APPENDIX A

THE EFFECT OF TEMPERATURE DROP LOAD ON STRUCTURAL ARCH ACTION

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Background

Conventional mass concrete dams are constructed as a series of vertical, monolithic blocks (see **Figure A1**). These blocks are proportioned to accommodate concrete autogenous and drying shrinkage and shrinkage creep that occurs during the hydration cycle. Limiting the dimensions of each block, restraint against shrinkage is reduced and residual tensile stresses are maintained below the concrete tensile strength, to eliminate the possibility of cracking. In the case of a gravity dam, which functions to transfer the water load directly into the foundation in 2 dimensions, the monoliths are connected with waterstops, but are otherwise simply allowed to shrink away from each other.

In the case of an arch dam, which transfers the water load in 3 dimensions into the foundation, it is necessary to re-establish structural continuity between the monolithic blocks. Once all shrinkage and creep has occurred, the hydration heat has been dissipated and the concrete is at a low temperature, continuity is consequently re-established by filling the gap between the monoliths with grout under pressure. In order to allow the joint grouting to be undertaken and subsequently the structure to be loaded, it is often necessary to draw out the hydration heat using chilled water circulated through looped pipes, which are cast into the concrete. In addition, ice is quite often added into the concrete during mixing in an effort to suppress the maximum temperature experienced during hydration. Constructing in vertical monoliths, with lift heights commonly of the order of 2.5 m, also allows some of the hydration heat to be dissipated before the subsequent lift is superimposed.

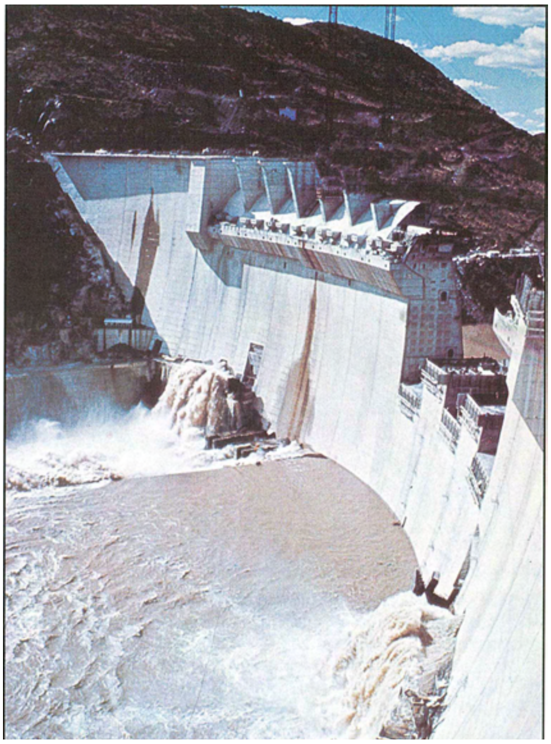


Figure A.1: CVC Arch Dam Construction in Monoliths

In the case of Roller Compacted Concrete (RCC) construction, the dam is essentially placed horizontally and contraction joints are induced rather than formed, while the process of bulldozer-spreading and roller compaction does not lend itself readily to the incorporation of cooling pipe loops. Furthermore, the rapid nature of the placement implies that the majority of the heat generated in the process of hydration is trapped within the body of the dam.

In Rubble Masonry Concrete (RMC) construction, the dam is also essentially placed horizontally, but in this case, no contraction joints are included. As the structures are generally small, the sections are thin, the cement content is low and construction is slow, instrumentation has demonstrated that the entire hydration heat escapes quickly and the temperature of the RMC material is not really raised in the process ofthe hydration cycle. While the temperature drop load on an RMC arch is accordingly limited to the difference between the placement temperature and the final coldest winter temperature, the thin sections imply that very little insulation is provided to the core of the dam and consequently, this load can quite easily exceed 10ºC. With no contraction joints and consequently no facilities to redress temperature shrinkage, the dam structure itself must be designed to accommodate the full temperature drop without developing deleterious stress levels.

Introduction

This brief document presents an explanation of the impacts of temperature drop loads on the structural function of arch dams. In view of the fact that they never have formed, or induced joints, RMC dams will be used to demonstrate the associated effects and impacts of a typical range of temperature drops.

Arch Dams and Temperature Drop Loads

Due to the fact that RMC arch dams are constructed without contraction, or expansion joints, all thermal effects, expansion as a result of hot temperatures and contraction as a result of cold, must be accommodated within the body of the structure itself. In relatively thin structures, such as arch and arch buttress dams on the scale applicable to RMC, the entire wall will be largely subject to surface temperature effects, significant insulation from external temperatures typically only occurring at depths in excess of 3 - 4 m from surface. Similar thermal phenomena and consequential effects have been studied in some depth for other concrete dam types and specifically for RCC dams. RCC arch dams suffer similar effects, particularly in respect of the fact that both RCC and RMC dams are constructed as continuous bodies, usually in horizontal placement layers from one flank to the other, and not monolithic vertical blocks as is the case for conventional concrete. Although placement rates and hydration heat related problems are significantly different in each case, parallels may be drawn and much experience gained in thermal and related structural analysis of concrete and RMC arches may be applied to RCC arches.

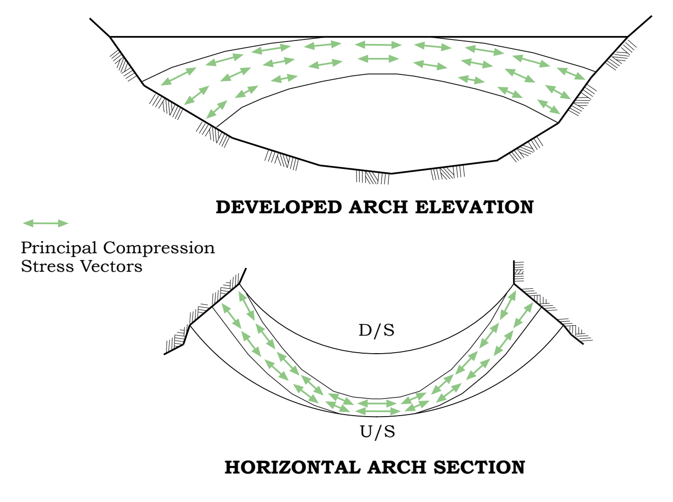


Figure A.2: Typical Stress Flow in Arch

All variants of the concrete arch dam are inherently susceptible to temperature related effects, although very efficient arches, such as those in tight V shaped valleys where arch stresses are high, are less sensitive than those in wider, open valleys, where cantilever stresses are more pronounced. Whilst an arch dam is an inherently safe structure which can generally be pushed way beyond design loadings before failure, nevertheless it is considered important that efficient function is preserved and that the mode of structural function is well understood by the designer.

In the case of an arch dam in a wide valley (width/height, or canyon factor > 3.5), the water load develops arch stresses that are transferred internally through the top of the dam in the centre down into the lower portion of the abutment on each flank (see **Figure A.2**). Very little lateral compression is developed in the lower portion of the central section of the wall. When subjected to low temperatures, the wall structure effectively shrinks, although its foundation remains unaffected, causing tension across the structure, from one abutment to the other. To accommodate the water load, the structure must take up these tensions through movement, which occurs by a general deflection of the crest downstream and an associated tipping forward of the dam wall, which causes increased tensions at the upstream heel and increased compressions at the downstream toe. In addition, the area of effective arch compression, through the upper portion of the dam in the centre (between abutments), decreases and associated levels of compression over this smaller area correspondingly increase. In broad and general terms, less of the structure functions to transfer water load into the foundations, stress within the effective areas increases and the structure becomes effectively less efficient in function, with a significant portion of its volume no longer carrying structural load.

This effect can be described by imagining the dam wall as a series of monolithic blocks as pictured in **Figures A.3 to A.6**. Temperature shrinkage of the wall would cause each of these blocks to reduce in size and shrink away from each other as illustrated in **Figure A.4**, the most significant opening between blocks occurring farther away from the restraining points (abutments).

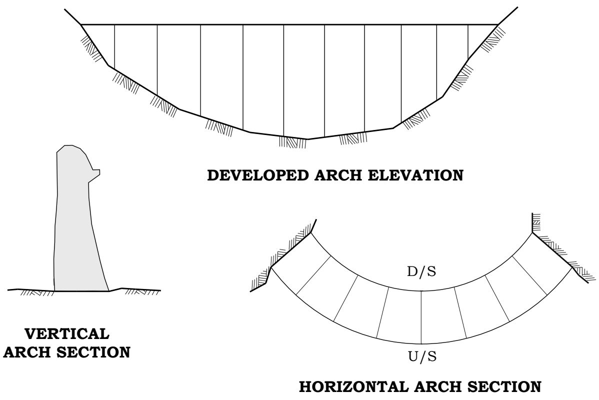


Figure A.3: Arch as Series of Blocks

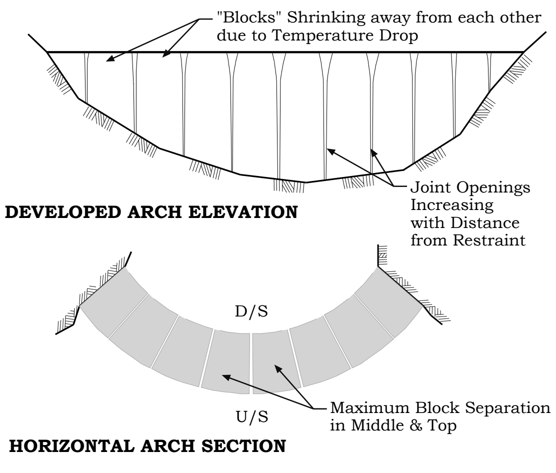


Figure A.4: Typical Temperature Loss Shrinkage

To accommodate the water load and associated arching stresses, the blocks deflect as cantilevers in a downstream direction until closure between blocks occurs at the crest. As a result of restraint of the wall against the abutment on either flank and the higher flexibility of the taller cantilevers, the central portion of the crest moves farthest, with each successive block to the sides moving less. The consequence of this effect is a final arch with a larger effective radius (see **Figure A.5**). The alignment of the sides of each block remains oriented on the original radius and accordingly the wedge shaped blocks are effectively too narrow at their downstream faces to form complete and even contact with each other on the larger, deflected radius. This in turn implies that the blocks will make contact with each other initially only over the upstream side of their respective surfaces and the arch will accordingly display a "bursting" effect. In this process horizontal compressive stresses in the central upstream portion of the arch increase, as do horizontal tensions in the downstream portion and tensions in the heel and compressions in the toe at the abutments. Looking at the wall in terms of a series of cantilevers, this effect is seen as a tipping forward of the upper portion as shown in **Figure A.6**.

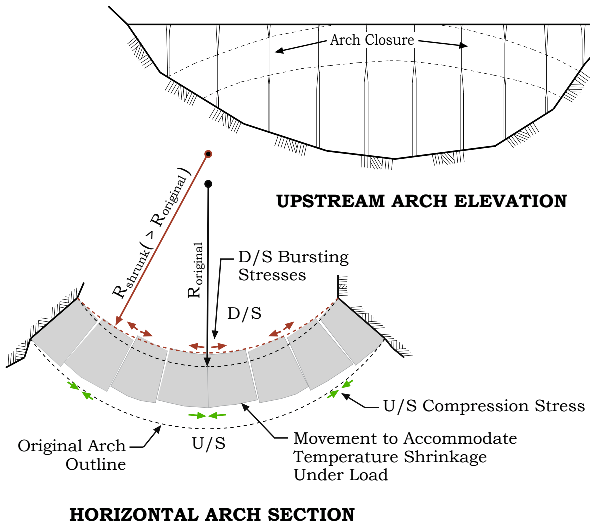


Figure A.5: Shrunk Blocks under Water Load

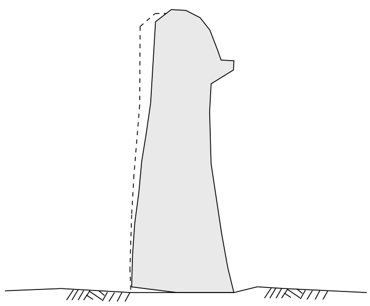


Figure A.6: Deflection of Cantilever

In the described process a great deal of the efficiency of the arch is lost, with only the portions of the structure illustrated in **Figure A.4** actually being effective. If a zero tensile stress is assumed for the RMC all areas of tension will be subject to cracking and compressive stresses in the remainder of the wall will correspondingly increase to redistribute structural load.

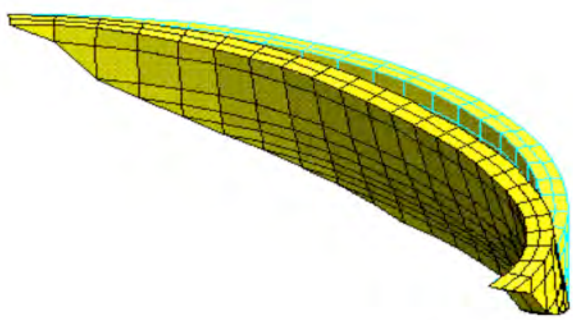


Figure A.7: Exaggerated Wall Deflections for Temp. Drop & Water Loads

In the case of a conventional concrete arch dam, these temperature effects are mitigated by construction in monolithic blocks, with subsequent grouting at low temperature to re-establish structural continuity between the blocks, on the original arch radius. In the case of an RMC dam, it is not possible to re-establish structural continuity by grouting and the design must accommodate these effects; in virtually every case, the most severe loading case for an RMC arch being hydrostatic, gravity, uplift and temperature drop loads.

Quantification of Typical Temperature Drop Impacts

In order to quantify the above temperature drop effects in the case of a typical RMC arch dam and to provide some illustration of the impact on stress patterns, a simple elastic Finite Element analysis was completed. The arch model was configured to a maximum height of 20 m using the COSMOS/M FE analysis system, with a constant extrados (upstream face) radius of 60 m, a wide valley canyon factor (crest chord length/height) of 5, a constant wall thickness of 3 m and a crest arch aperture angle of 120°. Whilst this geometry is fairly typical of a larger scale wide valley arch constructed in RMC, it also represents a very effective arch shape, in terms of structural function. Furthermore, an idealised, symmetrical arch was applied, as opposed to a real example, in order to ensure that secondary effects, or stress peculiarities resulting from topographical discontinuities, or irregularities did not cloud the structural and temperature evaluation.

A typical South African climate might see effective RMC placement temperatures averaging 22°C, final minimum winter water temperatures of 10°C and a minimum average daily winter air temperature of 8°C. Assuming some insulation and temperature time lag, and remembering the thin sections typical of RMC arches, an effective temperature drop of the RMC from placement to minimum winter temperature might exceed 10°C. For the Finite Element analysis, the stress patterns in a full dam were compared for the cases of an 8°C uniform body temperature drop and no temperature drop.

The following series of figures is presented as a means to illustrate the comparative critical stress levels and patterns, when temperature drop loads are ignored and when they are taken into account.

Figures A.8 and **A.9** illustrate clearly the impact of the 8°C temperature drop on the downstream face stresses, with the strong pattern of horizontal arching disappearing to be replaced by bursting tensions and a more vertical transfer of stresses into the foundation at the base of both flanks. The concentrated stress levels can further be seen to increase dramatically.

Figures A.10 and **A.11** illustrate the manner in which the temperature drop causes the even, horizontal arch stresses in the upstream face to become concentrated toward the top of the structure, as the shrunk cantilevers displace toward the downstream under load and make contact with each other at the crest. The concentration of stresses over a small contact area correspondingly causes the maximum values to increase. The general tipping forward of the cantilevers causes the heel tensions (and toe compressions) to rise very dramatically. In effect, the temperature drop causes the arch structure to become a series of propped cantilevers, with a propping action being provided by arching developed at the crest, as contact between adjacent cantilevers prevents further downstream movement. This further accounts for the vertical tensions on the tallest portions of the downstream face, as bending between the foundation and the "propped crest" induces a beam action.

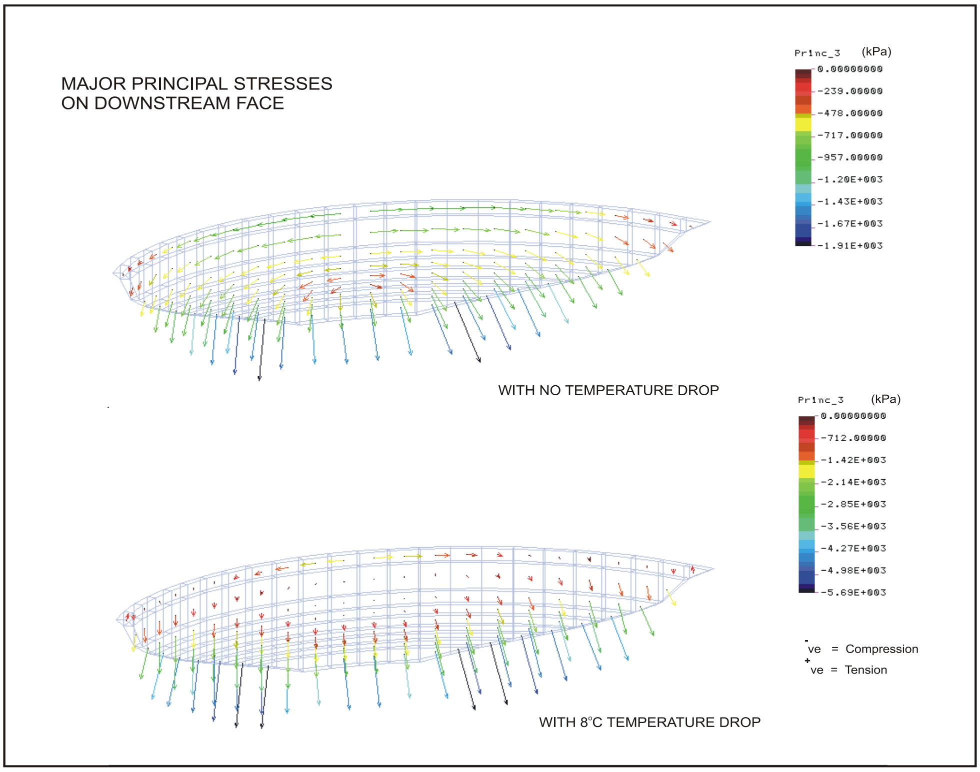


FIGURE A.8: MAJOR PRINCIPAL STRESSES ON DOWNSTREAM FACE

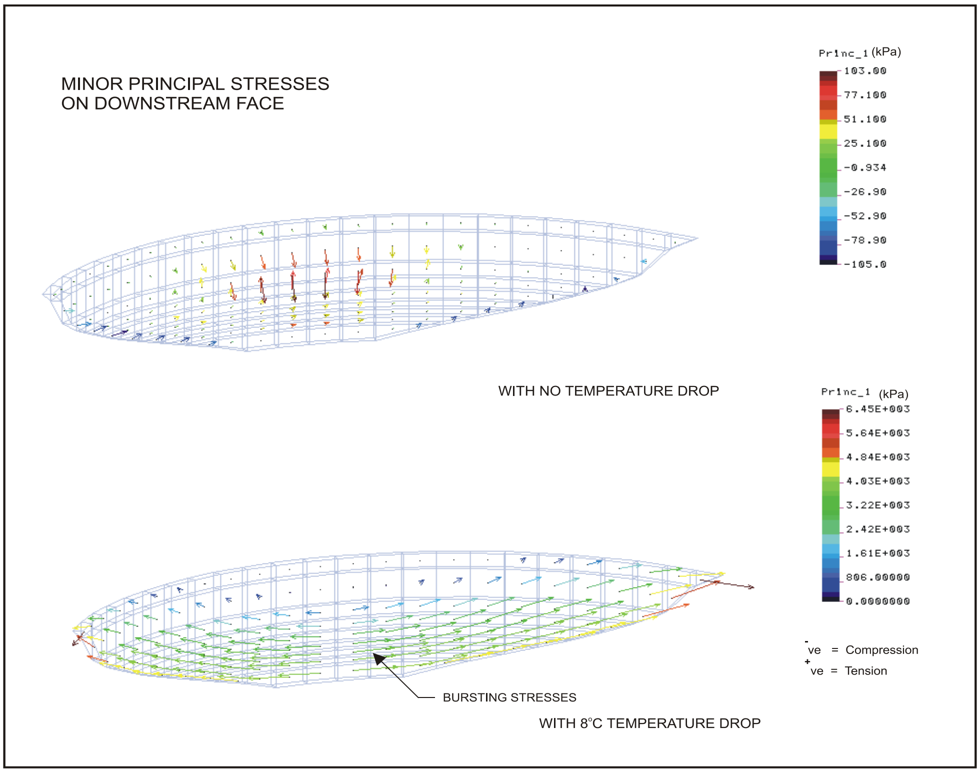


FIGURE A.9: MINOR PRINCIPAL STRESSES ON DOWNSTREAM FACE

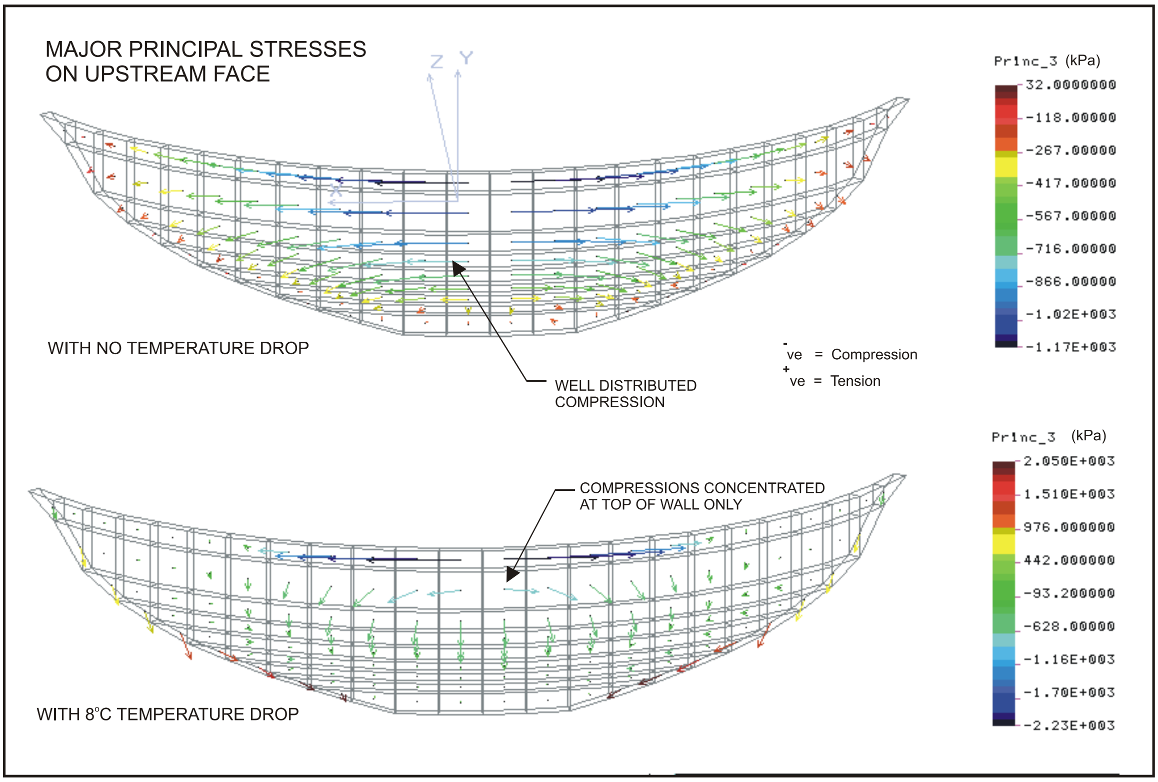


FIGURE A.10: MAJOR PRINCIPAL STRESSES ON UPSTREAM FACE

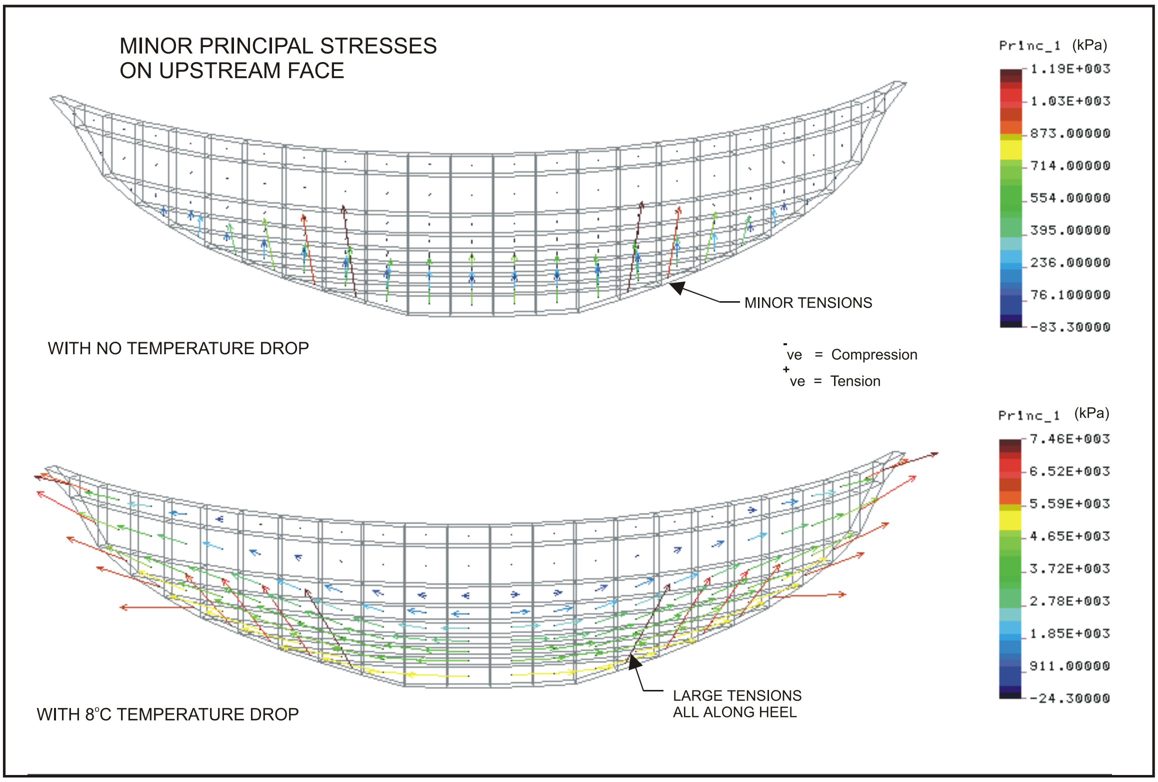


FIGURE A.11: MINOR PRINCIPAL STRESSES ON UPSTREAM FACE

Figure A.12 reflects the manner in which very significantly greater shear stresses are developed in the structure as a consequence of temperature drop. It should of course be borne in mind that the shear stresses indicated relate primarily to the restraint of the shrunk dam structure by the fixed foundation. In reality this effect will be mitigated slightly by the fact that the virtually constant temperature of the foundations will tend to ensure that temperature variations in the immediate areas of the dam are less significant than elsewhere.

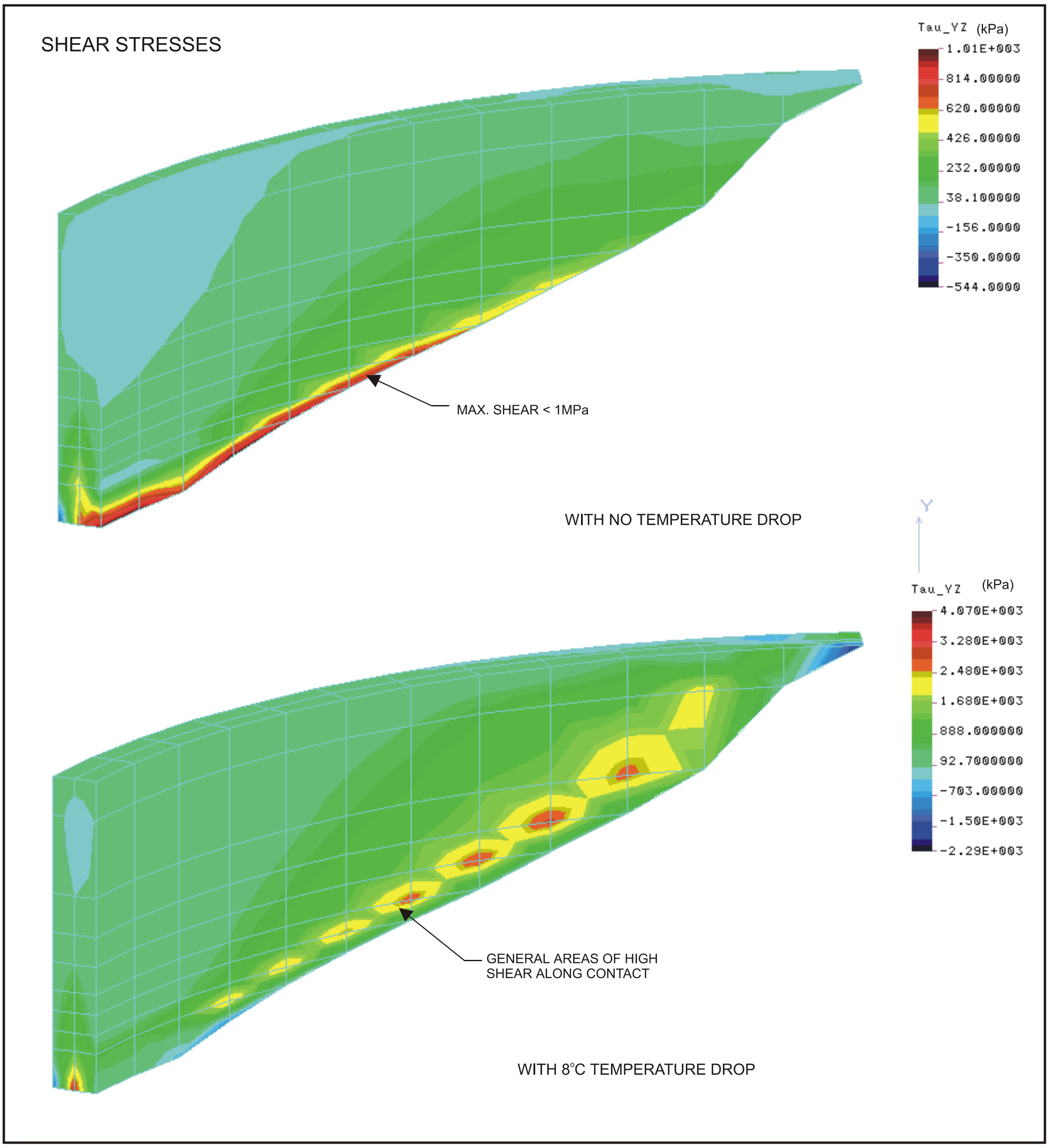


FIGURE A.12: SHEAR STRESSES

QUANTITATIVE ANALYSIS OF CRITICAL STRESS VARIATIONS FOR VARIOUS TEMPERATURE DROP LOADS AND MATERIALS PROPERTIES

Background

The foregoing discussion and analyses clearly reflect the very significant impact of a range of typical temperature drop loadings on an RMC arch dam, in terms of stress patterns. The following set of analyses was completed in order to quantify the impacts in terms of critical maximum stress levels in relation to variations in temperature drop and RMC constituent materials properties.

Analysis Description

For the purpose of this temperature sensitivity analysis, the same idealised, symmetrical, wide valley arch dam as developed for the previously described analysis was applied; with a maximum height of 20 m, a developed crest length of 120 m, an arch extrados radius of 60 m, a constant wall thickness of 3 m and a crest arch aperture angle of 120°.

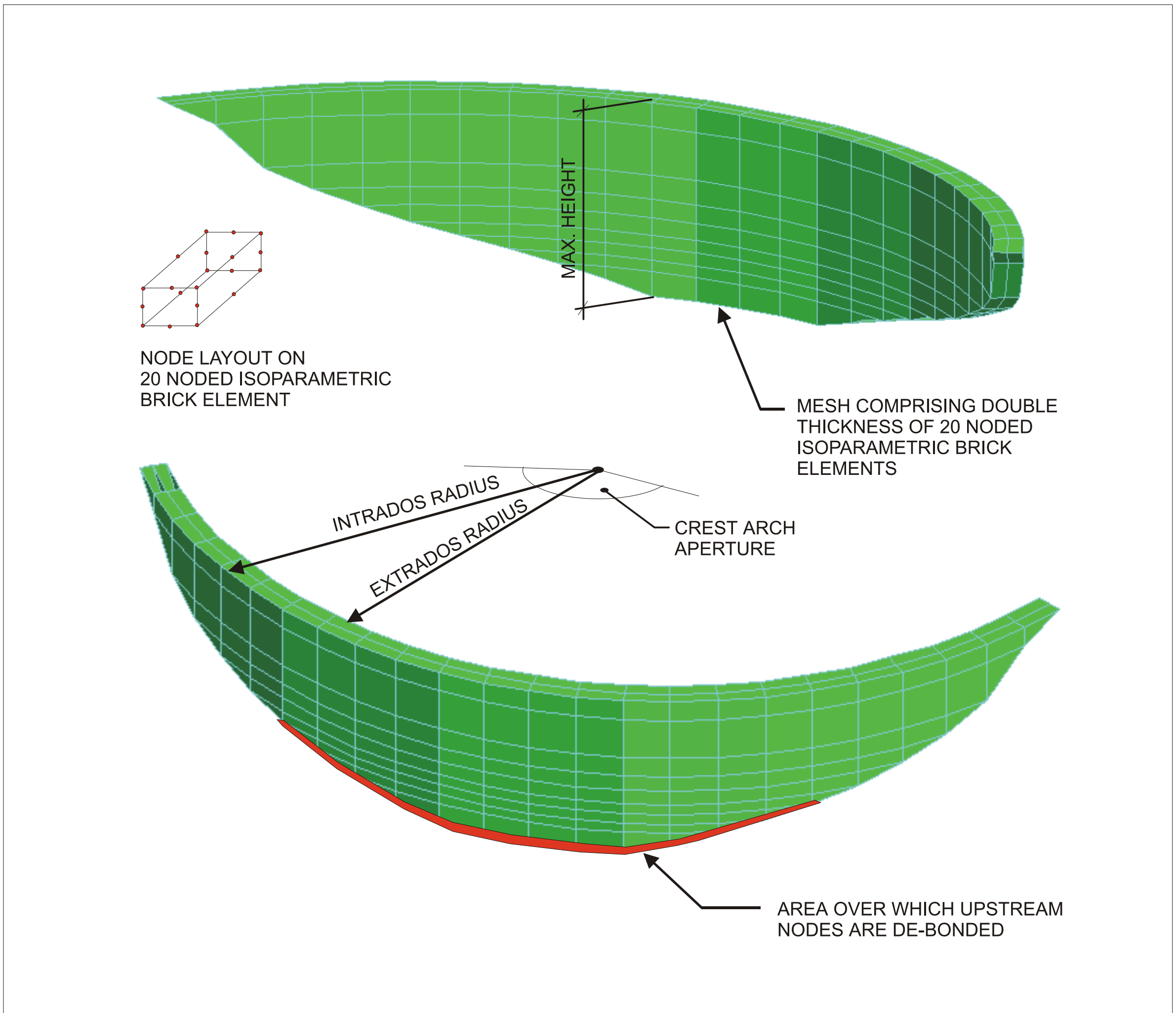


FIGURE A.13: ARCH MODEL DEFINITIONS AND DESCRIPTION

Analysis Methodology

All analyses were undertaken using a material density of 25 kN/m^3 and full supply hydrostatic loading, ignoring uplift and silt. Against these constants, the relative effects of various uniform temperature drops and variation of effective elastic modulus and thermal expansivity were reviewed. Whilst the actual effects of uplift are not likely to be significant, with a wall thickness of just 3 m, in particular circumstances, it could be unwise to ignore silt accumulation in a real design. However, in the case of the analyses addressed herein, the structural loading only really represents a reference against which respective temperature effects are evaluated in a qualitative manner and stresses are not derived for review against specific target, or limiting values. Indicated stresses are accordingly under-estimated. The COSMOS/M Finite Element Analysis system was applied for these analyses, using only the elastic module for simplicity.

Analysis Model

To reduce overall process time on the 33 analyses comprising this sensitivity study, the dam wall alone was analysed, without a foundation. Nodes on the foundation were constrained against translation, which creates conditions equivalent to a fully rigid foundation. While the wide-valley arch shape of the wall will allow this simplification without developing stress anomalies, the over-rigid foundation will result in an underestimation of total arch deflection and any downstream face bursting stresses (S1 - D/S) and an exaggeration of toe compressions (S3 – D/S).

Analysis Loadings and Material Properties

For the thermal sensitivity analyses, a range of three temperature drops was adopted; 6^o, 8^o and 10^{o}C. These figures represent realistic total structural temperature drops in a structure of relatively thin section (< 4m), in relatively moderate climatic conditions. Whilst the 6^{o}C temperature drop is considered low for all but thicker section structures in a very temperate climate, even 10^{o}C might be considered too low for a dam built during the summer months in an area that experiences low winter temperatures. A range of elastic moduli and thermal expansivities for RMC were adopted, in line with the appropriate values for concrete composed of various typical aggregate types. For example, RMC elastic moduli of 15, 20 and 40 GPa were applied. While 40 GPa might be considered rather high as an effective elastic modulus for RMC, it was included in an effort to evaluate the influence of a particularly high modulus that might result as a consequence of the direct contact of large size, high quality rock particles. Thermal expansivities of 5, 7 and 12 x 10^{-6} per ^{o}C were evaluated, which values reflect a typical range of equivalent figures for concretes composed of aggregates of granites and gneisses to quartzites and cherts respectively.

De-bonding Interface Nodes in Tension

The initial analyses revealed relatively high levels of tension at the upstream heel of the dam under normal loading conditions, ignoring temperature drop effects. To relieve some of these stresses and to bring the general tension to a more acceptable level, the upstream row of nodes at the heel in the centre of the wall was freed from restraint and allowed to move. Whilst this lowered general upstream tensions to typically acceptable levels under normal loading conditions, the imposition of temperature drop and a worsening in material properties took tensions on certain of the inner nodes to extremely high levels. Such tension would undoubtedly cause cracking and a significant rise in related toe compression levels. However, the model was not changed for such loading situations, as its purpose is one of comparison rather than isolating final stress levels.

Analysis Results

Stress and displacement plots were developed for each loading case and material property combination and contour versions of two such plots are illustrated here in **Figures A.15** to **A.18**. Colour vector plots are the preferred medium for result analysis for arch dams, as this output format allows the most effective evaluation of stress movement through the structure and the typical stress patterns applicable in the case of the arch dam studied can be observed on **Figures A.8** to **A.12**. The major stresses and displacements read off these plots are listed in **Table A.1**. The stress values listed are nodal values and these can be rather exaggerated in elastic FE analysis, particularly at a discontinuity.

In **Table A.1** the principal stresses indicated may be defined as follows:

- S3 (D/S) - Downstream Face Cantilever Toe Compressive Stress;
- S1 (U/S) - Upstream Face Cantilever Heel Tension;
- S3 (U/S) - Upstream Face Arch Compressions; and
- S1 (D/S) - Downstream Face Arch bursting Tensions.

The location of the critical stresses listed in the table are indicated on **Figure A.14**.

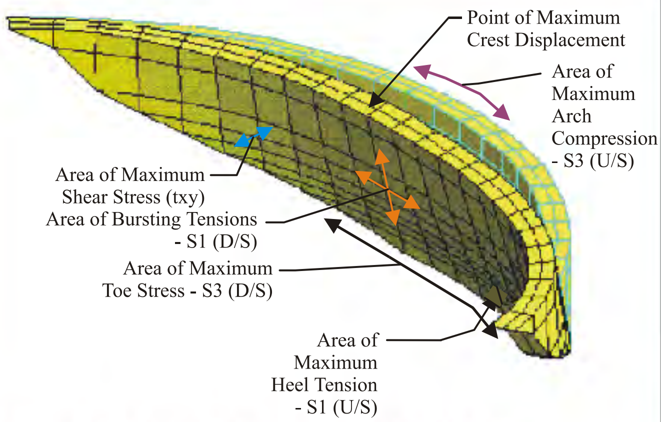


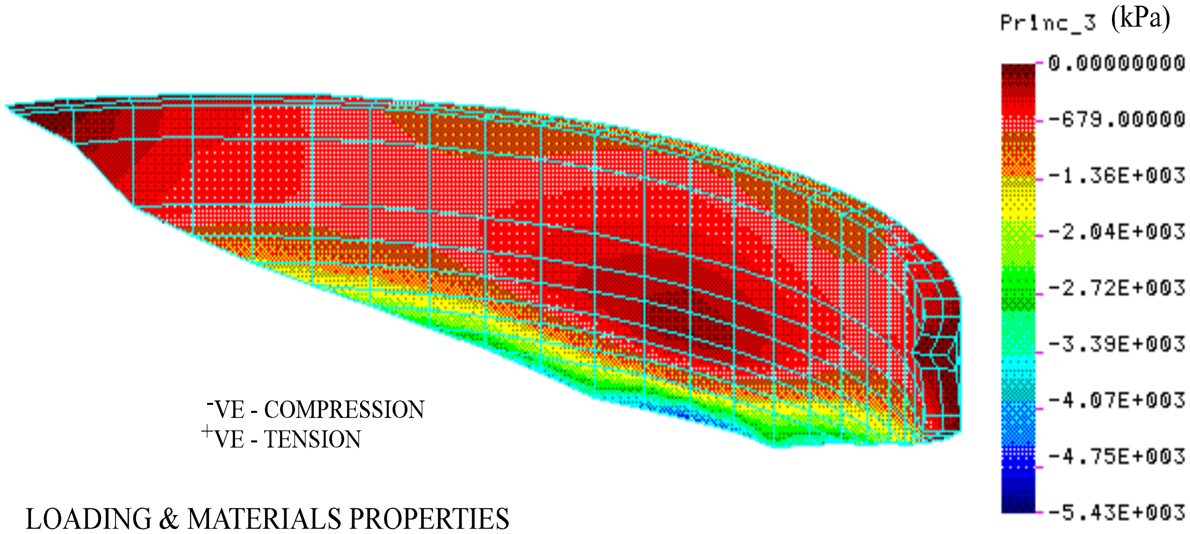
FIGURE A.14: AREAS OF MAXIMUM STRESS IN WIDE VALLEY ARCH DAM

Table A.1: Summary of Stress Analysis Results

Total Temp. Drop (°C)	**Thermal Expans-ivity** (Strain/°C)	**Elastic Modulus** (GPa)	**Max D/S Displac'nt** (mm)	**Stress** (MPa)				
				S3 (D/S)	**S1** (U/S)	**S3** (U/S)	**S1** (D/S)	**txy**
10	5×10^{-6}	15	10.3	7.25	- 4.75	1.65	- 0.76	1.30
		20	8.8	7.87	- 5.41	1.75	- 1.01	1.39
		40	6.5	10.40	- 8.09	2.51	- 2.01	2.00
	7×10^{-6}	15	12.0	7.99	- 4.75	1.77	- 1.06	1.41
		20	10.5	8.87	- 5.41	1.93	- 1.41	1.56
		40	8.2	12.40	- 8.09	3.28	- 2.82	2.60
	12×10^{-6}	15	16.2	9.88	- 7.55	2.32	- 1.81	1.85
		20	14.7	11.4	- 9.16	2.90	- 2.41	2.30
		40	12.4	15.8	- 16.2	3.23	- 4.83	4.12
8	5×10^{-6}	15	9.5	6.88	- 4.35	1.59	- 0.605	1.24
		20	8.0	7.37	- 4.88	1.67	- 0.805	1.32
		40	5.7	9.37	- 7.01	2.33	- 1.607	1.71
	7×10^{-6}	15	10.8	7.47	- 5.00	1.69	- 0.84	1.33
		20	9.3	8.17	- 5.73	1.87	- 1.13	1.44
		40	7.0	11.00	- 8.73	2.74	- 2.25	2.18
	12×10^{-6}	15	13.9	8.82	- 6.40	1.91	- 1.39	1.59
		20	12.4	9.98	- 7.66	2.35	- 1.85	1.94
		40	10.1	14.70	- 12.60	4.29	- 3.70	3.37
6	5×10^{-6}	15	8.6	6.51	- 3.96	1.23	- 0.46	1.18
		20	7.1	6.88	- 4.35	1.31	- 0.61	1.24
		40	4.8	8.37	- 5.94	1.83	- 1.20	1.47
	7×10^{-6}	15	9.7	6.95	- 4.43	1.60	- 0.64	1.25
		20	8.1	7.47	- 4.99	1.69	- 0.85	1.33
		40	5.8	9.58	- 7.23	2.2	- 1.69	1.77
	12×10^{-6}	15	12.2	8.07	- 5.62	1.78	- 1.09	1.42
		20	10.7	8.97	- 6.58	1.97	- 1.45	1.59
		40	8.4	12.6	- 10.50	3.36	- 2.90	2.66
0		15	6.2	5.43	- 0.5	1.36	-	1.06
		20	4.6	5.43	- 0.5	1.36	-	1.06
		40	2.3	5.43	- 0.5	1.36	-	1.06

+ve compression -ve tension

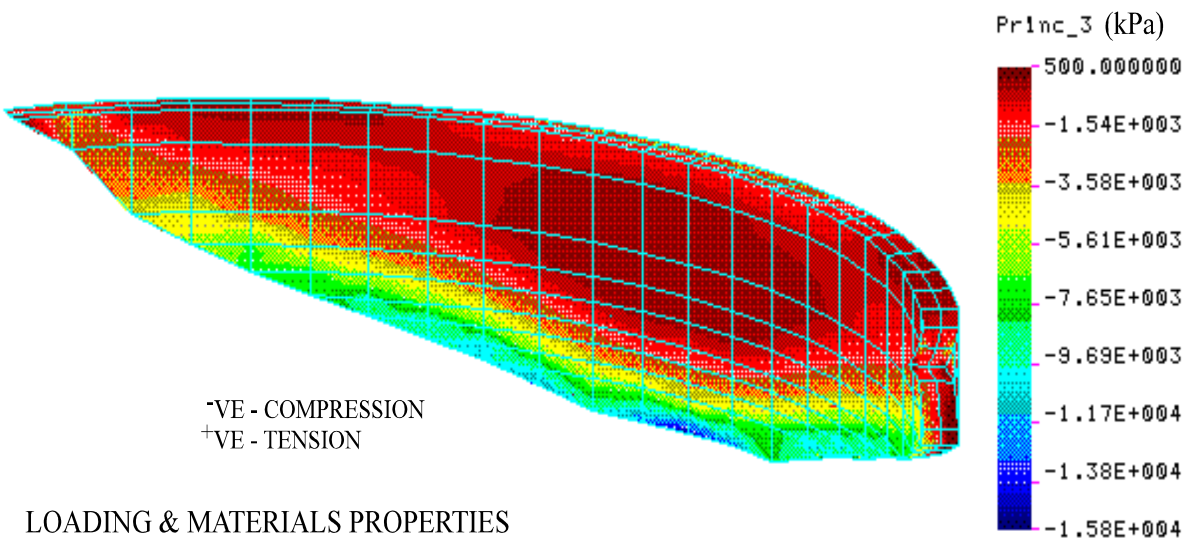
Stress levels shaded in red are considered excessive/unacceptable for RMC.



LOADING & MATERIALS PROPERTIES

FSL + Gravity + No Temperature Drop
Elastic Modulus = 40GPa
Thermal Expansivity = 12×10^{-6}

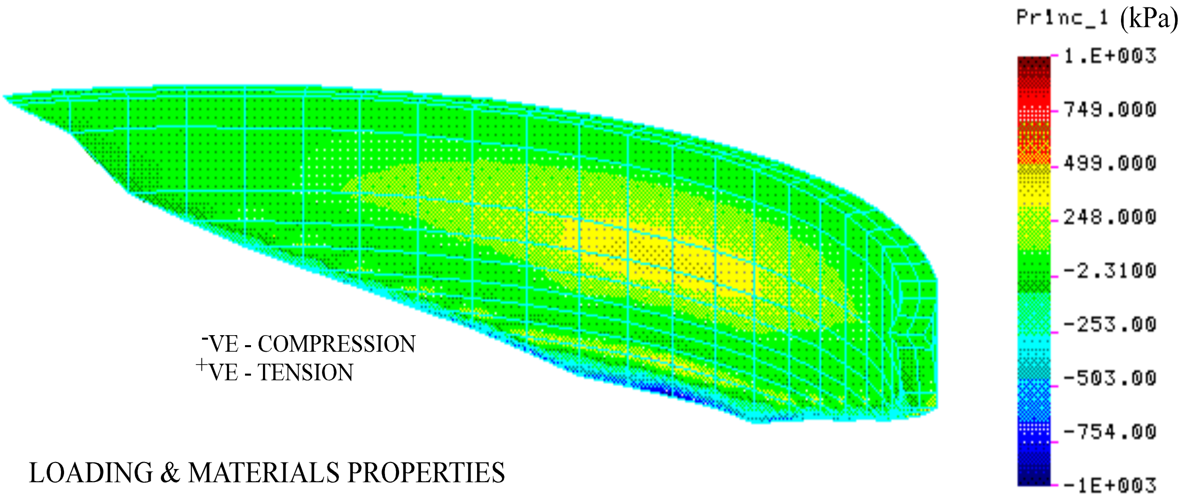
FIGURE A.15: CONTOUR STRESS PLOT – S3 DOWNSTREAM FACE



LOADING & MATERIALS PROPERTIES

FSL + Gravity + 10^{0}C Temperature Drop
Elastic Modulus = 40GPa
Thermal Expansivity = 12×10^{-6}

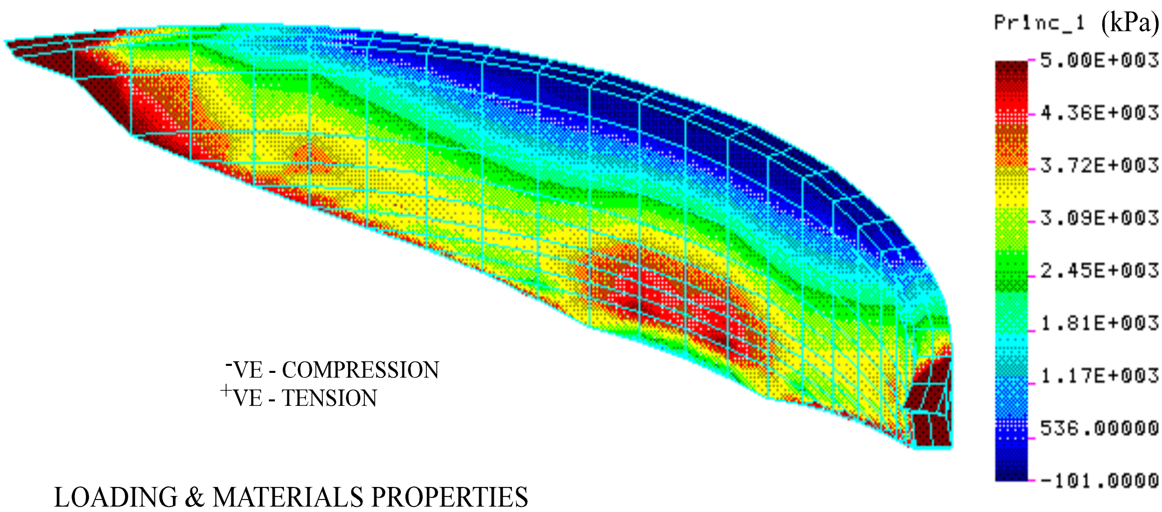
FIGURE A.16: CONTOUR STRESS PLOT – S3 DOWNSTREAM FACE



LOADING & MATERIALS PROPERTIES

FSL + Gravity + No Temperature Drop
Elastic Modulus = 40GPa
Thermal Expansivity = 12 x 10^{-6}

FIGURE A.17: CONTOUR STRESS PLOT – S1 DOWNSTREAM FACE



LOADING & MATERIALS PROPERTIES

FSL + Gravity + 10^{o}C Temperature Drop
Elastic Modulus = 40GPa
Thermal Expansivity = 12 x 10^{-6}

FIGURE A.18: CONTOUR STRESS PLOT – S1 DOWNSTREAM FACE

Result Summary

Table A.2 provides a basic summary of the findings presented above.

Table A.2: Impact of Material Properties and Temperature on Arch Stresses

Environment & Materials	**Max. Compression** (MPa)	**Max. Shear** (MPa)	**Max. Displacement** (mm)	**Max. Tension** (MPa)
Good Materials Ignoring Temp.	5.4	1.1	6.2	0.5
Good Materials + mild Temp effects	6.5	1.2	8.6	3.9
Unfavourable Materials + cold climate	15.8	4.1	12.4	16.2

Discussion

The shaded blocks in **Table A.1** indicate stress levels that might be considered unacceptable for RMC of typical strength. It is worth, however, bearing in mind that these high stresses are largely located against the foundation and the FE analysis method applied, using wedge elements in these areas and using node fixity to represent a completely rigid foundation, will tend to over-estimate toe compression stresses.

For certain of the material property-temperature drop combinations, stresses are undoubtedly high enough to result in failure, even allowing for stress re-distribution that would be evident through non-linear analysis. Ignoring the actual values of the stresses indicated, the results produced reflect the clear influence of temperature effects and RMC material properties on stress intensities.

When a temperature drop load is applied, significant advantage is obviously gained when the available construction materials produce an RMC of low thermal expansivity. It is, however, interesting to note that stress levels are typically increased by a similar factor by a doubling of the RMC Elastic Modulus, as a doubling of the RMC Thermal Expansivity. The same dam wall, under the same water load, will exhibit stresses over 3 times higher when constructed in a more extreme climate with harder materials of higher thermal expansivity than when constructed in a temperate climate with softer materials of lower thermal expansivity. Furthermore, toe compressive stresses can treble when a significant temperature drop is applied to a rigid structure of high thermal expansivity.

It is significant to note that the majority of RMC arch structures in southern Africa are exposed to a relatively mild climate.

Analysis Conclusions

The following primary conclusions may be drawn from the fore-going analyses:

1. Thermal effects are as critical in the design of RMC arch dams as the hydrostatic loads;

2. Thermal effects are highly dependent on RMC material properties, specifically thermal expansivity and elastic modulus;

3. Even in ideal climatic conditions, temperature drop related stresses are significant in relation to hydrostatic structural stresses, irrespective of RMC material properties;

4. A low thermal expansivity in RMC is of significant advantage in lowering temperature related structural stresses;

5. RMC with a low modulus of elasticity displays greater deformation, but lower critical stress levels, as the more malleable structure deforms and re-develops arching more effectively than a stiffer structure, in which stress is passed through smaller contact areas;

6. Where RMC of relatively high thermal expansivity and high elastic modulus is constructed in an extreme climate, temperature effects are critical and stresses may very easily reach dangerous levels. In such an environment, construction temperature control measures will be necessary; and

7. The slender structures typically applied for RMC arch dams give rise to their particular susceptibility to temperature drop loadings.

The above conclusions are valid, in principle, for all arch dams and the importance of addressing temperature drop loads in all arch design is consequently quite obvious. While the analyses presented are less critical and relevant in the case of a CVC arch dam, where structural continuity can easily be re-established by grouting the open joints between the blocks, they are specifically relevant in the case of RCC arch dams, where the grouting of induced joints and the timing of that grouting become fundamental considerations.

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