermal and hydrostatic loads. In this work the model proves to be yielding appropriate results. Consequently, analysis pertaining to Kariba Dam will be adequate to draw conclusions. In operational concrete arch dams thermal assessment is essential in performing a structural safety evaluation.

II. AIM

To develop a finite element model so as to investigate the effects of thermal stress on Kariba dam wall

III. OBJECTIVES

1. To develop and validate the finite element model Kariba Dam.
2. To investigate the effect of seasonal thermal variations on static characteristics of arch dams namely temperature distribution, stress distribution, displacements.
3. To investigate the effect of seasonal thermal variations on dynamic characteristics on concrete arch dams.
4. Investigate the effect of temperature gradient on the static and dynamic characteristics of arch dams

IV. LITERATURE SURVEY

A. TEMPERATURE EFFECT ON CONCRETE ARCH DAMS

Deterioration of concrete dams is caused by among other factors, thermal effects, with 19% cases attributed to freezing and thawing, and 9% to temperature variations [5]. Previous studies concentrated on the effect of various loading conditions namely gravity, seismic and hydrostatic loading. However, little study has been done on temperature loading conditions for evaluating the static and dynamic behavior of concrete arch dams in operation. Operational arch dams are permanently subjected to thermal action due to seasonal temperature variation which includes solar radiation, air, wind and environmental conditions. These conditions have a large influence in temperature field patterns observed within arch dams and they vary yearly. Static properties vary largely affected with seasonal temperature variation [7]. Dynamic properties have not been investigated for this effect. Temperature analysis is therefore partially evaluated for safety and performance of concrete arch dams in operation. Temperature variations are likely to cause failure in arch dams as a result of cyclic stresses during contraction and expansion of vertical and horizontal joints. There are various failure modes that are associated with temperature variation, which are assessed in relation to stresses. It makes sense to develop a discussion on thermal stress in concrete arch dams for the potential failures.

V. THERMAL STRESS ANALYSIS IN CONCRETE ARCH DAMS

Concrete follows certain temperature related changes when exposed to temperature load. It is proportionally to the coefficient of thermal expansion and therefore expands when temperature rises and shrinks when temperature drops. The expansion and contraction behaviour also depends on the support conditions. When the dam body is externally or internally constrained, volume deformation cannot occur freely, causing thermal creep stresses [7]. If the thermal creep is beyond the allowable thermal creep stress of the corresponding age of concrete, cracking occurs. The allowable creep stress is measured by the horizontal tensile stress in the dam body and is stipulated using design specifications for concrete arch dams. It is controlled by the equation presented below:

$$\sigma = \frac{E_p E_c}{K_f}$$

Where σ is the thermal creep stress caused by temperature difference. This depends on the concrete type. Class 40 and class 30 concrete have an allowable tensile strength of 1.80MPa and 1.60MPa , respectively; E_p is the ultimate tensile strain of concrete; E_c is the elastic modulus of concrete and K_f is the safety coefficient ranging between 1.3 – 1.8.

2.5 Temperature field in concrete arch dams. The temperature field in concrete dams is influenced by the conducting efficiency of the concrete [5]. The geometrical properties such as thickness and size also are also a contributing factor. For relatively thin arch dams, a linear temperature distribution from the reservoir temperature on the upstream face to the air temperature on the downstream face provides a reasonable approximation since internal heat is readily released to the environment. For thick arch dams, a nonlinear temperature distribution is suitable. It is informative to draw contrast between thin and thick concrete arch dams to understand the temperature profile involved. This allows judgment on thermally induced stresses, and the structural performance and safety before doing computational analysis.

VI. THERMAL ANALYSIS OF THE EFFECTS OF WATER TEMPERATURE

Bofang’s suggested with some small modification for prediction of water temperature was used for the reservoir temperature by using the air recorded temperatures. The water temperature T at depth y and time t becomes for the Kariba Dam as follows:

$$T(y,t) = T_m(y) + A(y)\cos(w(t - t_0 - \xi))$$

(T≥4.0 C)

With

$$T_m(y) = C + (17.6 - C)e^{(-0.04y)}$$

$$C = \frac{6-17.6g}{1-g}$$

$$g = e^{(-0.04H)}$$

$$A(y) = 13.25e^{(-0.018y)}$$

$$\xi = 65.4 - 39.42e^{(-0.0085y)}$$

$$w = \frac{2\pi}{365}$$

Where

y = depth of water (m)

t = time (day)

T(y, t) = water temperature at depth y and time t

t_0 = the day which the air temperature is maximum

H = depth of the reservoir

3.0 METHODOLOGY

While the work remains general and applicable to other arch dams, an existing arch dam was used in investigating the effect of seasonal thermal variations on dynamic characteristics of thin concrete arch dams, investigating the effect of foundation stiffness on the dynamic characteristics of concrete arch dams, validating the finite element model and using it to assess the temperature distribution, stress distribution and displacement. Kariba Dam was chosen for this work because it provides a good opportunity to carry out this investigation on a validated finite element model, since it has been monitored over its duration in operation. It was developed in a well-known finite element scientific package,

ABAQUS. The model was developed from two geometrical parts, which were merged into a single part. A decoupled analysis was chosen to carry out the objectives of this study. The decoupling involved producing two respective models for performing heat transfer analysis and later stress analysis. Fig 2 shows brief modelling steps for creating the FE model.

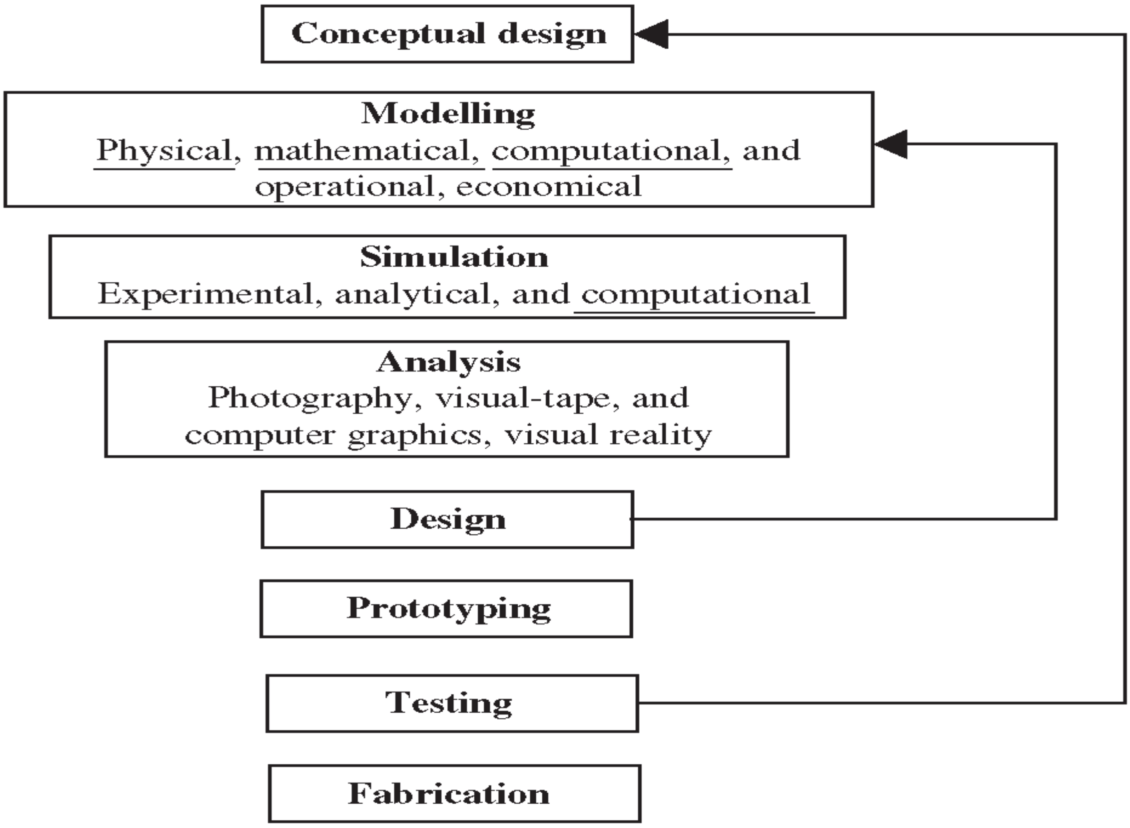


Fig 2: Development of finite element model for Kariba Dam. ((Computer Simulation, 2015)

VII. DEVELOPMENT OF FINITE ELEMENT MODEL FOR KARIBA DAM

The finite element dam model was created using a sophisticated software package called

ABAQUS/CAE. Two parts were considered in the finite element model; wall system and the foundation system.

1. Wall system
2. Foundation system
3. Complete finite element model

VIII. MESHING THE FINITE ELEMENT DAM MODEL FOR KARIBA DAM

U.S. Army Corps of Engineers [5] state that there are no established rules for selecting an optimum mesh size for subdividing an arch dam in the different surface directions. However, they recommend a good approach of defining and analysing several meshes of different element types and sizes and selecting the one that is computationally efficient and provides reasonably accurate results. A similar approach was followed in this work.

IX. THERMAL AND MECHANICAL PROPERTIES OF THE FINITE ELEMENT MODEL

Thermal and mechanical properties were assigned to the finite element model. The concrete properties were extracted from the design data provided by the Zambezi River Authority. The foundation properties were assumed based on the geology of the area near Kariba. The basic properties for performing thermal stress analysis include specific heat c, thermal conductivity k, convection coefficient h, coefficient of thermal expansion , modulus of elasticity E, density , Poisson’s ratio , solar absorptivity a, and emissivity e.

X. APPLICATION OF BOUNDARY CONDITIONS

The thermal response of the FEM dam model is determined by the application of temperature boundary conditions and energy loading. They are applied in the heat transfer decoupled model, under the load and boundary conditions modules of ABAQUS.

XI. SELECTION OF MODELLING ALGORITHM

Calibration of finite element model

Validation of finite element model of Kariba Dam

In summary, this chapter begins with the modelling process followed in developing the finite element dam model for this work. It identifies the temperature boundary conditions and how they are assigned using mathematical temperature models for solar radiation, air temperature, water temperature and foundation temperature. The selected modelling algorithm is also discussed to identify the treatment of the modelling parameters. The finite element model is calibrated and used to carry out the objectives of this study. The objectives include investigating the effect of seasonal thermal variations on dynamic characteristics on thin concrete arch dams, investigating the effect of foundation stiffness on the dynamic characteristics of concrete arch dams, validating the finite element model and using it to assess the temperature distribution, stress distribution and displacement. An investigation is further carried out on two high temperature gradients (and) to determine the thermal effects on static and dynamic analysis.

XII. RESULTS AND DISCUSSIONS

A. VALIDATION OF FINITE ELEMENT MODEL

The finite element model was initially validated for static analysis due to solar radiation, air, water and foundation temperatures. This was done by comparison of FEM displacements produced by the combined action of thermal and hydrostatic loads, with empirical data obtained over the period of operation of the dam.

The validation process involved two stages:

(i) investigating the effect of foundation stiffness properties on static analysis, which was mainly for interpolating of foundation stiffness properties that would produce minimal variation in the difference in crest displacement produced by the full and quarter-full reservoir and,

(ii) using the model with appropriated model stiffness to compare its displacement data with experimental data as means of completing the validation process of the model for static analysis , [6]. The difference in the empirical crest displacement for extreme water level conditions, that is and quarter-full), was approximately 46 mm.

A. EFFECT OF FOUNDATION STIFFNESS ON STATIC BEHAVIOUR

A full field investigation to provide an extensive definition of the variation of modulus of the deformation is costly and may not be necessary [5]. The foundations that were considered in the parameter sensitivity studies are soft and hard foundation. Eight cases of foundation moduli were studied for respective crest displacements of full dam under mainly thermal loading. The crest displacements were very sensitive to variation in foundation modulus. Low sensitivity was observed in the difference of crest displacement with change in foundation modulus. More upstream displacements are observed for a hard foundation modulus as compared to soft foundation. U.S. Army Corps of Engineers [5] also highlight similar observations on the displacement with change in foundation modulus. The appropriate foundation modulus was made by considering a foundation scenario that produced substantial upstream deflections but that produced minimal sensitivity in the delta displacement.

C. VALIDATION OF FEM FOR STATIC ANALYSIS

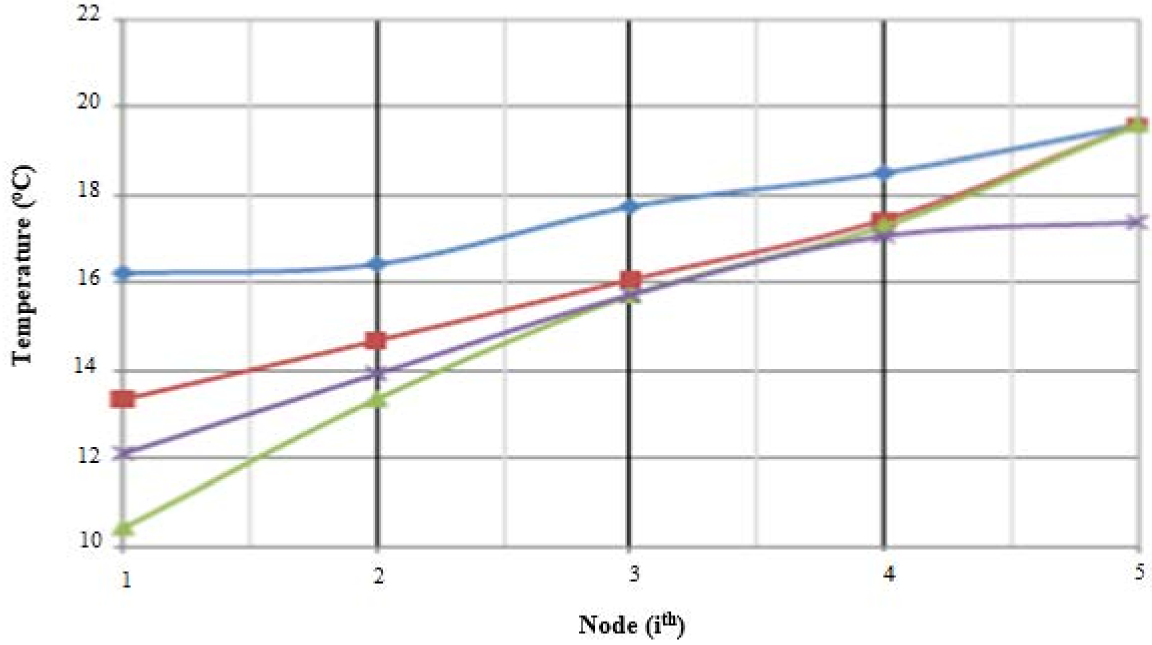
The assumed foundation modulus, case 4, was confirmed to being capable of predicting the static results of analysis and was ultimately used for validating the dam model. It is important to note that the dam wall almost displaces upstream when thermal loads act independent of any parameter. The hydrostatic load however, counteracts this displacement thereby forcing the dam to displace downstream. The difference in crest displacements between assessed water levels, was found to be approximately 38 mm.

D. EFFECT OF GEOMETRY ON THERMAL STRESSES

In the thermal analysis of the double walled concrete arch dams, the dam foundation interface acted as a hinge zone which attempted to open up when upstream deflection occurs. When significant heat was radiated on the dam, the upper wall section deflected upstream, while the lower wall section opened up towards the left and right abutments thus creating a high expanse of tensile action in the downstream face near the abutments. This is influenced by the double curved geometry and support conditions of the arch dams, which showed results in a swap of stresses along most of the depth of wall. The swapping of tensile stresses occurred at approximately half wall depth and for compressive stresses it occurred at approximately quarter wall depth. Placing the water level at the point where the swapping of tensile stresses occurs, showed no tensile failure in the upstream face near the crest. Increasing or decreasing the water level beyond half wall depth, resulted in tensile failure in the upstream face near the crest.

Table I: Investigated case of the foundation displacement

Studied cases	Foundation description	Foundation modules	EY/Ex (Ec = 31GPa)	Displacement (mm) Quarter - full
Case 1	soft	6	0.2	41.0
Case 2	soft	15	0.5	38.5
Case 3	soft	20	0.6	37.8
Case 4	soft	23	0.7	37.8
Case 5	soft	25	0.8	37.8
Case 6	hard	31	1.0	37.8
Case7	hard	40	1.3	37.7
Case 8	hard	46.5	1.5	37.7



: at -58m (dam body) : at – 64m(dam body) : at -31m (dam body) : at -4m(dam body)

Fig 3: Temperature gradient between the upstream and downstream face of the dam

E. FULL DAM ANALYSIS

In full-reservoir analysis the maximum temperature gradient between the upstream and downstream face was approximately 9. This was because of the difference between the upstream water temperature, and the downstream air temperature with solar radiation. The highest temperature was observed at the spillway level. Near the dam-foundation interface, there was relatively high temperature decreases. The largest tensile principal stress occurred in the upstream face near the crest, and observed for nodes. Temperature loading caused tensile failure at this location. For the interior concrete layers no thermal failure was expected because tensile stresses were below the tensile stress limit.

For tensile action, the vectors were directed away from the wall-foundation interface and were highly concentrated in the lowest elevation of the wall. For compressive action, the vectors were directed towards the wall-foundation interface and followed gently the distribution around the interface. The areas that were prone to possible tensile failure are highlighted in grey. The tensile failure was observed in the upstream face near the crest and in the downstream near the abutments.

F. EFFECT OF SEASONAL TEMPERATURE VARIATION ON DISPLACEMENTS OF ARCH DAMS

The above crest and longitudinal thermal displacements were computed using the assumed foundation properties. It was observed that thermally induced displacement in a half-full and quarter-full dam are slightly similar. It was also gathered that the crest displacement between a full and quarter-full dam differs by approximately 14 mm in the prescribed temperature boundary conditions only. When both thermal and hydrostatic loads were considered, the difference in crest displacements was found to be approximately 38 mm. It was then found that the hydrostatic loading component caused a 24 mm displacement when assessed for the critical temperature conditions notably, winter and summer seasons

G. EFFECT OF TEMPERATURE GRADIENT TO STATIC AND DYNAMIC CHARACTERISTICS

The reservoir level was a case of analysis for an arch dam placed in locations with much higher air temperature gradient than Kariba dam which is about 30ºC. Two air temperature gradients were chosen and investigated to carry out this objective namely 30ºC and 40ºC. All three cases chosen were compared for static temperature distribution, thermal stresses, thermal displacements and natural frequencies.

Thermal stresses were largely affected by the increase in temperature gradient. It was observed that a 40ºC temperature gradient caused upstream tensile failure to extend to near the middle horizontal of the dam wall. The highest observed failure tensile stress was 5,5MPa and occurs near the crest area of the node set. The dam was noted to behave well in compression for the assessed temperature gradients. Thermal displacements were very sensitive to change in temperature gradient. The crest displacement increased with increase in temperature gradient.

XIII. SUMMARY

Double walled concrete arch dams are always permanently subjected to thermal action owing to the surrounding environment. The variation in environmental seasonal temperatures and climatic conditions have high influence in the static and dynamic behaviour of double walled arch dams. A major portion of deterioration of arch dams has been associated with temperature loading and fortunately finite element techniques can be used to economically do the analysis. Finite element modelling techniques have been used efficiently in previous research to carry out safety evaluation of operational concrete arch dams.

XIV. CONCLUSIONS

The safety evaluation of concrete arch dams requires a realistic interpretation of temperature and thermal loads including the related time variations. Temperature variation has the greatest influence on the static behaviour of double walled arch dams. The examined dam, Kariba Dam located in Kariba, Zimbabwe, undergoes annual seasonal variations comprising of four seasons that have a temperature gradient of approximately 20ºC. Repeated heating and cooling cycles, and frost penetration in the small upstream wall cracks, contributes significantly to strength and stiffness degradation of the dam wall. In the past study, thermal static stresses and dynamic natural frequencies have been regularly estimated using basic mathematical procedures and assumptions. Now, static and dynamic analysis can be obtained in a more rigorous manner by employing finite element models that model heat transfer, conduction and convection in conjunction with stress analysis, either in a coupled or decoupled approach. In both coupled and decoupled procedures, dynamic results are requested after stress analysis.

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