CHAPTER 7

7. THE INFLUENCE OF THE BENEFICIAL BEHAVIOUR OF HIGH-PASTE RCC ON DAM DESIGN

7.1. INTRODUCTION

Earlier chapters clearly demonstrated that the early behaviour of RCC during the hydration cycle differs significantly from that of CVC and Chapter 6 consequently proposed a new understanding of the early behaviour of high-paste RCC in large dams. However, it is considered of particular importance to go on to demonstrate the impact of applying this new understanding on the design of RCC dams. In this Chapter, the author consequently discusses the implications and applications of the findings of his research in respect of a number of key aspects of the design of a large RCC arch/gravity dam.

For the purpose of comparing the conventional theory in respect of induced joint spacing and openings with a more modern approach and of comparing the related implications of traditionally assumed RCC behaviour with that developed on the basis of this Thesis, the example of the joint spacing evaluation for the Changuinola 1 Dam in Panama is summarised in the ensuing Chapter.

The influence of the new understanding of the behaviour of high-paste RCC is most critical in respect of the design and performance of arch dams and the related impacts are demonstrated through comparative analysis and discussion for the Changionola 1 Dam.

Changuinola I Dam is a 105 m high RCC arch/gravity structure, the first in the world outside China and South Africa. The dam is currently under construction on the Changuinola River in Bocas del Toro province on the Gulf coast of northern Panama. The dam site is located at approximately 9° north of the equator and in a particularly temperate climatic region where monthly average temperatures range between 23.5 and 27.2°C.

7.2. JOINT SPACING DESIGN

7.2.1. THE CONVENTIONAL APPROACH TO DETERMINING CRACK JOINT SPACING

7.2.1.1. Background

The approach to determining appropriate induced joint spacing in RCC dams has essentially evolved directly from the methods traditionally applied for conventional concrete dams. This approach functions on the principle that the spacing of the joints should be sufficient to ensure that the tensile strain capacity of the concrete is not exceeded in between.

Transverse induced joints are included in RCC dams as a means to manage mass gradient thermal effects. As discussed in Chapter 3, the induced joints must accommodate the thermal shrinkage that will occur as the concrete temperature drops from its “zero stress” temperature (T3) to its final long term equilibrium state seasonal minimum, reached only once all of the hydration heat has finally been dissipated (T4). Considering the fact that it can take some decades for the hydration heat to be fully dissipated from the core of a large RCC dam, the maximum opening of transverse induced joints can take some time to be realized. By the same token and dependent to a certain extent on climatic conditions, the seasonal temperature experienced within the core of a large dam will not vary by more than a degree, or two and accordingly, the temperature T4 is relatively easily determined. As discussed in Chapter 3, while the temperature T3 is somewhat more difficult to define, the same value as T2, or the maximum hydration temperature, is usually accepted as the “zero stress”, or T3 temperature.

7.2.1.2. The Function of Joint Openings

In view of the fact that the purpose of the transverse induced joints is to manage a long-term effect and one that will usually take a number of years to be fully realised, it is appropriate to use mature RCC strength properties for the calculation of joint openings, etc. The relevant RCC properties for thermal shrinkage cracking are the thermal expansivity and the tensile strain capacity.

In respect of the transverse induced joints, it is the horizontal tensile stress capacity that is of importance. Unlike the vertical tensile strength of RCC, the horizontal tensile strength is not compromised through placement in horizontal layers and a value of approximately 10% of the compressive strength is consequently probably typical for tensile strength. For RCC with compressive strengths of between 15 and 30 MPa and corresponding long-term elastic moduli of between 10 and 20 GPa(1), a tensile strain capacity of approximately 150 microstrain might be evident(2). To make an allowance for a factor of safety, it might be more appropriate to assume a tensile strain capacity for RCC of approximately 100 microstrain.

Whether the transverse induced joints either function to create a substantial tensile weakness in the RCC, or to completely de-bond the RCC on a specified cross section, it can be assumed that the tensile stresses developed as a consequence of the long term thermal shrinkage will cause crack development and opening to be initiated at these joints. The design principle for the joint spacing is consequently to ensure that the tensile strain capacity of the RCC is not ever exceeded between the induced joints. Accordingly, should the total long-term thermal shrinkage in a particular dam measure 300 microstrain, it would be assumed that the RCC tensile strain capacity would be exceeded by 150 microstrain and the induced joints would be assumed to open to accommodate that shrinkage.

With a shrinkage strain to be accommodated, the joint opening is a function of the joint spacing applied. Theoretically, an infinite number of opening and spacing combinations exist. However, dependent to some extent on the total temperature drop to be accommodated, a practical minimum joint spacing would probably be 10 m and a maximum, 30 to 50 m. In reality, the foundation restraint condition must be given adequate consideration in deciding on joint spacings and discontinuities, singularities, roughness and general geometrical constraints will usually induce stress concentrations that might result in intermediate cracking for joint spacings exceeding 30 to 50 m. On a particularly uneven foundation, a 30 m induced joint spacing could even be excessive. Subjectively, it would also seem unadvisable to design for maximum induced joint openings of more than perhaps 3 to 5 mm.

A further factor to be considered is the dam height at the location in question. An induced joint spacing/height ratio exceeding 2/3 would rarely be considered advisable.

Some thermal shrinkage of the concrete immediately against the foundation will occur in all dams and while this will largely be accommodated through plastic deformation and micro cracking in the concrete and the foundation rockmass, it is not realistically possible to quantify the influence of this effect. For this reason, it is always particularly advisable to limit concrete placement temperatures immediately against the foundation, or other structural restraints.

7.2.1.3. Quantifying Joint Openings

Theoretically, unrestrained concrete subject to a temperature drop will simply shrink linearly. When restrained against such shrinkage, the concrete will obviously experience tensile stress in proportion to the extent of the restraint.

To establish the induced joint spacings/openings, it is first necessary to establish the total restrained thermal shrinkage strain as follows(2):

$$\epsilon = (C_{th}).({}_{d}T).(K_R).(K_f)$$

where

ϵ = Strain in concrete caused by temperature change

C_{th} = Coefficient of thermal expansion (microstrain/°C)

${}_{d}T$ = Temperature change in concrete causing strain (°C)

K_R = Structure restraint factor

K_f = Foundation restraint factor

The structure restraint is a function of the length/height ratio (L/H), while the foundation restraint factor is a function on the nature and rigidity of the foundation.

The following empirical relationship for K_R was developed by the American Concrete Institute(3):

$$K_R = \left[\frac{\frac{L}{H} - 1}{\frac{L}{H} + 10}\right]^{\frac{h}{H}}$$

where

L = Length of block

H = Height of block

h = Height above foundation of point of interest.

While K_R might be negligible at the top of an 80 m high block in a dam, it will be very significant at the base of the same block and it is often consequently appropriate to apply a value of 1.

On a rigid rockmass, as generally appropriate for a concrete-type dam, the foundation restraint would probably be only marginally less than 1, perhaps 0.95.

For the following typical conditions:

C_{th} = 10×10^{-6} /°C.

${}_dT$ = 30°C

K_R = 1

K_f = 0.95

a thermal shrinkage strain of 285 microstrain would be developed.

Assuming that 100 microstrain remains in the tensile capacity of the RCC, a shrinkage of 185 microstrain shrinkage must be accommodated at the induced joints. For an induced joint spacing of 30 m, this translates into a maximum joint opening of 5.55 mm, or 3.7 mm for a spacing of 20 m.

7.2.1.4. Comparing Traditionally Predicted Joint Openings with those Anticipated by the New RCC Materials Model

Taking the case of Changuinola 1 Dam, a maximum placement temperature of 29°C is to be applied and a heat of hydration of 22°C has been predicted by heat-box testing. Subsequently the thermal analysis predicted a maximum core temperature of approximately 51°C, during construction, and a final long-term minimum core temperature of approximately 25°C. Situated only 9° north of the equator, the dam will experience a particularly temperate climate and accordingly, the long-term temperature drop from peak hydration will be limited to approximately 25°C.

In accordance with the traditional approach and RCC behaviour model, the induced joints would be designed for a temperature drop of a full 25°C. With a coefficient of thermal expansion of 8.8×10^{-6}/°C, a structural restraint factor of 1 and a foundation restraint factor of 0.95, the total shrinkage strain to be developed would accordingly be 209 microstrain. Allowing for a residual RCC tensile strain of 100 microstrain, the maximum joint opening at a spacing of 20 m would be 2.18 mm.

Applying a more realistic RCC behaviour on the basis of the findings of this Thesis, and allowing for creep equivalent to increasing the "zero stress" temperature by 2°C, then the total maximum applicable temperature drop would be between 1 and 5°C. The total shrinkage associated with such a temperature drop would develop a tensile strain of approximately 25 microstrain, which is significantly less than the RCC tensile strain capacity.

In accordance with the traditional approach, this would imply that the RCC would not crack. However, in reality, with joint inducing substantially reducing the tensile strength of the structure, the indicated thermal shrinkage would probably cause core joint openings of approximately 1 mm on every second, or third induced joint.

7.2.1.5. Discussion

The traditional approach to the evaluation of induced joint spacings and openings has proved to function well in practical application because it is in reality rather conservative. However, it is in fact unrealistic in allowing such high levels of residual tensile stress in the RCC between induced joints. The Finite Element analyses completed for Wolwedans Dam and presented in Chapter 5 clearly demonstrate that the residual tensile stresses between induced joints in a large dam are surprisingly low, even when only every third joint opens.

Considering this fact, it is apparent that a linear shrinkage, equivalent to $C_{th}.dT$ should be applicable at a location remote from any restraint. Taking the example under 7.2.3 above, the total joint opening at the crest of a high dam, with joint spacings of 30 m, would exceed 6.5 mm.

The USACE EM 1110-2-2006 guideline on *Roller Compacted Concrete*. 2000(4) addresses the subject of transverse induced joint openings on RCC dams, reflecting the fact that typical maximum joint openings vary between 1 and 3 mm. The same publication indicates that transverse induced joints have generally been spaced at separations of between 15 and 40 m, although some instances of over 90 m exist.

Again, the conventionally accepted practices and design procedures for RCC in dams and the realities of measured performance can be seen to be disparate.

7.2.2. CHANGUINOLA 1 DAM JOINT SPACING DESIGN

7.2.2.1. Introduction & Approach

For the purpose of establishing the maximum joint spacing in tandem with a maximum RCC placement temperature for the Changuinola 1 RCC arch/gravity dam, a detailed thermal analysis was undertaken(5) and this is described briefly in Chapter 5. The first phase of analysis incorporated a 2-dimensional sectional profile that was essentially built up on the basis of the proposed construction programme. Through this model, it was possible to evaluate the critical temperature gradients and the resultant stresses that are likely to develop through the dam section in the process of hydration heat development and subsequent cooling. In addition, the long-term equilibrium temperature state for the dam could be established. While the former was used to investigate whether cooling of placed RCC would be required at any stage to prevent the development of surface gradient cracking, the latter was of most specific relevance in respect of the spacing of the transverse induced joints.

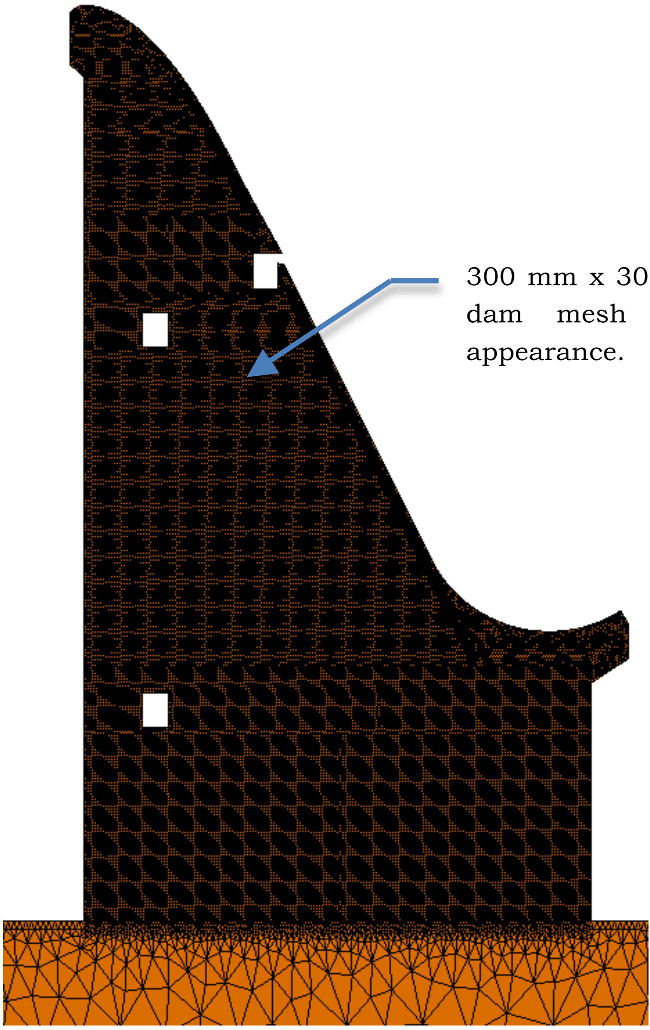
With the temperature distributions at placement and at maximum hydration, it was possible to establish the effective long-term temperature drops that would be anticipated for the conventional RCC materials behaviour model and for the proposed new materials model.

7.2.2.2. Thermal Analysis

The thermal analysis simulated construction on a weekly basis, applying a daily time step and inputting heat energy in 300 x 300 mm elements to realise the maximum hydration temperature rise after 7 days, while allowing surface convection over the same period. The RCC placement temperature at any particular point in time was input as the average monthly ambient + 2°C. Measurement on the first full scale trial for the dam suggested that heat of approximately 3°C was added to the RCC through all of the various handling processes, etc. Not all of the temperature control measures to be applied for the dam were in use during the trial and accordingly, it was considered that a temperature increase of 2°C for the handling processes, etc, would be a more appropriate figure. On the basis of this scenario, a maximum placement, or built-in RCC temperature of 29.2°C was found to be applicable for the warmest period of the year, while a maximum temperature of 48.5°C was indicated within the core of the dam structure shortly after completion in August 2011. It should be noted that this maximum temperature has already dropped slightly from the peak of approximately 51°C experienced during construction between September and November 2010.

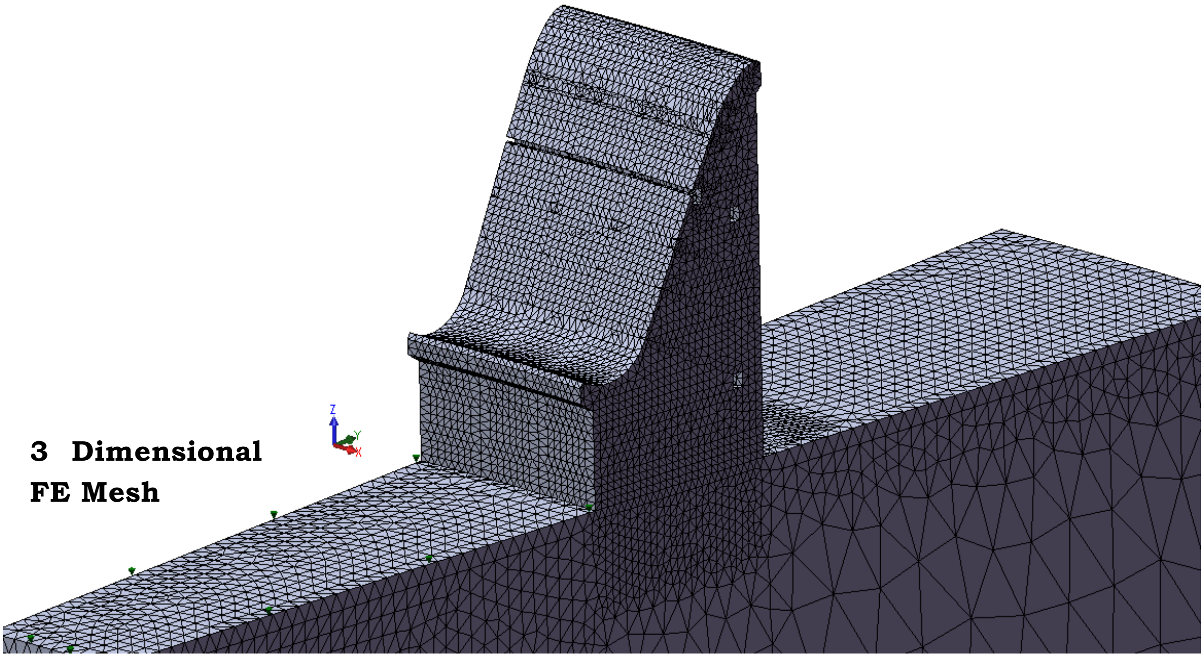
Building up the dam model using the COSMOS(6) Finite Element software (see **Figure 7.1**), the structure was subsequently subjected to external seasonal air and water temperature variations over a period of 4 decades. In this process, it was established that an equilibrium state of seasonal temperature variations was reached, with all hydration heat dissipated, approximately 30 years after construction completion. The subsequent minimum seasonal temperature distribution within the dam structure was consequently established as the final (T4) state against which the long-term temperature drop was measured. The process of cooling from the maximum heat state, on completion of construction, to the final cool equilibrium state is illustrated on **Figure 7.2**.

For the above model, a foundation depth equal to twice the dam height was applied and the initial temperature of the rockmass was established by subjecting the FE model to the external monthly average ambient temperature until a final condition of equilibrium was reached.



300 mm x 300 mm element size in dam mesh takes on a solid appearance.

2 Dimensional FE Mesh



3 Dimensional FE Mesh

Figure 7.1: 2 & 3-D Finite Element Meshes used for Thermal Analyses(5)

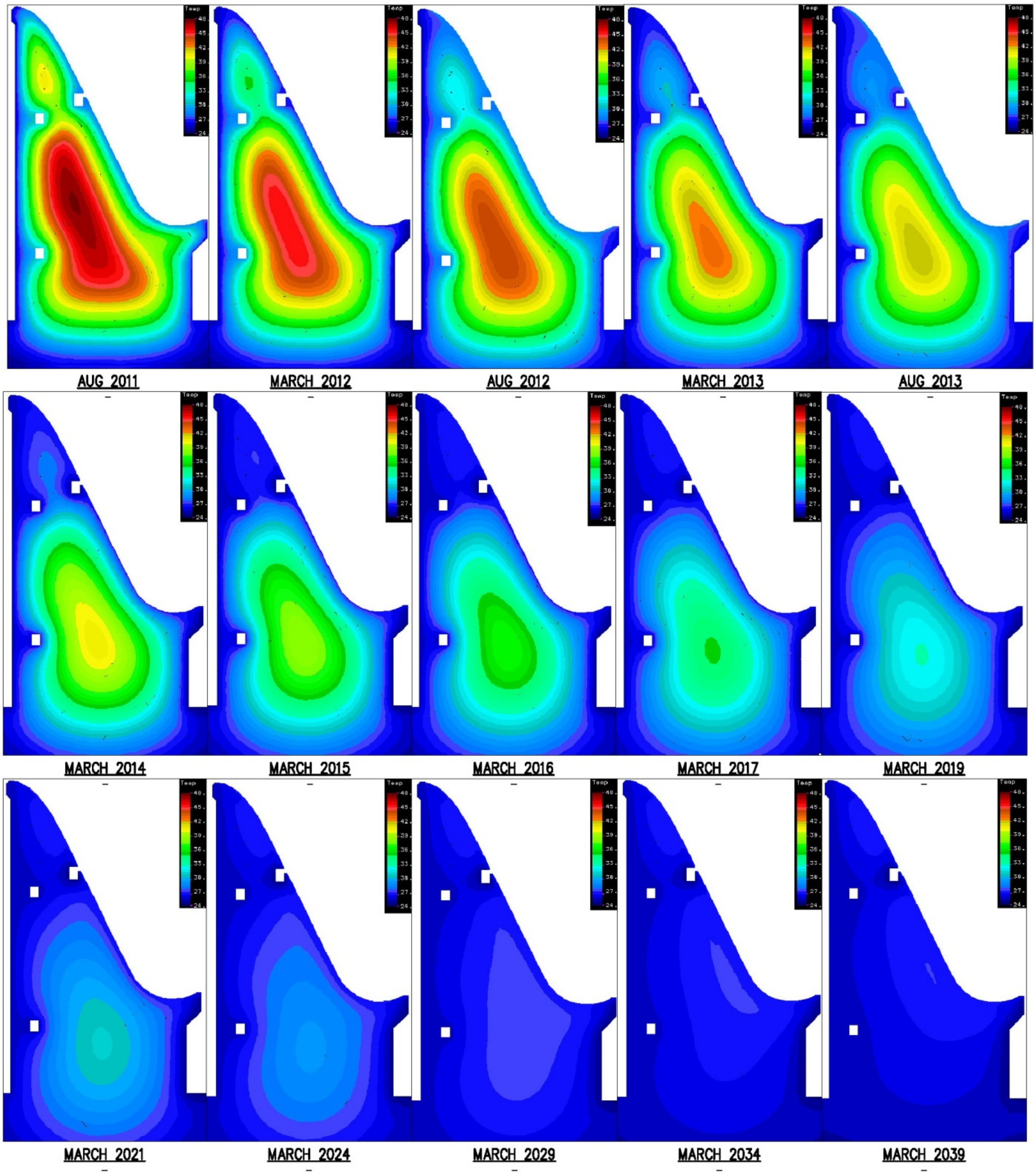


Figure 7.2: Process of Dam Body Cooling to Long-term Equilibrium State

7.2.2.3. Joint Spacing Evaluation

To evaluate an appropriate maximum transverse induced joint spacing to be applied for Changinola 1 Dam, a 100 m long FE model (see **Figure 7.1**) was established with gap elements spaced at 5 m centres. By binding, or releasing these elements, it was possible to investigate joint spacings at various multiples of 5 m. The model was taken at the tallest section of dam structure, on the spillway, and a flat foundation geometry was assumed to ensure that the temperature-related influences could be evaluated in isolation.

Applying a distribution of temperature drops down to the final cool equilibrium state, two conditions for the "zero stress" (T3) temperature were applied; the first taking the maximum hydration temperature distribution, in accordance with a conventional RCC materials model, and the second conservatively assuming an effective creep equivalent to 2°C, in accordance with the RCC materials behaviour established in this Thesis (termed "New" RCC model for brevity), and setting the "zero stress" temperature at 2°C above the effective placement temperature. While it has been demonstrated that an RCC with no significant shrinkage, or creep is possible, and while the Changuinola 1 RCC is extremely high quality, the thermal analysis was completed before the final full scale trial, for which strain measurement will be undertaken and accordingly, it was considered appropriate to retain a degree of conservatism.

Figures 7.3, **7.4** and **7.5** illustrate the final T4 distribution and the T3 states at maximum hydration (T3 = T2) and at placement + 2°C (T3 = T1 + 2°C) respectively.

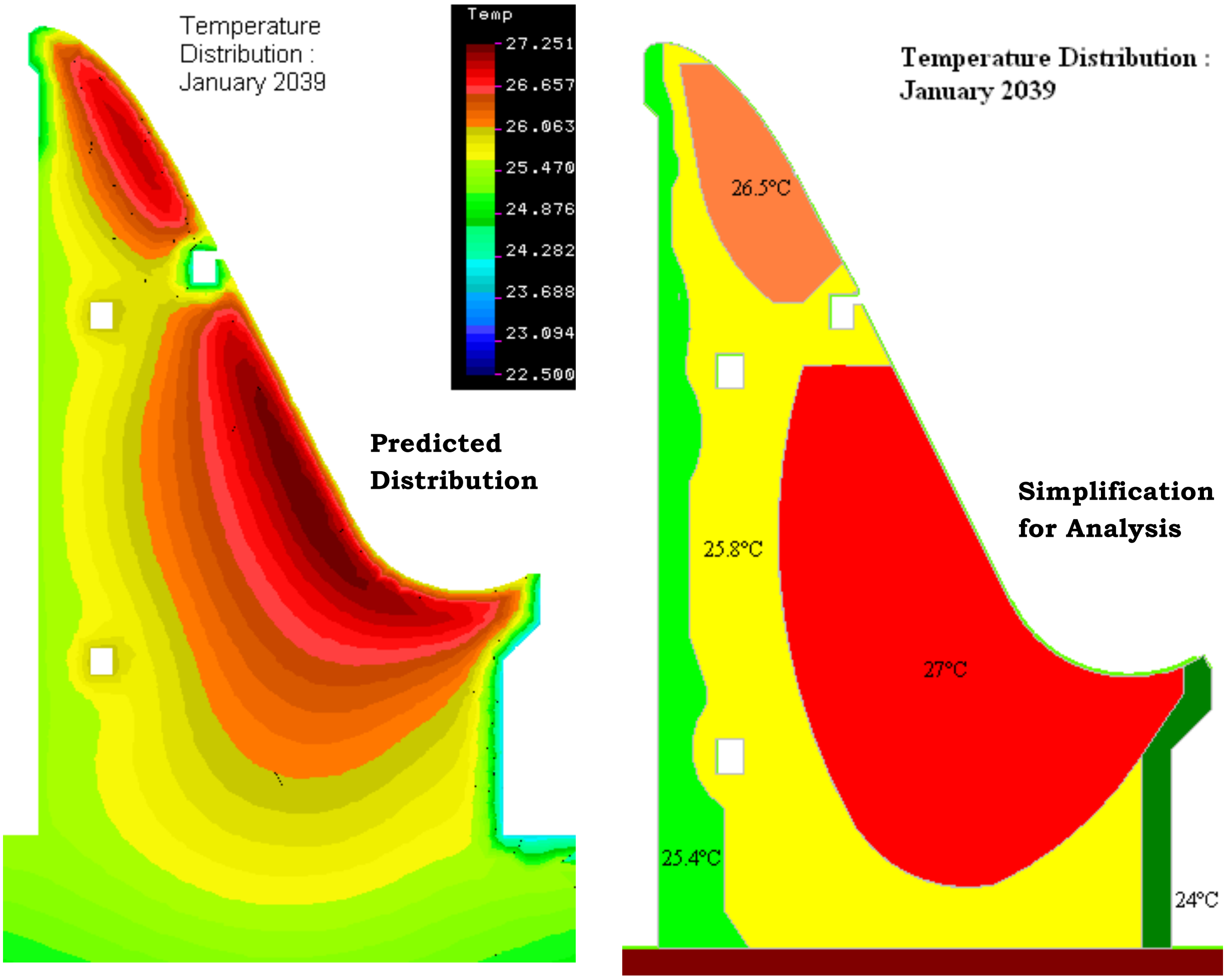


Figure 7.3: T4 Temperatures Predicted at Jan 2039 & Associated Simplified Distribution for Analysis(°C)

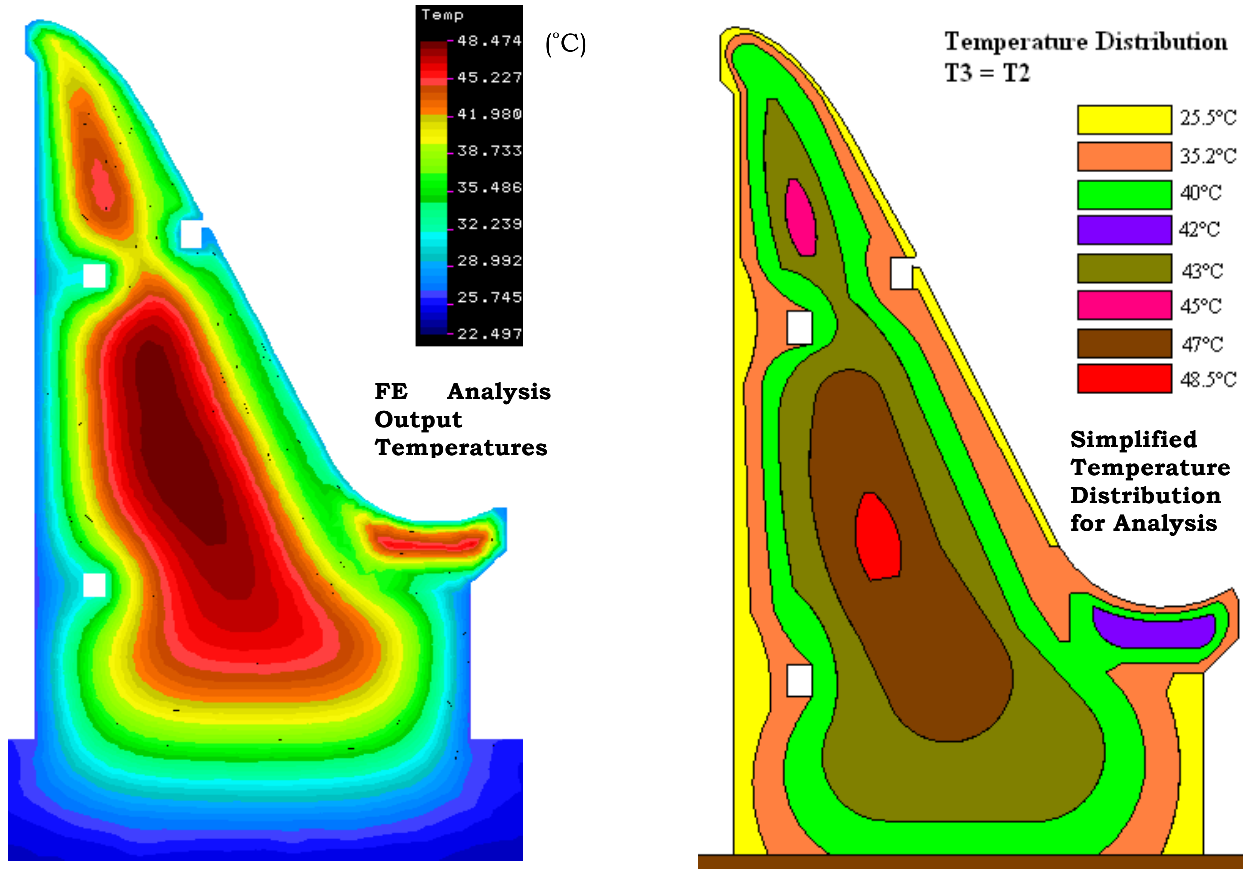


Figure 7.4: T3 Temps for Traditional RCC Model – Actual & Simplified (°C)

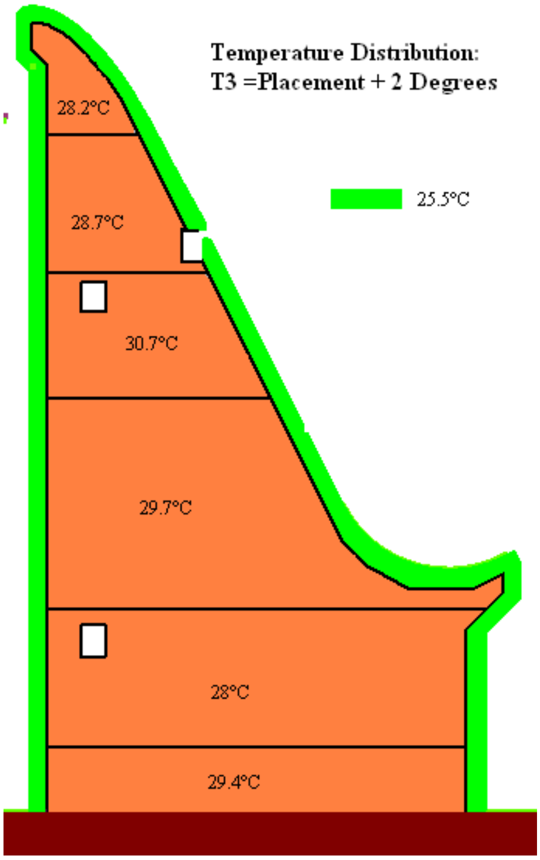
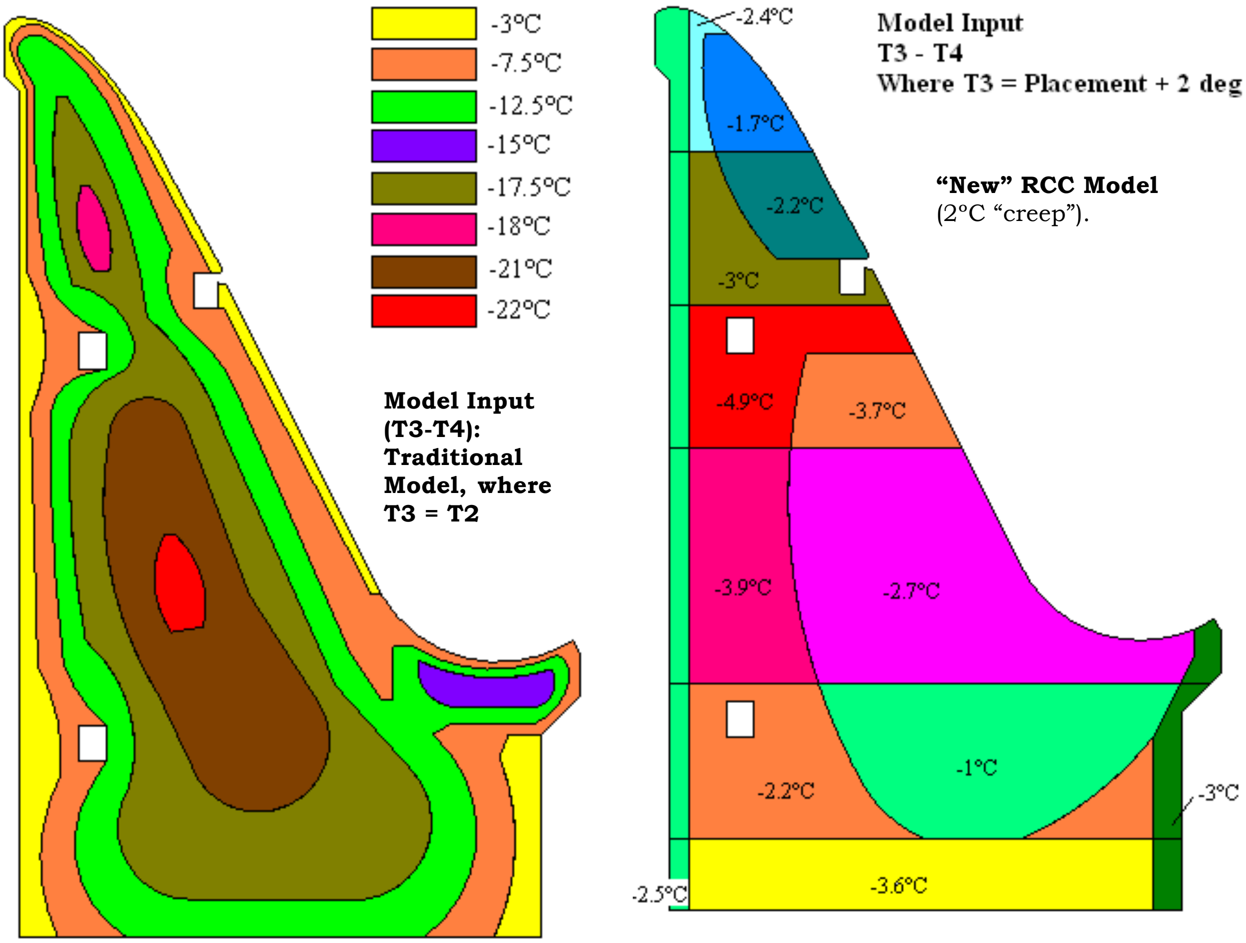


Figure 7.5:
T3 Temperatures for "New" RCC Model (°C)



Model Input (T3-T4): Traditional Model, where T3 = T2

Model Input T3 - T4 Where T3 = Placement + 2 deg

"New" RCC Model (2°C "creep").

Figure 7.6: Temp. Drop Loads Applied for Traditional & "New" RCC Models (°C)

Figure 7.6 illustrates the effective structural temperature drop loads applied for analysis to represent the Conventional and the "New" RCC materials models respectively.

7.2.2.4. Presentation of Results

It is considered important to take note of the fact that the Finite Element analysis takes into account the initial cooling effect of the foundation on the heated dam structure. Using the temperature distributions developed through the thermal analysis as input data for the temperature drop analysis, the consequential cooling of RCC placed close to the foundation implies a relatively gentle temperature gradient between the base of the dam structure and the foundation rockmass. The simplified conventional theory effectively assumes an abrupt interface between the concrete, in which a temperature drop is applied, and the foundation, in which no temperature drop is applied.

The results from the joint spacing analyses are presented here for the selected maximum spacing of 20 m. **Figures 7.7** and **7.8** present the predicted maximum induced joint openings and the mid-block maximum residual tensile stresses for the conventional RCC materials model, respectively, while **Figures 7.9** and **7.10** present the same for the “New” RCC materials model.

Table 7.1 provides a summary of the critical observations in respect of the two models/modes of behaviour:

Table 7.1: Finite Element Joint Spacing Model Critical Output

RCC Materials Model/Behaviour Mode	**Critical Behaviour**		
	Max Opening (mm)	**Max Residual Tensile Stress** (MPa)	**Max Residual Tensile Strain**
Traditional	3.85	1.0	50 microstrain
“New”	0.76	0.4	20 microstrain

The above FE analysis results can be compared with conventional joint theory predicted openings of 2.18 mm and 0 for the traditional and the “New” RCC materials model, respectively, assuming 20 m joint spacings and 100 microstrain residual tensions.

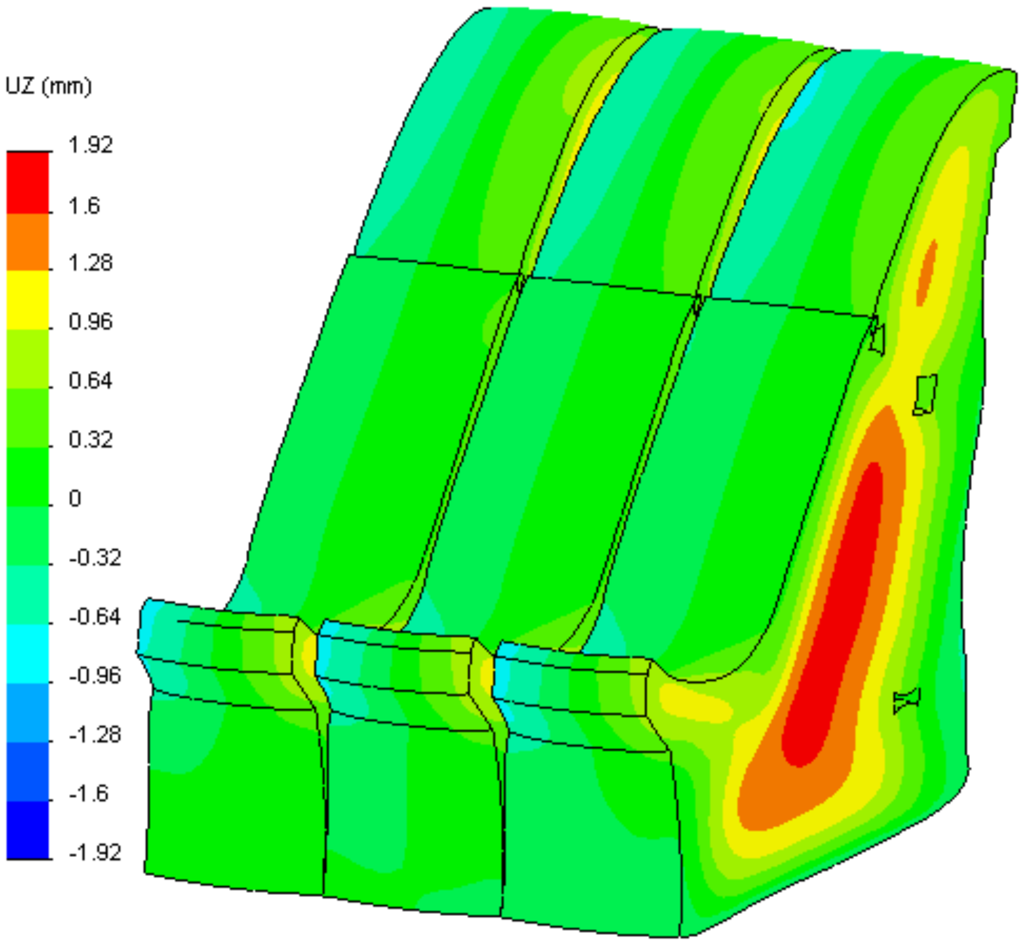
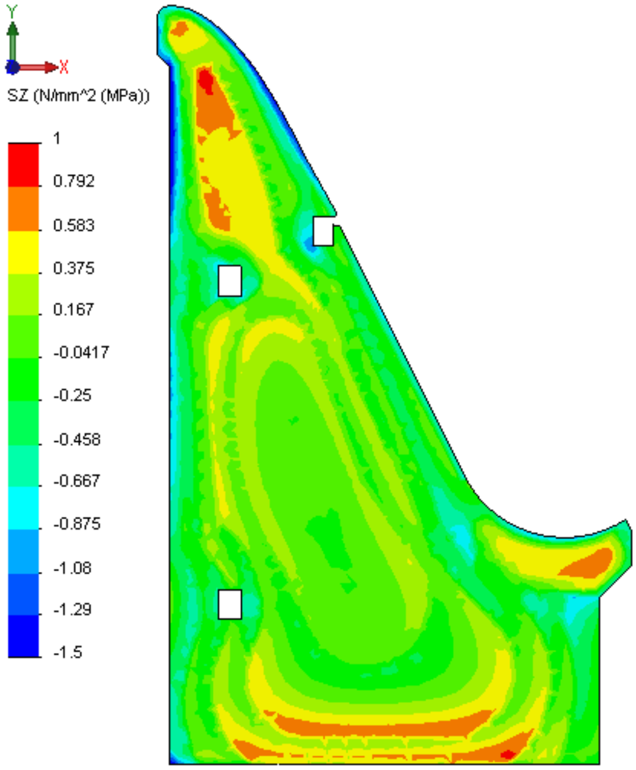


Figure 7.7: Maximum Induced Joint Openings for Traditional RCC Model



(+ve = Tension, -ve = Compression)

Figure 7.8: Central Block Residual Stress for Traditional RCC Model

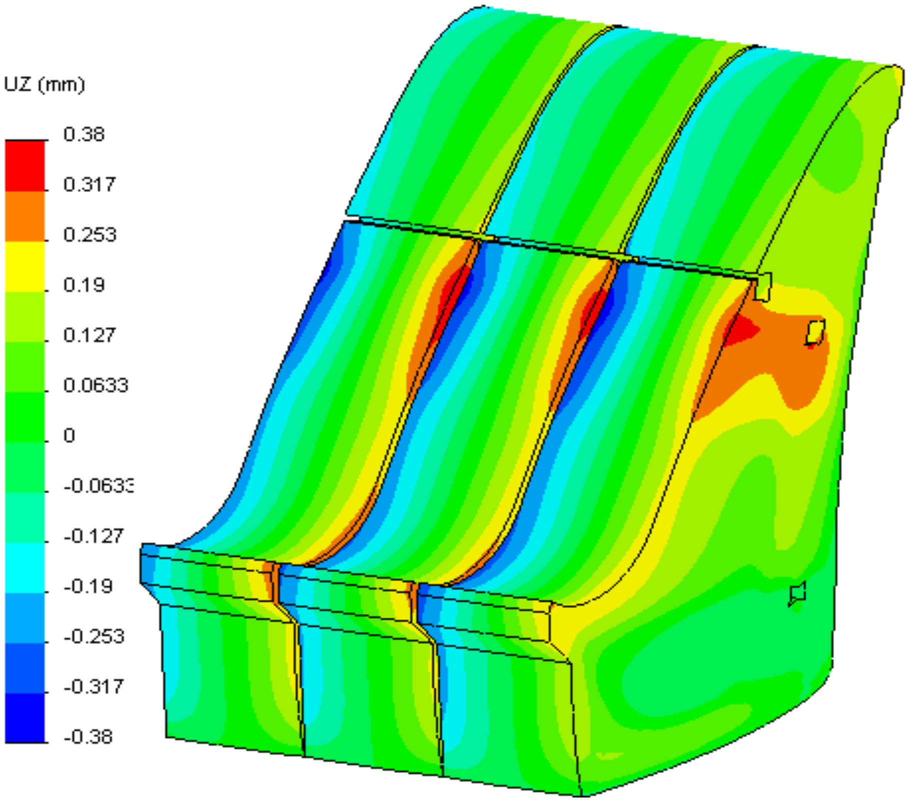
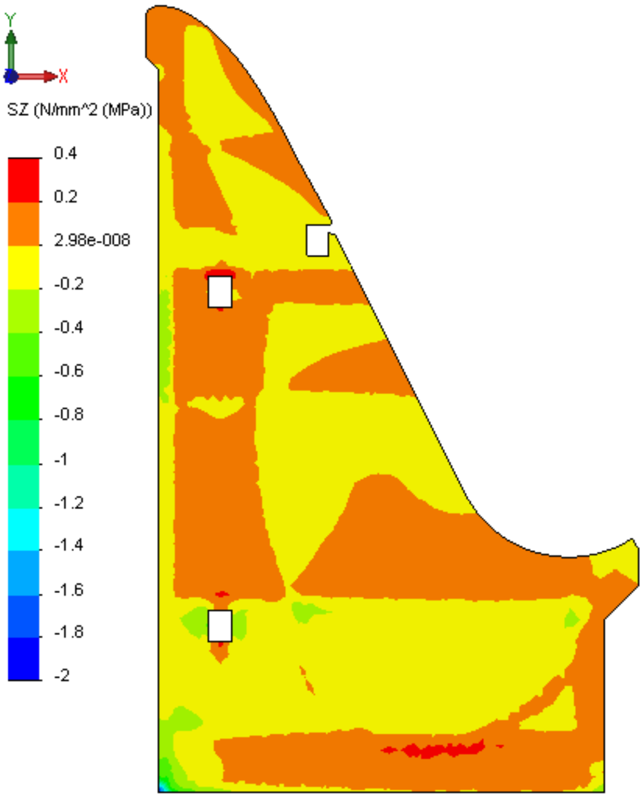


Figure 7.9: Maximum Induced Joint Openings for "New" RCC Model



(+ve = Tension, -ve = Compression)

Figure 7.10: Central Block Residual Stress for "New" RCC Model

7.2.2.5. Discussion of Results

The FE analyses summarised above confirmed that the anticipated residual tensile stresses between induced joints spaced at 20 m are in fact minimal, peaking at only 50 microstrain even for a temperature drop of the order of 20°C. As a consequence, however, the induced joint open in an unrestrained manner and the maximum joint openings predicted for the traditional RCC model/behaviour mode are approximately double those estimated in accordance with the conventional, simplified theory.

In the case of the "New" RCC materials model/behaviour mode, even the residual tensile stress indicated immediately against the foundation was low and well within the tensile strength capacity of the RCC. The very fact that the joint opening is of the same order as would have been anticipated for a simple linear shrinkage, however, confirms the indications of the stress plot that residual stress within the block at crest elevation is negligible.

It is in this last fact that the most important comparison can be made with the conventional theory. As previously demonstrated on the Wolwedans Dam model and confirmed on the prototype structure, only a few open joints across the length of a relatively large structure are sufficient to dissipate the great majority of the tensile stress associated with the long-term temperature drop. Consequently, the full shrinkage associated with the temperature drop should be evident on the induced joints at the crest of the dam. In the particularly temperate climate of the

Changuinola 1 Dam site, maximum induced joint openings of no more than 1 mm would be anticipated. If an induced joint opening of 4 mm were realistically to be anticipated at a dam such as Changuinola 1, as predicted for the traditional RCC materials model/behaviour mode, very significantly greater induced joint openings would have been measured on other major RCC dams in more extreme climates, contradicting the 1 to 3 mm stated as typical in the USACE's EM 1110-2-2006. *Roller Compacted Concrete.* 2000(4) guideline on the subject.

The fact that the conventional theory significantly over-estimates the magnitude of the effective temperature drop that causes thermal shrinkage is substantially mitigated by its incorrect assumption of the level of the residual tensile stresses within an RCC block between induced joints.

7.2.2.6. Induced Joint Spacing for Changuinola 1 Dam

The joint spacing analysis summarised above allowed the following conclusions to be drawn for Changuinola 1 Dam;

1. No matter what the material model adopted, an induced joint spacing of 20 m was sufficient to ensure that residual tensions do not exceed the concrete tensile strain capacity;
2. No artificial RCC cooling will be required for an induced joint spacing of 20 m, as long as the temperature control measures put in place are sufficient to ensure that the placement temperatures do not generally exceed 2°C above the average ambient, with an associated maximum allowable placement temperature of 29°C; and
3. Considering the obvious conservatism of the conventional RCC materials model in respect of the high-paste RCC used at Changuinola 1, a significant factor of safety can be considered to exist in the proposed induced joint design.

The above findings might suggest that a placement temperature of well above 29°C could be allowed, or that a transverse induced joint spacing of well in excess of 20 m could be applied. In the case of Changuinola 1, however, other factors in respect of the arch/gravity dam design needed to be given consideration. Bearing in mind the construction schedule and the need for rapid impoundment, a significant advantage was perceived in being able to eliminate grouting of the arch/gravity structure before impoundment and therefore minimising the applicable maximum temperature drop load.

7.2.3. CONCLUSIONS

The above analyses and comparisons clearly demonstrate the over-simplification of the conventional theory for induced joint spacing and opening. Furthermore, the assumptions in respect of residual tension and consequently the methods for calculating joint openings have been demonstrated to be flawed. To date, conventional theory has worked because it substantially over-estimates the magnitude of the long-term temperature drop that is applicable in the case of RCC. Applying the "New" materials model for early RCC behaviour, in line with the findings of this Thesis, the conventional joint spacing model must be modified. This model is anyway a rather crude tool that should only realistically be used for first estimation, as simple FE modelling can readily provide substantially more credible analysis.

The FE analyses clearly demonstrate that residual tensile stresses are fully dissipated within approximately 10 m above the constraint of the foundation for a joint spacing of 20 m. This is particularly important, as it implies that the full thermal shrinkage will be manifested in the opening of the induced joints at the crest of the dam. When reviewing the induced joint openings typical on RCC dams on the basis of this knowledge, it is quite clear that the magnitude of opening that the traditional RCC model would predict simply does not occur in reality. While experience demonstrates induced joint openings typically in the range of 1 to 3 mm, even such openings are never evident at every induced joint, unless the spacing is very significant. Although this observation may be subjective, it is yet another confirmation that the traditional materials model does not correctly predict the actual behaviour of RCC and that certainly high-paste RCC in fact behaves quite differently to CVC in respect of shrinkage and creep during the hydration heat development and cooling cycle.

7.3. THE IMPACT OF TEMPERATURE DROP LOADS ON ARCH DAMS

7.3.1. INTRODUCTION

The application of the findings of this Thesis will be of greatest importance in respect of RCC arch dams. While the new understanding of the early behaviour of high-paste RCC will give rise to new opportunities for dam design, its application will also require that a number of aspects, from aggregate testing to the construction programme, be given greater attention at the design stage.

7.3.2. TEMPERATURE DROP LOADS

The impact of temperature drop loads on arch dams is discussed in **Appendix A** and summarised in Chapter 5. For further information, reference should be made to the author's MSc thesis entitled "The Role of Temperature in Relation to the Structural Behaviour of Continuously Constructed RCC and RMC Dams"(7), or his 2003 paper "The Development of RCC Arch Dams"(8).

In summary, a temperature drop load on an arch dam essentially implies that the structure shrinks to a smaller size than the space that it was constructed to fill. With shrinkage increasing with distance from the restraining foundation, the central crest of the dam is most significantly impacted. If the structure is constructed with transverse joints, or induced joints, these will open and the structure will effectively stand as a series of separated vertical, cantilever monoliths. When water load is applied to this structure, the cantilevers are inadequately stiff to carry the full load and they consequently deflect downstream. With deflection increasing with distance from the restraint of the foundation, they make contact with each other, first at the crest and then progressively lower as greater load is applied. In this process, the cantilevers shed load laterally at the top, the crest area becomes an arch and additional structural stiffness is provided to the top of the cantilevers, as arch action assists in resisting additional downstream displacement.

In this process, the longer central cantilevers deflect more than the shorter cantilevers on the flanks and the centre of the arch effectively moves downstream relative to the flanks. As resistance to downstream deflection is provided to the top of the cantilevers in the form of arching, the central section of the cantilevers begins to experience vertical bending (or beam) stresses as they span between the supports of the foundation at the bottom and the arch at the top. The consequence is that the central portion of the arch structure begins to experience vertical (and subsequently horizontal) tensions on the downstream face, in a sort of bursting action (see **Appendix A**).

Imposing a temperature drop onto an arch dam reduces the extent of the structure that contributes to transferring stress through arch action, concentrates stresses towards the crest and initiates distress on the longer cantilevers. Accordingly, it can be seen that a temperature drop substantially compromises the efficiency of an arch structure, consequently compromising its final load carrying capacity.

7.3.3. THE TRADITIONAL APPROACH TO ARCH DAM DESIGN FOR TEMPERATURE DROP LOADS

As a consequence of the above impact of temperature drop loading on the efficiency and the load carrying capacity of an arch structure, it is general practice to restore the original “un-shrunk” geometry of an arch dam by filling contraction joints with cementitious grout at an appropriately low temperature.

CVC arch dams are constructed as a series of independent vertical monoliths, each usually the full thickness of the dam wall, but limited in width to approximately 15 m. Assuming the “zero stress” temperature approximately, or marginally conservatively, equal to the maximum hydration temperature (T2), a significant temperature drop load is applicable down to the final long-term equilibrium state winter minimum. For a hydration heat of perhaps 25°C and a difference between placement and the final minimum internal winter temperature of perhaps an additional 10°C, the total applicable temperature drop would be 35°C. For such a temperature drop, the contraction joints between 15 m wide monoliths would open by over 5 mm, creating a void that can readily be filled with grout.

The hydration heat within the dam, however, can take years to dissipate naturally and it is not a practical option to wait for this to occur before impounding water, or before grouting the contraction joints. Consequently, it is common practice to install pipe loops in the mass concrete through which chilled water is circulated in order to accelerate the withdrawal of the hydration heat. While the cooling process is sometimes applied to cool to the final winter equilibrium minimum, an alternative approach is to pump the grout into the joints under pressure, effectively further opening the joints using grout pressure. Provision must of course be made for the quite considerable autogenous shrinkage of a cement/water grout. The grouting systems are usually designed to allow re-grouting at some time in the future, should this ever be considered necessary. Depending on the temperature at which the grouting is undertaken and the pressure applied, the dam structure may still be designed to accommodate a minor temperature drop below its grouted temperature.

7.3.4. RCC ARCH DAM DESIGN AND TEMPERATURE DROP LOADS

7.3.4.1. General

Constructing RCC dams in continuous horizontal layers does not allow the inclusion of formed joints, with shear keys and grouting systems, as applied for CVC. Furthermore, placement in 300 mm layers using large, vibratory rollers makes the inclusion of pipe cooling loops rather impractical, although this has apparently been successfully accomplished in China(9). In view of the fact that one of the primary benefits of RCC dam construction is speed, it further makes no practical sense to wait for natural cooling to occur before grouting and impounding the reservoir. Consequently, the design of an arch, or an arch/gravity dam in RCC must include careful consideration of the processes and methods applied to ensure structural integrity at all times.

If impounding is commenced at an RCC arch immediately on completion of the RCC placement, the structure will still retain a good proportion of its hydration heat, with the structural integrity only starting to become compromised as the heat is dissipated into the water, the atmosphere and the foundation. However, to wait to grout until the heat has dissipated naturally, with a filled dam, would effectively require the structure anyway to be structurally safe for the full applicable long-term temperature drop, without grouting of the induced joints.

7.3.4.2. Discussion on the Accommodation of Temperature Drop Loads in RCC Arch Dams

Depending on the nature of the arch dam design, a number of alternative approaches can be considered for the accommodation of temperature drop loads; the case of a thin RCC arch in a narrow valley being quite different to that for a heavy arch/gravity structure in a wide valley. The situation in an extreme climate will also be quite different to the situation in a climatically temperate region. In general, however, the approach will either be one of designing the arch for temperature drop loads without grouting, or one of cooling the concrete, locally or generally, to allow early grouting of the induced joints. Whatever the approach, a grouting system will usually be included on the induced joints to ensure that grouting can be undertaken, should the need ever be considered to arise.

While artificial cooling to withdraw all of the hydration heat is only realistically practical where the dam section is thin, it is probably only realistically necessary in such instances, where the structural reliance on arching is high and the arch action is continued quite low in the dam wall structure. In the case of an arch/gravity structure, three dimensional stress transfer will only really ever occur within the upper portion of the wall, where some flexibility of the stiff cantilevers exists, and arch function will never be required in the lower sections of the structure, where more heat retention will be experienced.

7.3.4.3. Comparing Predicted Arch Behaviour for a Traditional RCC Model with that Anticipated for the "New" RCC Materials Model

Taking into account the above, the findings presented in Chapter 6 and the practical realities of timing the induced joint grouting and the reservoir impoundment, a completely different situation can be perceived whether the traditional, or the "New" RCC materials behaviour model is applied. In the case of Changuinola 1 Dam, a long-term structural temperature drop of approximately 22°C must be taken into account in the dam design when applying the traditional model, while this figure becomes approximately 3°C when applying the "New" RCC model/behaviour mode.

In the case of the former temperature drop, the structural impact would be too great to allow any question of loading before full joint grouting within the critical zones of the dam crest had been completed. In the case of the latter temperature drop, the structural integrity of the arch structure would undoubtedly be assured without any joint grouting.

7.3.5. THE INFLUENCE OF THE "NEW" RCC MATERIALS MODEL/BEHAVIOUR MODE ON RCC GRAVITY DAM DESIGN

7.3.5.1. Background

In the case of RCC gravity dams, the only critical issue in respect of long-term temperature drop loads is the potential for the development of cracking parallel to the dam axis. This problem has long been acknowledged as an important factor to be considered in the design and construction of large mass concrete dams and there are many examples where such cracks have developed in mass concrete. In the warmer areas of South Africa, thermal cracking has occurred at several CVC dams, such as Gariep and Inanda Dams, while these problems are currently being experienced at De Hoop Dam for concrete placed during the winter months.

Generally, this problem is addressed in CVC through pre-cooling of the concrete by incorporating ice in the mix, or by post-cooling, both with the objective of limiting the maximum temperature experienced within the concrete mass compared to the external ambient. On the basis of limiting the T2 temperature (hydration peak), the T3 temperature (zero stress) temperature is reduced, as the two temperatures are generally considered as the same for CVC.

7.3.5.2. The Situation for RCC Dams

Applying a CVC materials behaviour model for RCC, this problem is generally approached in a similar manner to the derivation of appropriate transverse joint spacing. It is also, however, one of the primary reasons for which a comprehensive thermal study is considered necessary for all major RCC dams. Limiting horizontal tensile stresses in an upstream – downstream direction in a large RCC dam will usually represent the determining factor in establishing the maximum allowable RCC placement temperature and accordingly, the level of the expensive pre-cooling measures that need to be applied.

In the cases of the two largest RCC gravity dams constructed to date, the issue in respect of potential cracking parallel to the dam axis has been handled differently. In the case of La Miel Dam (190 m) in Columbia(10), an induced joint was constructed from the base to 1/3 height in the middle of the dam wall, running parallel to the dam axis. While provision has been made to grout this joint, it has not yet indicated any signs of opening, as the dam was completed in 2002 and it will be many decades before all of the hydration heat has been dissipated from the core.

At Longtan Dam (195 m – phase 1) in China(11 & 12), post-cooling pipes were installed to draw out the hydration heat and to limit the maximum temperatures experienced.

7.3.5.3. Applying the "New" RCC Materials Model for Gravity Dams

Applying the proposed "New" RCC early material behaviour model, a very different situation is created in respect to the long-term temperature drop loads for large RCC gravity dams.

For a 150 m high gravity dam, a typically appropriate RCC mix might indicate an adiabatic hydration heat of approximately 15°C. In a relatively temperate climate, the critical placement temperature might be 25°C, while the long-term equilibrium core temperature might be in the vicinity of 18°C. Applying a traditional CVC model, a zero stress temperature (T3) of 40°C (maximum hydration) would be considered to apply, resulting in a final long-term temperature drop of 22°C. For a thermal expansivity of 10 x 10^{-6}/°C and an elastic modulus of 15 GPa, the above would give rise to a final shrinkage of 220 microstrain and a maximum theoretical restrained tension against the foundation of 3.3 MPa. Such a tension would substantially exceed the actual RCC horizontal tensile strength, which is likely to be less than 1.5 MPa.

Applying the proposed new RCC materials behaviour model and conservatively allowing for 2°C of shrinkage/creep, the total long-term temperature drop applicable would be 9°C (25 + 2 – 18). On the basis of the same material parameters, this would give rise to a maximum shrinkage of 90 microstrain and an associated maximum tensile stress of 1.35 MPa, which is consequently substantially less likely to cause any cracking.

Taking the case of Çine Dam (see Chapter 4), the 136.5 m high structure, which is located in a relatively temperate climate, was constructed over 6 winter seasons. With an adiabatic heat of hydration of approximately 12°C, maintaining placement temperatures at around 10 to 12°C ensured that the core temperatures within the structure never really exceeded 24°C. For a long-term core equilibrium temperature of approximately 18.5°C, the applicable maximum temperature drop to be experienced will consequently be just 5.5°C. For a thermal expansivity of 7.1 x 10^{-6}/°C, even assuming a CVC materials behaviour model would only give rise to a final shrinkage of less than 40 microstrain.

However, according to the “New” RCC materials behaviour model and even assuming a shrinkage/creep equivalent to 2°C, the RCC of the core of Çine Dam will never experience any long-term thermal shrinkage.

The implications of the proposed new RCC materials behaviour model in respect of large gravity dams are obvious; temperature issues represent a lesser constraint on dam height than had been previously considered, while significant savings in pre-cooling of RCC will be possible. Furthermore, as a consequence of the apparent elastic behaviour of RCC during the hydration cycle and the apparent absence of creep, post-cooling in gravity dams has no real purpose, but to limit the short-term thermal gradients across the dam structure.

While a high gravity dam is likely to use a high strength RCC, designing a high quality mix for negligible shrinkage and creep will incur additional cost. The savings associated with the reduction, or elimination of mix cooling would, however, substantially outweigh any such costs.

7.3.6. CHANGUINOLA 1 DAM PRELIMINARY STRUCTURAL ARCH DESIGN

7.3.6.1. Introduction

The Changuinola 1 arch/gravity RCC dam presents a particularly useful example through which to illustrate the influence and impacts of the new RCC behaviour materials model on the design of an arch dam. While the applicable climatic conditions are extremely mild, the 100 m high structure is a relatively heavy arch/gravity dam currently under construction in a wide valley.

7.3.6.2. Dam Description

Changuinola 1 Dam is a 105 m high structure with a crest length of 510m, comprising 890 000 m^3 of RCC. The central section and the right flank of the dam are on an arch with an upstream face radius of 525 m, while the left flank has a straight alignment. The spillway section has a downstream face slope of 0.5H:1V and is flanked on either sides by transition zones and gravity walls thereafter, as illustrated on **Figure 7.11**.

The dam is located on the Carribean coast of Panama at 9° North of the equator, where the climate is extremely temperate, with average monthly temperatures varying between 23.5 and 27.2°C year round. The area is also relatively seismically active and the dam is consequently subject to comparatively high earthquake loadings.

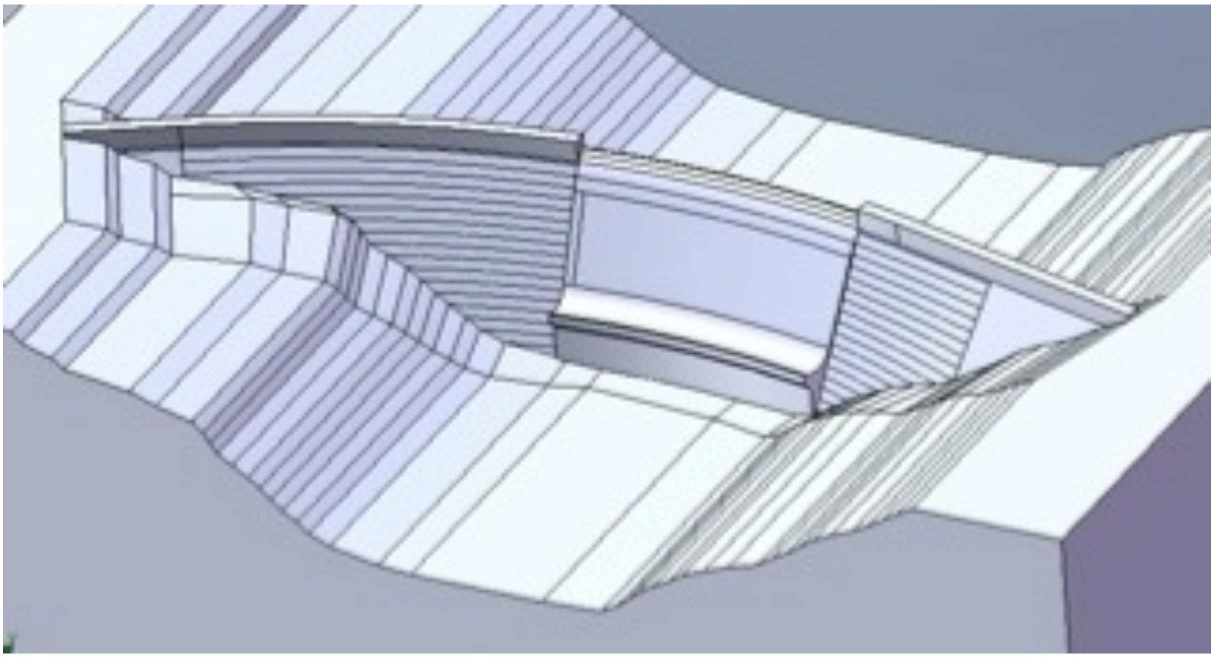


Figure 7.11: Layout of Changuinola 1 Dam

7.3.6.3. Thermal Analyses

For the purposes of illustrating the impact of the new RCC materials model on the design of an RCC arch dam, only the relevant design issues in respect of Changuinola 1 Dam are discussed.

For Changuinola 1 Dam a comprehensive thermal analysis was undertaken on the basis of measured materials properties, recorded climatic data from the site and the proposed construction programme(5). A basic outline of the thermal analysis is provided in Chapter 5 of this Thesis. On completion of the dam construction, the model applied external conditions equivalent to the annual climate cycle and an assumed water temperature cycle for a period of a few decades, until it was evident that an annual equilibrium temperature cycle was reached. Comparing these temperatures with the placement and the maximum hydration temperatures, the applicable maximum, long-term temperature drop for a traditional RCC model (as per CVC) and the "New" model could be developed.

For the purposes of ensuring a realistic approach, an effective 2°C creep was applied for the "New" RCC model.

Figures 7.12 and **7.13** illustrate the effective structural long-term temperature drop that would consequently be applicable for the traditional and the "New" RCC materials behaviour model, respectively.

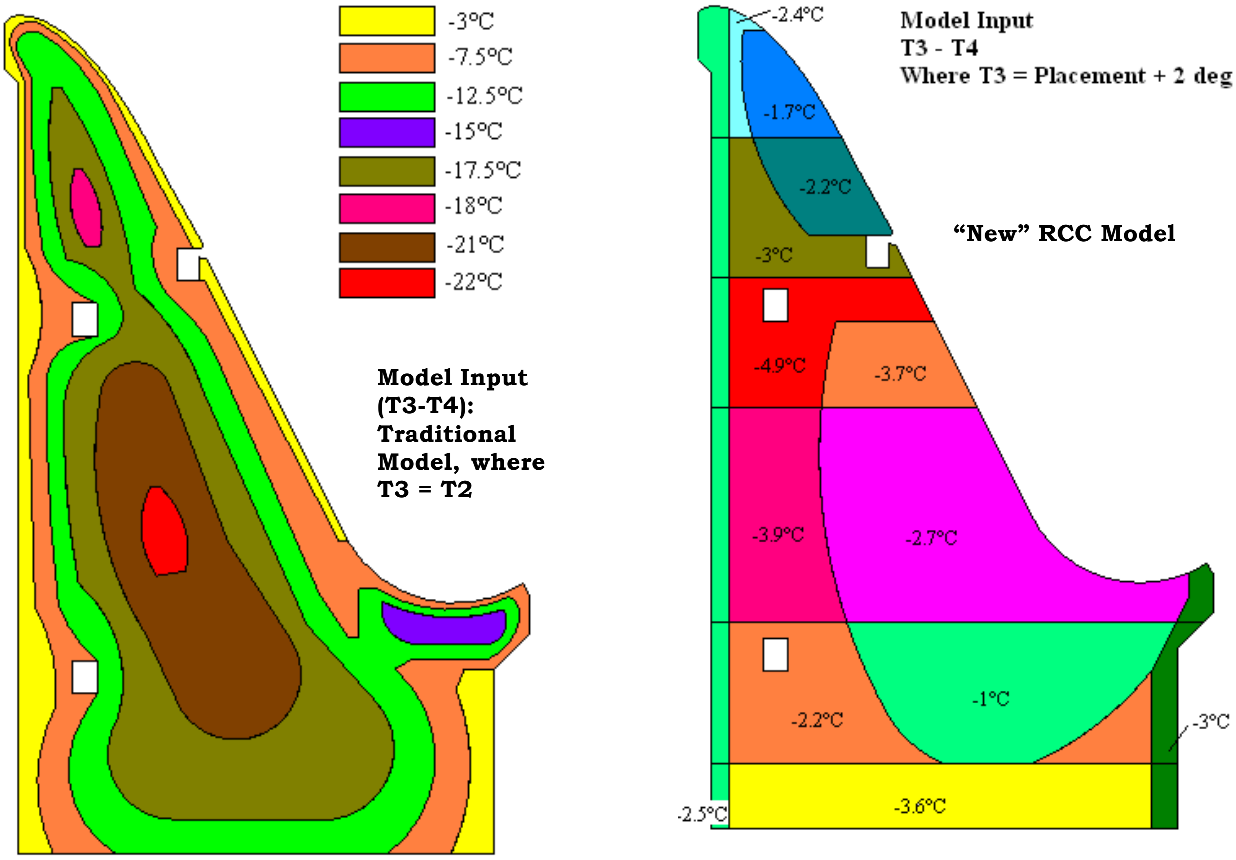


Figure 7.12 & 7.13: T3-T4 for Traditional and "New" RCC Materials Models (°C)

In addition, a study of potential cooling options was undertaken. Focusing on the section of the dam structure at and above the upper gallery, various options for the inclusion of cooling pipes were investigated. Realistically, only this upper section of the dam structure will carry any arch action under load and as long as this portion of the structure is effectively managed, ongoing cooling in the lower core of the structure can continue with no impact on the load carrying capacity of the dam.

A final arrangement was selected, whereby 4 No. 300 mm steel pipes were included in the dam model at 4 to 5 m vertical intervals between the upper gallery and the dam crest. Two cooling scenarios were subsequently analysed; one circulating chilled water at an average temperature of 6°C and the other circulating river water at approximately 25°C.

Figure 7.14 illustrates the temperatures of the concrete within the upper section of the dam structure on completion in April 2011, while **Figure 7.15** illustrates the same section after water at a temperature of 25°C has been circulated through the four cooling pipes for a period of 1 year and **Figure 7.16** illustrates the same situation after 4 months of circulation of water chilled to 6°C.

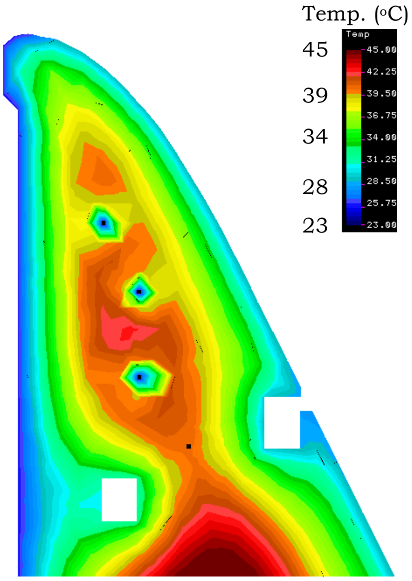


Figure 7.14
Temp. after Construction (°C)

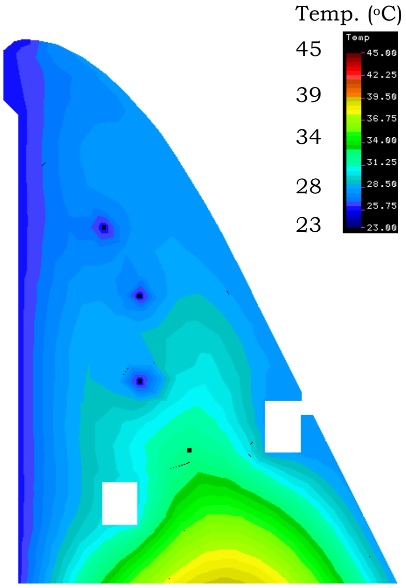


Figure 7.15
12 months of 25°C Water

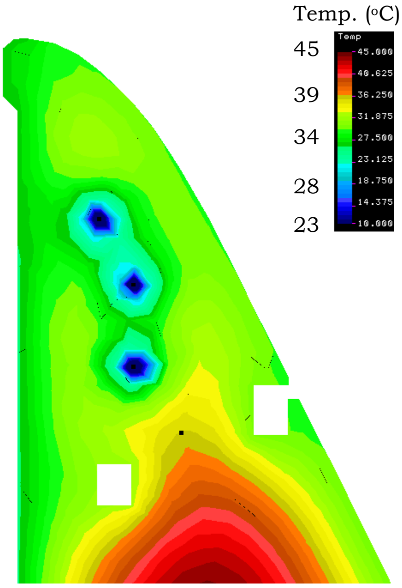


Figure 7.16
4 months of 6°C Water

7.3.6.4. Structural Design for Long-Term Temperature Drop

Traditional RCC Materials Model

According to the traditional RCC materials behaviour model, an 18°C structural temperature drop would be experienced within the core of the important upper section of the Changuinola 1 Dam structure. Over a crest length of approximately 500 m, this would imply a total shrinkage of the order of 90 mm. This is a very significant figure and, without completing a structural analysis, it can be stated with confidence that such a temperature drop would undoubtedly unacceptably compromise the structural integrity of the dam. Consequently, adopting a traditional RCC materials behaviour model implies that at least the crest of the dam structure must be cooled significantly and grouted before impoundment loading is commenced.

Circulating water chilled to between 4 and 6°C through the 300 mm steel pipes previously discussed, such cooling could be achieved within 4 months of the dam completion. A period of a full 12 months would be required if water were to be circulated at approximately 25°C.

Considering a penalty of US$ 90 000 per day for delayed commissioning of the hydropower project of which Changuinola 1 Dam is a part, there can be no question of delaying impoundment to grout the dam structure. While it would probably be possible to accommodate the 4 month 6°C cooling period within the envisaged construction programme, the impact of the significant temperature gradients between the upper section and the lower core section of the dam wall would still have to be investigated in great detail.

Proposed New RCC Materials Model

In the case of the proposed "New" RCC materials behaviour model, the thermal analyses indicated that a structural temperature drop of just 1.7 to 3°C would be applicable for the upper section of the dam, even allowing for an additional 2°C creep effect.

In order to ensure a significant level of conservatism, the proposed dam structure was analysed for long-term structural temperature drops of up to 6°C using the COSMOS(7) Finite Element structural analysis software. **Figure 7.17** illustrates the dam analysis model used, including a large massless foundation block, while **Figures 7.18** to **7.25** illustrate the critical stresses and displacements for the dam under full supply loading conditions (non-linear analysis), with and without a 6°C temperature drop applied across the full structure.

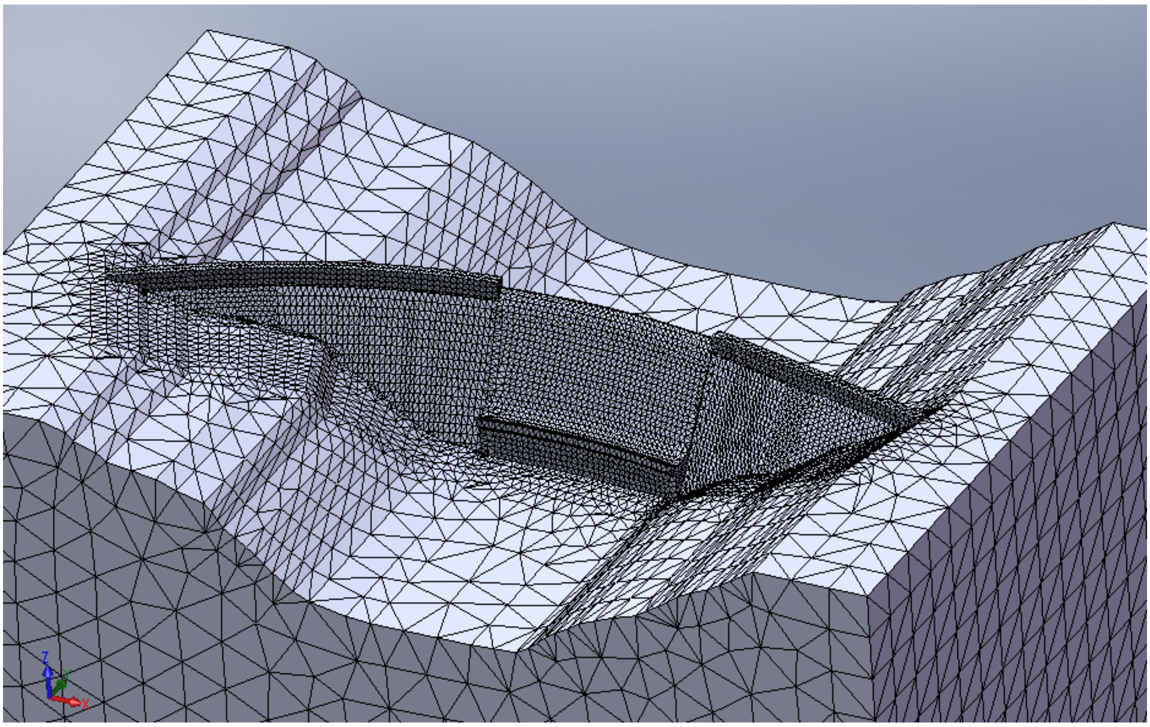


Figure 7.17: FE Analysis Model Mesh

For the above FE model, the extremes of the foundation block were constrained against movement in all directions. The 6°C temperature drop was uniformly applied to the dam wall, but not to the foundation. While this will give rise to exaggerated stresses immediately against the foundation, it is the stress state higher up the dam structure that is of specific interest in terms of this exercise.

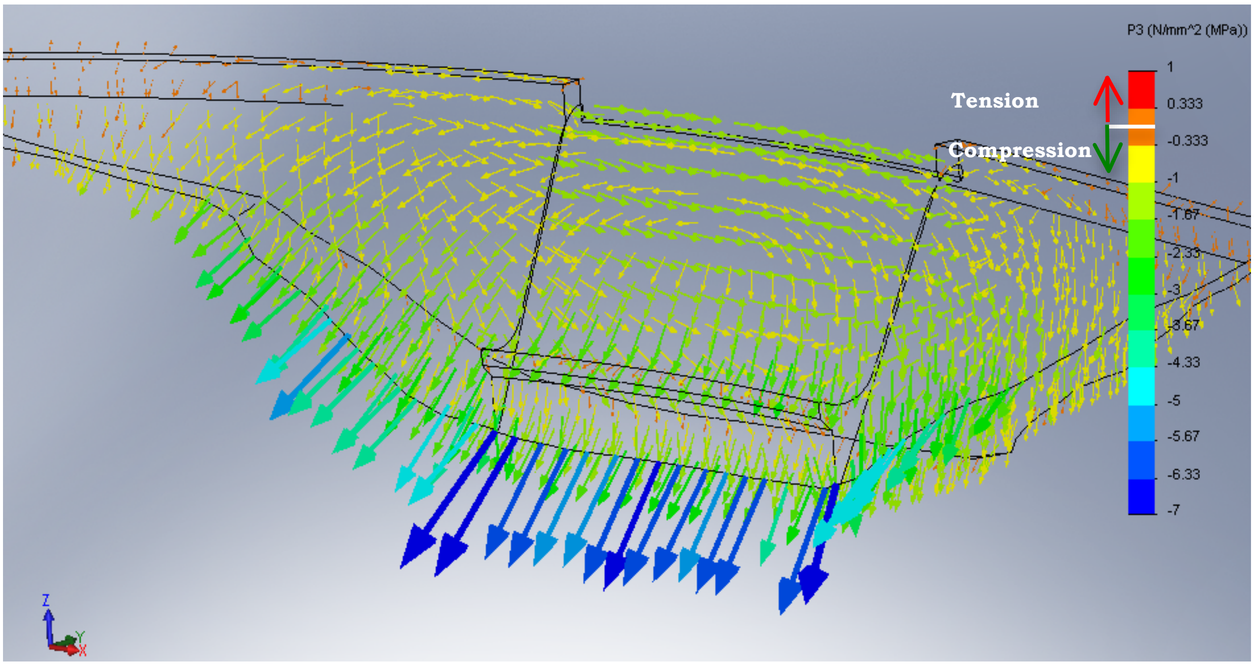


Figure 7.18: Maximum Principal (Surface) Stress Plot for FSL Load Case

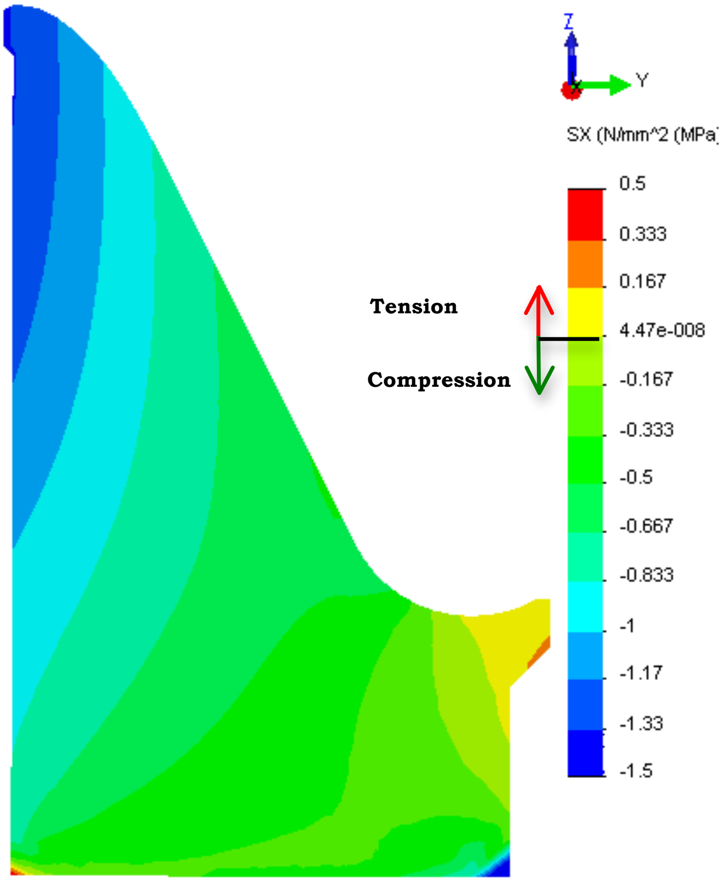


Figure 7.19: Horizontal Stresses (due to Arch Action) on Crown Cantilever for FSL Load Case (No Temperature Drop)

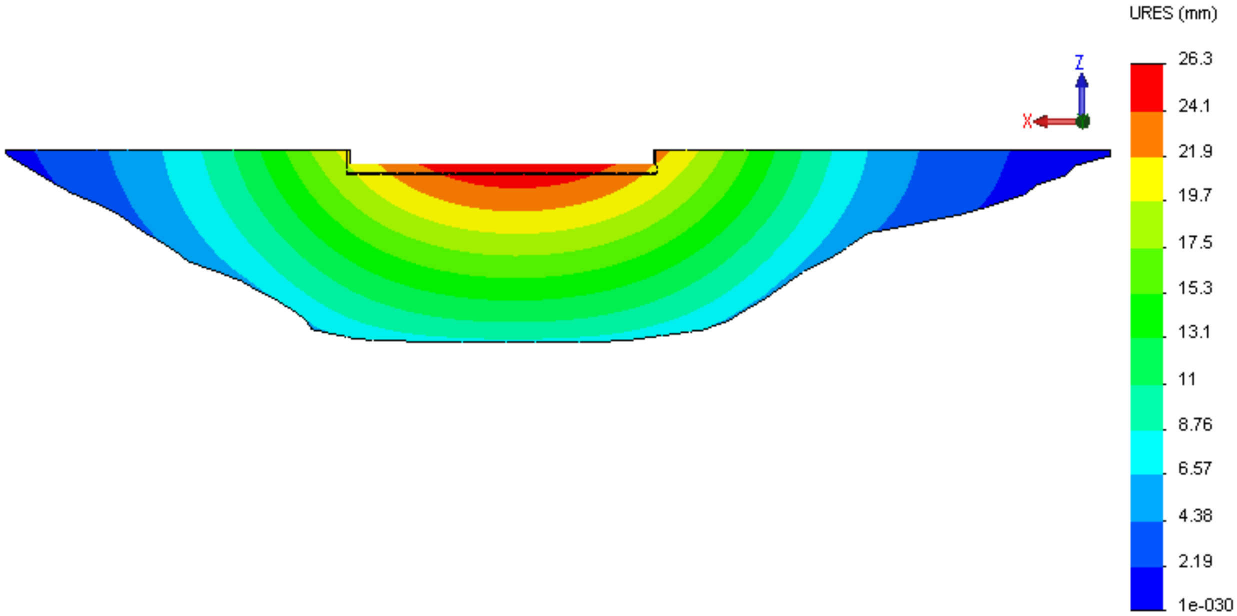


Figure 7.20: Maximum D/S Displacements for FSL Load Case (viewed from U/S)

As illustrated, ignoring temperature drop loading, the zone of arching covers almost the entire dam section, with arch stresses peaking at the upstream crest and progressively reducing with height and in a downstream direction. The maximum compressive arch stresses are 1.5 MPa.

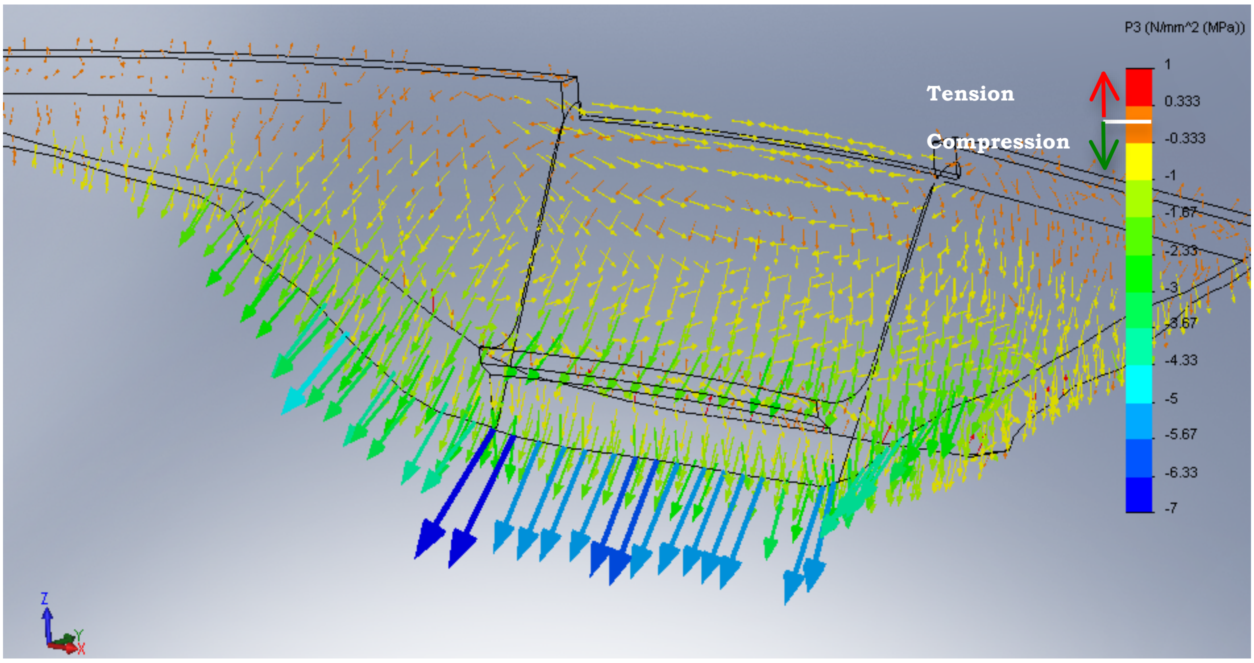


Figure 7.21: Maximum Principal (Surface) Stress Plot for FSL + 6°C Temperature Drop Load Case

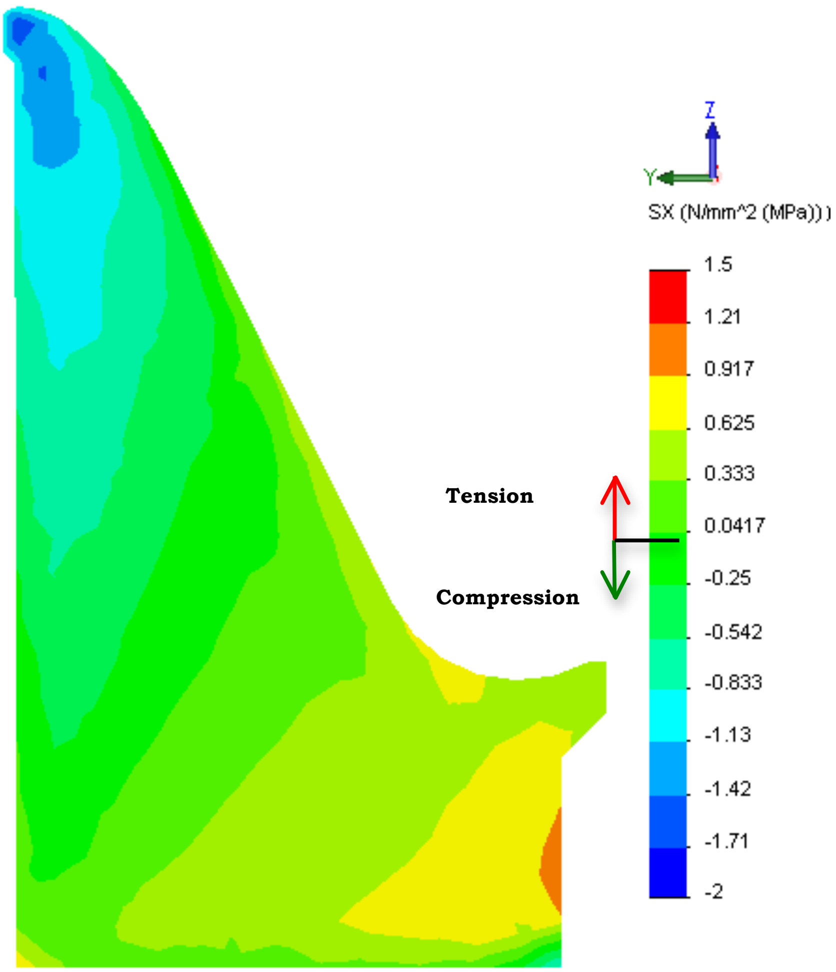


Figure 7.22: Horizontal Stresses (due to Arch Action) on Crown Cantilever for FSL + 6°C Temperature Drop Load Case

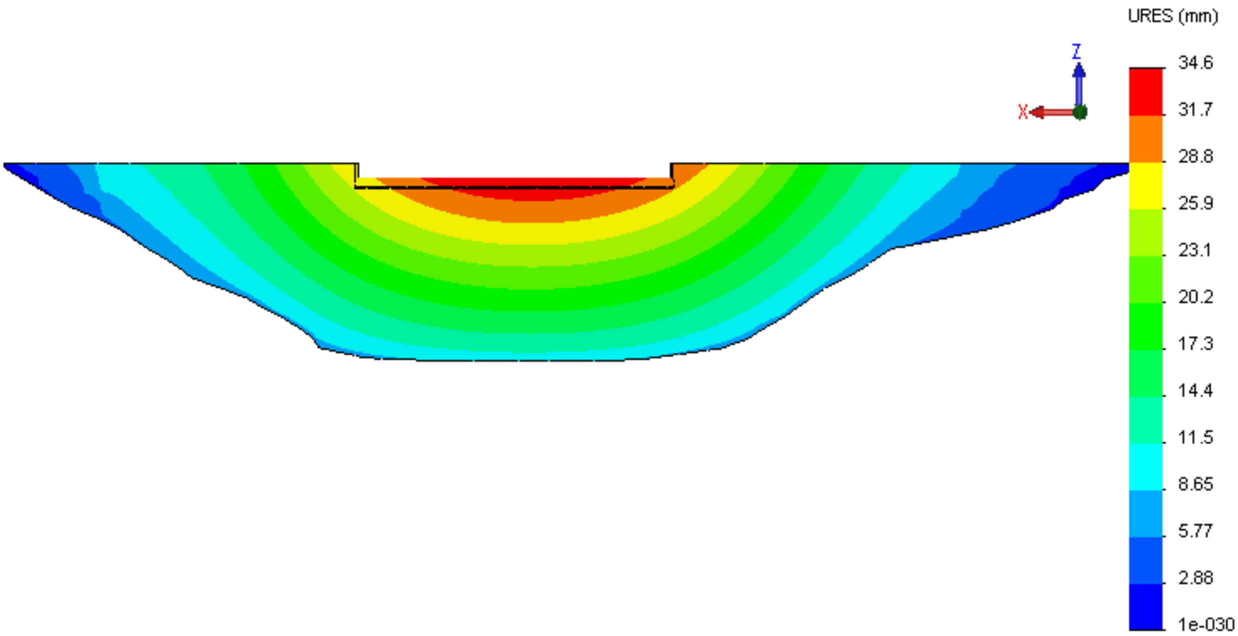


Figure 7.23: Maximum D/S Displacements for FSL + 6°C Temp. Drop Load Case (Viewed from Upstream)

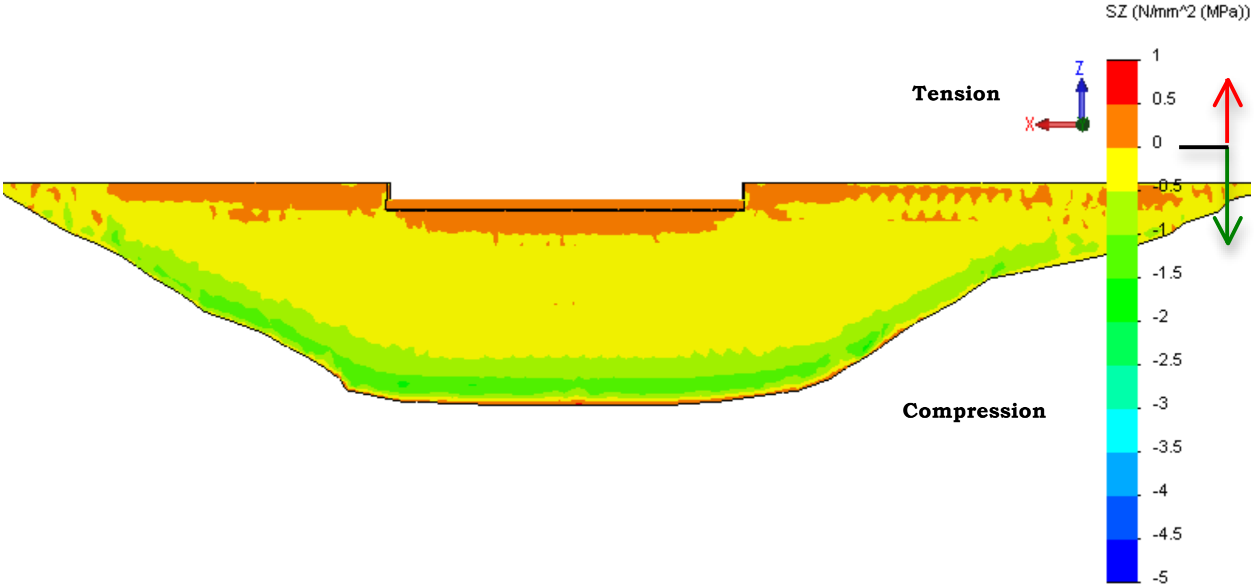


Figure 7.24: Upstream Face Vertical Stress for FSL + 6°C Temp. Drop Load Case

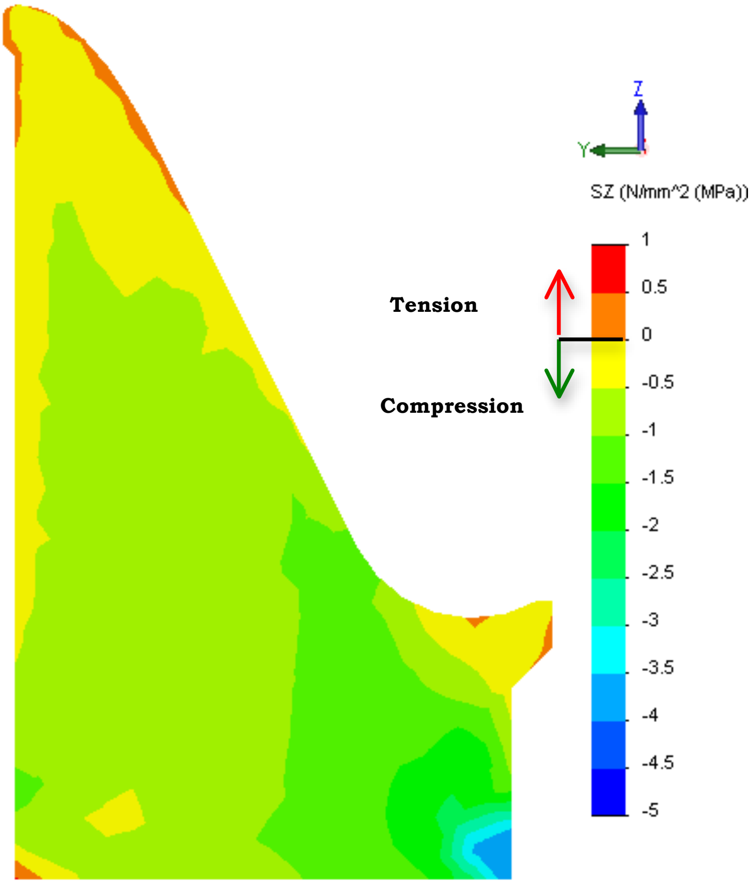


Figure 7.25: Vertical Stress on Crown Cantilever for FSL + 6°C Temp. Drop Load Case

The analysis completed applied a uniform deformation modulus with a limiting vertical RCC tensile strength of 500 KPa, which is conservative, as the RCC has been designed for a characteristic vertical tensile strength of 1.07 MPa. The materials property curve applied assumed that the RCC indicated a deformation modulus of 15 GPa for compression stresses and tensile stresses below 500 KPa. For tensions exceeding 500 KPa, the deformation modulus was reduced to zero.

Applying the 6°C temperature drop load, the arch stresses become more horizontal through the central section of the structure, but dip down more steeply through the gravity flanks. The maximum arch stresses increase to approximately 2 MPa, while the maximum downstream crest displacement increases from 26 to approximately 35 mm. The displacement plot also illustrates the evenness of the arch deflections, indicating that the structure retains an effective and efficient action, despite the imposition of the temperature drop.

The section presented in **Figure 7.22** illustrates unsurprisingly that arch stresses peak at the dam crest and decrease with height, while it can further be seen that a very substantial part of the dam structure still experiences arch compression stresses. Comparing the crown-cantilever arch stresses with and without the temperature drop, however, the introduction of horizontal tensile stresses on the downstream face as a consequence of the temperature drop is clearly evident.

Although the analyses demonstrate that the structural function of the Changuinola 1 arch/gravity structure would be compromised by the imposed 6°C temperature drop, reducing the total load carrying capacity, the relatively conservative geometry of the dam ensures that all critical stresses remain well within the capacity of the RCC, confirming the fact that the structure can satisfactorily withstand a temperature drop of this level, without joint grouting.

While a 500 KPa limiting vertical tensile strength was applied for the structural analyses, it can be seen that the residual tensions were confined to a very localized area at the heel of the structure, with the remainder of the base of the dam on the central section exhibiting compressive bearing stresses.

7.3.6.5. Discussion of Results

The above design example illustrates very simply the critical beneficial impact that the new RCC materials behaviour model will have on the future design of RCC arch dams.

Applying the traditional model would imply that extensive joint grouting would be required before loading of the dam could be permitted. In view of the fact that this grouting could only realistically be undertaken after adequate cooling of at least the upper section of the dam structure had been successfully achieved, a very significant impact on the dam design and the construction programme could be anticipated. On the other hand, structural analysis using the new RCC model, even when conservatively applied, suggests that the dam structure would perform quite adequately without joint grouting, removing any constraint on impoundment. To maintain even greater levels of conservatism and to recognise that new developments take time to gain general acceptance, Changuinola 1 Dam will be constructed with a groutable induced joint system installed in all of the structurally critical sections of the dam structure. The option of artificially cooling the concrete of the upper dam structure with water circulated through large steel pipes will also be retained until the properties of the RCC have been adequately confirmed.

It should further be noted that testing is currently underway at Changuinola 1 Dam to verify the fact that no significant creep will be encountered in the high quality RCC to be placed there and to verify the effectiveness of the joint inducing and grouting systems to be installed.

It should further be noted that the structural/thermal analyses have indicated significant upstream movement of the dam crest under gravity and temperature loading and accordingly, low containment stresses in the critical central upper arch will very likely prevent any creep being incurred during the hydration temperature rise.

7.3.7. CONCLUSIONS

7.3.7.1. Summary of Findings

In this Chapter, the author has illustrated the very significant impact of the new materials model for RCC on the design of large new gravity and arch dam structures. Furthermore, the findings of the investigations addressed herein go a substantial distance in removing a significant impediment in the design of large RCC dams. If RCC does not suffer from many of the problems inherent to CVC, there is no reason to be compromised by those problems in the design of RCC dams.

7.3.7.2. The Impact of the New Understanding of RCC Materials Behaviour

Adopting the proposed new understanding of the early behaviour of RCC, or the “New” materials behaviour model for RCC, consideration can be given to the construction of RCC arch-type dams in temperate climates without groutable joints, while the need and approach to pre- and post-cooling of RCC will require a re-think.

7.3.7.3. Application of the New Understanding of RCC Materials Behaviour

Considering the fact that the proposed new understanding of the early behaviour of RCC has yet to be broadly tested and explored, it should be conservatively applied at this stage. However, it is considered that testing of RCC on a full-scale trial should be routinely undertaken in an effort to more clearly understand the nature of the specific RCC to be used at each and every dam. Furthermore, the inclusion of appropriate temperature and strain measurement instrumentation in all RCC dams is encouraged as a means to develop a broader database and to better understand how, when and why RCC behaves differently to CVC. On the basis of this information, associated confidence levels will be increased and it will consequently be appropriate to apply the new materials understanding for RCC less conservatively.

Testing at Changuinola 1 Dam has verified the functionality of the joint inducing and grouting system to be installed. During early testing with grouting of the joint system to be included in the main dam structure, it proved possible to sustain a grout pressure of 2 MPa and to consequently break open and comprehensively grout a crack.

In the event that it is decided to grout the installed system at Changuinola 1, the 2 MPa grout pressures that can be achieved would be able to effectively mitigate the impacts of a 13°C temperature drop. This would also potentially allow the grouting of induced joints while the dam structure is under load, implying that grouting might not need to delay the impoundment date.

Testing is also ongoing on the main dam at Changuinola 1 in effort to confirm whether any shrinkage, or creep in the RCC might be experienced during the hydration cycle. Should this testing yield meaningful results, it is considered that the groutable joint system will be installed as a safety back-up, with the intention only to grout the joints should some unexpected behaviour be observed.

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