Finite Element Transient Thermal Analysis of the Enlarged Cotter Dam

Craig Messer\textsuperscript{1}, Francisco Lopez\textsuperscript{2}, and Manoj Laxman\textsuperscript{2}

\textsuperscript{1}, Dam Engineer, GHD Pty Ltd
\textsuperscript{2}, Principal Dam Engineer, GHD Pty Ltd

The Enlarged Cotter Dam is a new 80m high Roller Compacted Concrete Dam being constructed to augment the water supply for the Canberra region. Due to the size of the main dam and the extreme climatic variations in the ACT, where temperatures range from sub zero in winter to in excess of forty degrees in summer, it is expected that significant stresses will be generated during the cooling of the structure. For this reason it is essential that an understanding of the magnitude of these stresses is developed through the initial strength development period and at critical periods such as the first and second winter when the temperature differential between ambient conditions and the core of the structure may be greatest. The development of thermal stress within the structure has critical impacts on both the RCC mix design and the dam construction equipment and methodology.

For the Enlarged Cotter Dam, thermal stresses were investigated using both two and three dimensional finite element transient heat transfer analyses, making use of the thermal properties derived from laboratory testing including instrumented thermal blocks, as well as established literature. Modelling of the thermal stresses in the dam required the development of time dependent concrete properties, such as strength, stiffness and heat generation, with the latter based on test results and calibrated to actual measured values. Additionally, site dependent conditions for ambient temperature, external conduction, convection and radiation factors, dam foundation temperatures and restraint, dam construction sequence, formwork, joint spacing, insulation and timing of reservoir filling were also modelled.

Initial thermal modelling of the dam demonstrated that significant tensile stresses and potential cracking could develop within the structure, at both early and mature concrete ages. Subsequent analyses were developed to investigate methods of reducing these stresses to within acceptable limits. This paper presents the results of the thermal analyses, including the methods to be employed during and after construction to minimise cracking without impacting construction costs and even optimising the speed of construction.

\textbf{Keywords:} RCC, concrete, FEA, finite element, transient thermal analysis.

\section*{INTRODUCTION}

The Enlarged Cotter Dam Project incorporates the proposed new main dam, an approximately 80 m high Roller Compacted Concrete (RCC) gravity dam, two saddle dam embankments and a hard rock quarry.

As the main dam is of significant size it is important to analyse its thermal behaviour during both the construction process and at later ages. Due to the low conductivity of concrete, the heat generated by the hydration of the cement during the hardening of concrete may take several years to be dissipated. This situation generates two distinct conditions that may lead to cracking of the dam: a) surface gradient, resulting from thermal gradients between the core of the dam and the environment, and b) mass gradient, resulting from the external restraint provided by the foundation rock.

This paper outlines the thermal analysis that has been conducted for the main dam of the Enlarged Cotter Dam Project.

\section*{Project Background}

The existing Cotter Dam is located on the Cotter River and is approximately 18 km west of Canberra in the Australian Capital Territory (ACT). The existing Cotter Dam has a storage capacity of approximately 4 GL. The Cotter Dam, in combination with the two other storages on the Cotter River (Bendora and Corin Dams) and the Mt Stromlo Water Treatment Plant, supply about 60\% of Canberra and Queanbeyan's water supply needs.

The enlargement of the existing Cotter Reservoir is required in order to ensure a safe and sustainable supply of water. The project involves the construction of a new 80 m high RCC dam, approximately 125 m downstream of the existing Cotter Dam, and two saddle dams. The Enlarged Cotter Dam will have a total storage capacity of 78 GL.

The Bulk Water Alliance was formed in May 2008 to design and build the Enlarged Cotter Dam. The Alliance partners are ACTEW Corporation (owners), GHD Pty Ltd (designers), and an Abigroup John Holland Joint Venture (constructors).

A typical cross section and the general arrangement of the main dam are presented in Figure 1 and Figure 2, respectively.
Figure 1 Typical cross section of the Enlarged Cotter Dam

Figure 2 General Arrangement of the Enlarged Cotter Dam

Thermal and Stress Analyses
The thermal analysis of Cotter Dam went through several distinct stages of modelling. The following sections briefly outline the modelling steps which took place and the key outcomes from the analyses.

2D and 3D Model Calibration with Thermal Block Trials

The initial phase of the thermal modelling was primarily focused on the collection of the thermal and structural properties required for the analysis. A key parameter to this was to determine the amount and rate of heat generated by the concrete during construction of the dam. During the early stages of this study physical thermal block trials were undertaken simultaneously for two concrete mixes with different fly ash content. In the absence of a heat generation curve at this stage of the study, a Finite Element (FE) model was used to determine this concrete property replicating the data obtained from the thermal block trials. This key parameter was later used in all subsequent thermal modelling stages.

The thermal blocks where modelled in both 2D and 3D using different analysis packages. Initially it was difficult to calibrate the models with the instrumentation readings. On closer inspection of the thermal block it was found that instrumentation was attached to plastic encased metal bars and cast into the concrete with the ends of the metal bars were exposed to the ambient temperature. Once the model was revised to account for this additional source of heat loss it calibrated well with the instrumentation readings. Figure 3 presents a comparison between the results of the 3D calibration model and the instrumentation readings from the thermal block trials. It can be seen that the calibration model results were in good agreement with the recorded data. Please note that...
Figure 3 shows a period with no recorded data which is due to a technical fault in the data logger. The estimated heat generation from the calibration models was later found to match the actual laboratory testing results for heat of hydration conducted on the concrete mix.

**Preliminary 2D Analysis**

Following the calibration modelling, a 2D analysis of the dam was undertaken. The 2D analysis of the dam was conducted using HACON software package. The purpose of the 2D analysis was to act as a preliminary and relatively quick screening measure to assess various options before proceeding with a more detailed 3D analysis. The preliminary 2D analysis focused on the maximum dam section because at this location the dam experiences the highest temperature gradients, in addition to the greatest reservoir and gravity loading.

The preliminary 2D analysis assumed a plane strain condition, which overestimates the stresses in the cross valley direction. This modelling simplification was later improved during the 3D analysis.

One of the first variables assessed in the preliminary analysis was the variation in RCC placement temperature. In particular, placement temperatures of 5°C, 10°C, 15°C and 20°C were investigated. Typically, the results of the analysis showed an approximately 0.2 MPa decrease in tensile stress in the high tension areas of the model for every 5°C drop in placement temperature. A comparison plot of the maximum tensile stress of the dam in the cross valley direction, for the different RCC placement temperature is shown in Figure 4.

Another important variable assessed was the effect of the construction start date on temperature and stress development in the dam. Most of the 2D models were run assuming the start of construction on 1st January 2011, which was the target start date at the time of the 2D analysis. Earlier and later start dates were also considered in the analysis (October 2010 and April 2011). The results from these analyses showed improvements in the stress state of the dam at early ages, particularly for the model starting on April 2011 (winter start dates were more favourable). A comparison plot of maximum cross valley stress for the different start dates is shown in Figure 5.

The preliminary 2D analysis was also used to gauge the sensitivity of the model to material properties. Key material properties analysed were the Young’s modulus and coefficient of thermal expansion of the RCC. Both properties were compared to literature values from other constructed RCC dams documented in ACI 207.5R-99. The coefficient of thermal expansion for Cotter Dam was found to be higher than most of the other documented dams (refer Figure 7), while the Young’s modulus was also shown to be above average (refer Figure 6). Both of these parameters result in higher stresses for an equivalent temperature gradient. As expected, the model was very sensitive to both material properties, as observed in the
comparison of tensile stress in the cross valley direction presented in Figure 8 for variations of Young’s modulus and thermal expansion coefficient combinations.

![Figure 6 Young’s Modulus Development Comparison RCC Dams](image)

![Figure 7 Coefficient of Thermal Expansion Comparison RCC Dams](image)

![Figure 8 2D Analysis - Sensitivity to Young’s Modulus and Coefficient of Thermal Expansion](image)

3D Analysis and Detailed 2D Analysis

A basic linear 3D model of a single 15 m wide monolith located at the maximum dam section was generated and analysed with the FE package Strand7. The 0.3 m thick placement lifts were explicitly modelled only for the lowest 12 m of the dam in order to increase the frequency of inputs at early ages during the construction process when cooling of a single layer has greatest impact on the entire structure. The rest of the structure was modelled by groups of 1.2 m thick layers which represented the total thickness of RCC placed daily. Figure 9 shows the 3D model and the mesh used for the analysis.

As can be seen in Figure 9 the 0.3 m thick elements near the base of the dam have a high aspect ratio. A model was tested with a much finer mesh to assess the accuracy of these elongated elements. There was insignificant difference in stresses between the fine mesh and the coarser mesh. The coarser mesh was then retained to reduce model run times.

Owing to the linear nature of the model, the contact between lifts was assumed as fully bonded and no cracking generation and/or progression was explicitly modelled.

Filling of the reservoir was assumed to be completed 3 years after the start of construction. The filling of the dam was modelled as an instantaneous loading at this time. Due to the complexities involved in modelling the temperature of water behind the dam during the filling process the reservoir was assumed to have a fully developed temperature profile with depth once the dam was filled. The modelled temperature profile of the reservoir was based on data recorded from the existing Cotter reservoir.

As the 3D analysis progressed a better understanding of the model behavior was gained and it was concluded that some aspects of the 3D dam behavior, such as the development of stress in the upstream/downstream direction near the foundation interface, could be more effectively estimated using a detailed 2D plane strain analysis with a finer mesh. This 2D detailed analysis, also developed in Strand7, was more complex than the preliminary 2D analysis performed with HACON.
General Temperature Results

Figure 10 provides a summary plot of the variation of peak temperatures with time at the core of the dam for concrete placement temperatures of 5°C, 10°C, 15°C and 20°C, up to 20 years after construction of the dam. As expected, the results of the analysis showed the surfaces exposed to ambient conditions cooling faster than the core of the dam, creating a higher temperature bulb in the core of the dam. With the filling of the reservoir the heat exchange process of the dam is altered as greater heat is dissipated into the reservoir. Before the filling of the reservoir greatest heat loss was through the downstream face as this had the greatest area exposed to ambient conditions. In the longer term it was found that a very stable temperature gradient was developed in the cross sectional area of the dam, with exception of the most superficial areas of the dam faces which are influenced by changes in ambient conditions. Figures 11, 12 and 13 present the distribution of temperature within the dam at various ages.
When comparing the effects of different placement temperatures on the temperature development within the dam body (Figure 10) it is observed that an increase in placement temperature of 5°C produces an increase of around 2°C to the maximum temperature on the core of the dam. It is also noted that for all the analysed placement temperatures the temperature of the core eventually converged to a similar temperature profile.

General Stress Results

The results of the 3D analysis indicated that the generated tensile stresses in the cross valley direction are, at all times and for all placement temperatures, less than the estimated tensile capacity of intact RCC of 2 MPa. The intact RCC tensile capacity is appropriate for stresses in the cross valley and upstream downstream directions because cracking as a result of these stresses would occur through intact concrete and not along the lift joints. Potential cracking along the lift joints as a result of stresses in the vertical direction was assessed against joint strength but was not found to be an issue because vertical stress is dominated by self weight of the dam and typically compressive over much of the structure. As such, it was concluded that contraction joints spaced at 15 m are an appropriate measure to control the thermal stresses in the cross valley direction.

The 3D analysis also exposed a less common condition for which existing literature appears to be less explicit: high thermal stress in the upstream/downstream direction that may lead to vertical cracking along the axial direction of the dam. A band of high tension stress in the upstream/downstream direction was found at the base of the dam, most likely as a result of the restraint provided by the foundation rock which opposes the expansion and contraction of the RCC when it heats or cools.

The stress developed in the upstream/downstream direction starts as a region of higher stress at the downstream toe of the dam. This region of high stress increases in both size and magnitude as time progresses, eventually becoming more dominant than the stresses in the cross valley direction. When the reservoir is filled, the cantilever effect of the applied hydrostatic force generates tension at the heel and compression at the toe of the dam, effectively shifting the location of the total maximum tensile stress from the toe to the heel of the dam.

Stresses developed in concentrated areas around the toe and heel of the maximum section of the dam were found to exceed the adopted tensile capacity of the RCC. However, the magnitude of such overstress was considered to be in part the result of a numerical inaccuracy due to the sharp edge of the geometry and possibly to the less than optimal aspect ratio of the finite elements in that area of the model. Elsewhere the stresses are generally below the adopted tensile capacity of the RCC.

Figure 14 and Figure 15 present, the magnitude and direction vectors of the maximum principal tensile stress at the centre of the monolith 20 years after the start of construction (2031). The vectors of principal stress indicate that the high stress band near the foundation is predominately upstream/downstream direction. This is further demonstrated in Figure 16 which presents the magnitude of stresses in upstream downstream stresses for the same time step.
Sensitivity to Placement Temperature

The results of the analysis for models with different RCC placement temperatures (20°C, 15°C, 10°C and 5°C), show that all cases produce very similar stress magnitude and distribution at all times considered in the analysis. Typically, a reduction of 0.2 MPa was observed for every 5°C decrease in placement temperature. The stress reduction observed when the RCC mix placement temperature was reduced from 20°C to 15°C was not enough to overcome the potential issues of high tensile stress observed in the models. A model that considered a lower bound 5°C placement temperature still produced tensile stresses above 1 MPa. This sensitivity exercise confirmed that the observed band of high tensile stresses near the base of the dam was primarily caused by the restraint from the foundation (mass gradient) and, in minor proportion, by the RCC’s placement temperature.

Definition of Monolith Width

Vertical contraction joints spaced at 15m were introduced in the analysis. The results of the study confirmed that the cross valley stresses developed within monoliths this wide were less than the expected tensile strength of RCC. Therefore, this spacing was adopted for construction of the dam.

The preliminary design of the dam considered vertical contraction joints to be explicitly formed only to two thirds of the thickness of each RCC lift, expecting that the thermal tensile stresses generated soon after the placement will crack through the remaining third of the lift, creating continuous vertical contraction joints from the foundation to the crest of the dam.

It was recommended that the transverse joints are fully formed through the whole thickness of each RCC lift during the construction process to minimise the high stresses generated in the cross valley direction.

Sensitivity to Foundation Stiffness

As the analysis of the dam progressed it became increasingly apparent that the foundation restraint was the main cause of the high tensile stress, particularly in the upstream/downstream direction at later ages, in the lower portion of the dam. Consequently, an assessment of the sensitivity of the model to changes in the Young’s modulus of the foundation rock was undertaken, using the detailed 2D model with both plane-stress and plane-strain formulations and isotropic modulus.

Figure 17 presents the stress in the upstream downstream direction 20 years after the construction of the dam for a model with a foundation Young’s modulus of 4.3 GPa.

When compared with the results of a model with a stiffer foundation at the same age (refer Figure 16, corresponding to a foundation Young’s modulus of 8.5 GPa), it became evident that the model was sensitive to changes in the foundation modulus. This effectively meant that the regions of high stress in the upstream downstream direction near the foundation were caused primarily by restraint provided by the foundation (mass gradient) and not by restraint from within the dam itself (surface gradient).

Delayed Start Model

By the time the thermal analysis commenced the understanding was that the RCC placement would begin in the middle of summer, on January 2011. However, due to anticipated delays caused by rain, the start of RCC placement was then moved to April 2011. A preliminary 2D analysis indicated a significant reduction in tensile stresses in the model in the short term, particularly in the cross valley direction, when a theoretical winter start was implemented. Subsequent 3D models were used to analyse in greater detail the impacts of the delayed start to RCC placement.

The results of the 3D sensitivity analysis indicated that the regions of high stress were reduced in both area and magnitude for the later April 2011 (winter) start date when compared to a January 2011 start (summer). This reduction of tensile stress at earlier ages was most noticeable at the downstream toe. At later ages this reduction in stress is not significant.
**Abutment Block Model**

In addition to the maximum section monolith, a model of a shorter monolith on the left abutment of the dam was analysed. The abutment model, presented in Figure 18, incorporates the dam monolith and the RCC abutment return channel.

The results from the abutment model are consistent with the maximum section model, particularly in regards to the band of high tensile stresses in the upstream/downstream direction. However, the stresses in the abutment monolith were of lower magnitude and more orientated to the upstream heel. This is most likely the result of insulation of the downstream toe by the RCC of the left abutment return channel. On the downstream toe and along the foundation interface, the reduction in tensile stress magnitude is likely to be the result of the abutment monolith being smaller in comparison to the maximum section, thus generating thermal gradients of less magnitude. In addition, a smaller contact area with the foundation provides less restraint to the long term deformation of the dam. No thermal cracking is expected in the abutment monoliths.

**CONCLUSIONS**

FE modelling was employed to assess the thermal behaviour of the Enlarged Cotter Dam during both the construction phase and at later ages. The heat generated through the hydration of the cement will take many years to fully dissipate from the body of the dam.

Thermal gradients (mass and surface) may produce significant tensile stress. If larger than the tensile strength of the RCC, such stresses may cause both transverse and longitudinal cracking, and may compromise the safety of the dam. In order to limit the transverse cracking, vertical contraction joints are to be formed in the dam during the construction stage to relieve the thermal stresses in the cross valley direction. The analysis confirmed that no excessive tensile stresses are developed for monoliths spaced at 15 m block, thus this spacing was recommended for construction. It was also recommended that the transverse joints be fully formed during the construction process to ensure that continuous the vertical joints are fully developed at early ages and that stress at the upstream and downstream faces is minimised for short term conditions.

The results of the thermal FE modelling showed that high tensile stress in the upstream/downstream will develop across the full width of the maximum section of the dam near the foundation. This is most noticeable in the long term, when the dam has cooled to a stable temperature condition. The high tensile stresses in the upstream/downstream direction are most likely caused by the restraint provided by the unjointed 70 m long contact with the foundation. In the cross valley direction the tensile stresses caused by the restraint of the foundation are not as high, since the contact between the dam and the rock is reduced to 15 m between monoliths. Similar behavior was observed on the abutment model, although the tensile stresses are of lesser magnitude.

In general, the study showed that the magnitude of the generated thermal stresses is typically less than the tensile strength of the parent intact RCC (2.0 MPa). Localised tensile stresses above 2.0 MPa were observed concentrating at the toe and heel, however this was considered a numerical singularity caused by modelling constraints.

Modelling of cooling of the RCC’s placement temperature produced only minor reductions in the stress concentration zones and maximum temperature in the dam core. Typically, a 5°C decrease in placement temperature resulted in a reduction of 0.2 MPa in regions of high stress and 2°C reduction in maximum temperature within the dam core. It was therefore recommended that a placement temperature of RCC of 20°C be adopted instead of 15°C since the change will not increase the likelihood of cracking but have a significant effect on costs.
The analysis showed that a winter start for RCC placement is beneficial at early age, but is insignificant in the long term.

It is concluded that thermal cracking will be minimised if the recommendations made to the construction methodology are undertaken.

**Acknowledgements**
The authors gratefully acknowledge the support and permission provided by the BWA and ACTEW in order to publish this paper.

**BIBLIOGRAPHY**
ACI, 1999, Roller Compacted Mass Concrete, American Concrete Institute, ACI 207.5R-99


