Initiation of Thermal Cracks in a Weir

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Introduction

The mass concrete weir considered in this study is supported in a trench of solid rock at the bed of a river. This study follows the observation of surface cracks at a few locations in the weir after a few days of casting. Heat of hydration developed in mass concrete is considered to be the main cause for the cracks. A finite element analysis was done on the weir to understand the thermal stresses due to heat of hydration. Based on the stresses obtained in this study, an attempt is made to predict the locations of initiation of cracks using the principles of fracture mechanics.

Two-dimensional plane-stress and plane-strain analyses were carried-out on the weir using SAP2000 (1998) finite element code for thermal loads. A four-node quadrilateral isoparametric element was used for the analysis. These analyses would provide the general thermal stresses developed in the weir due to temperature variation across the cross section of the weir.

Methodology

A two-dimensional finite element model was created according to the actual dimensions of a weir, which is currently under construction. The bottom of the weir is considered to be connected to solid rock. Therefore, it was considered as a rigid base and the bottom boundary was fixed against both vertical and horizontal displacements. The grout curtain between the bottom foundation and the weir was assumed to be fully in place and hence uplift thrust was not considered in the analysis (Shyamalee *et al.*, 2007a and 2007b). The weir is to be made from Grade 25 concrete and the Poisson's ratio of the concrete was taken as 0.2.

Locations of the largest values of major principal stresses due to thermal loads during the initial hydration of the fresh concrete and the major principal stress contours due to thermal loads and self weight are obtained from finite element analyses and are reported herein. These stresses values are then used to predict the locations of initiation of cracks due to thermal effects.

The finite element mesh used for the analysis is shown in Figure 1. X and Y are horizontal and vertical axes, respectively. Bottom nodes along the X-axis are fixed to prevent both horizontal and vertical displacements. The Z direction is horizontal and along the weir.

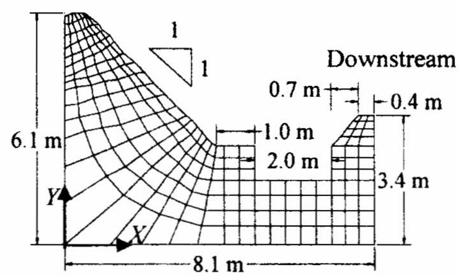

Figure 1. Finite element mesh used in the analysis

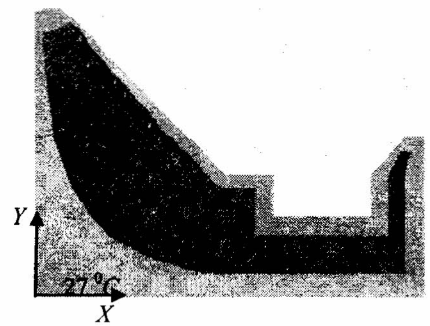

Figure 2. Temperature contours due to heat of hydration

Concrete is placed at 20 °C and the maximum hydration temperature was measured to be 77 °C at the core of the weir. It was also observed that the hydration temperature at the outer surfaces of the weir was the ambient temperature. Therefore, the hydration temperature was given as temperature contours for the purpose of finite element analysis with a maximum temperature of 77 ^{0}C at the core and the outer surfaces at the ambient temperature of 27 ^{0}C as shown in Figure 2. Since the weir was cast as a series of longitudinal segments, each nearly 5 m long, the stress analyses were done for two extreme cases of plane stress and plane strain to understand the distribution of thermal stresses in the weir.

Results

The contours of major principal stress for the case of plane stress analysis are shown in Figure 3.

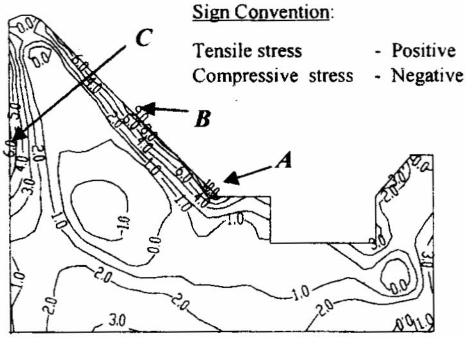

Figure 3. Contours of major principal stresses in MPa for plane stress analysis

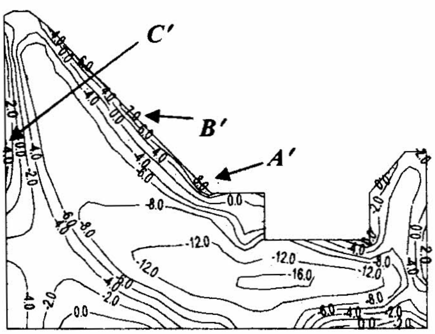

Figure 4. Contours of major principal stresses in MPa for plane strain analysis

It was observed that the largest value of major principal stress occurred at location ***A*** on the weir surface as shown in Figure 3. The value of principal stress at location ***A*** was 10.1 MPa in the direction of -38^0 at *X*-axis. At location ***B*** of the inclined surface of the weir, the major principal stress was found to be 9.1 MPa at the direction of -45^0 to *X*-axis. On the upstream face, the highest value of major principal stress was observed as 6.2 MPa at the location ***C*** in the direction of 89^0 to *X*-axis.

For the plane strain analysis the highest major principal stress occurred at *A'*, shown in Figure 4, and identical to *A* in the earlier figure. On the inclined surface of the upstream end of the weir, the highest major principal stress was observed at *B'* again identical to *B* in the earlier figure. The principal stresses at locations *A'* and *B'* were 8.6 MPa in the direction -38^o and 7.5 MPa in the direction -45^o, respectively. On the upstream face, the highest value of major principal stress was observed as 4.4 MPa at location *C'*, identical location to *C* in the earlier figure, in the direction of 89^o to *X*-axis.

The major principal stress variations were also studied at locations *A*, *B* and *C* for different core temperatures and are reported in Figures 5 and 6, respectively, for plane stress and plane strain conditions.

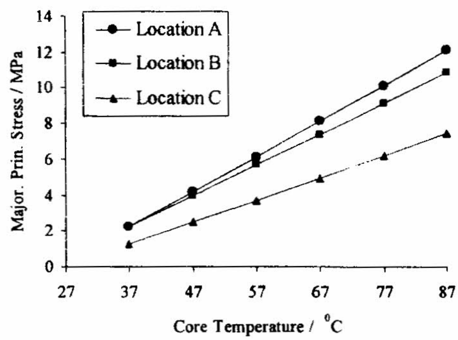

Figure 5. Maximum principal stress variations (plane stress) at critical locations

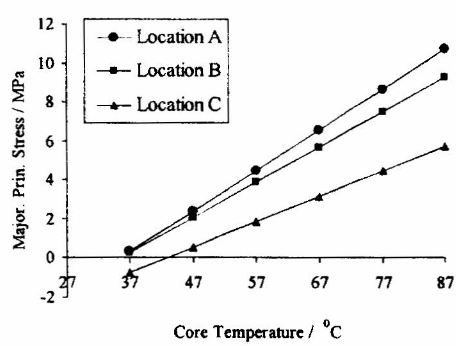

Figure 6. Maximum principal stress variations (plane strain) at critical locations

Discussion of results and conclusions

From the results, the locations, where high principal stresses occured were identified as *A*, *B* and *C* (also identified as *A'*, *B'* and *C'*). Since the location *A* is an intersection point where inclined and horizontal surfaces meet together, a significant amount of reinforcements were provided at this location even without having any knowledge about thermal effects and that might be enough to resist the tensile stresses developed by the hydration heat. Therefore, no cracks may appear near location *A* during the initial hydration period of the weir.

Locations *B* and *C* were also identified as possible critical locations for initiation of cracks and actually there were two surface cracks initiated from those locations and propagated in inward normal directions of the surface during the initial hydration period of the concrete. The values of principal stresses and their directions were not significantly different at locations *B* and *C* for both plane stress and strain analyses.

For plane strain condition, the stress intensity factors calculated for 1 mm surface flaws of the concrete at locations *B* and *C* are 0.5 MPa $m^{1/2}$ and 0.3 MPa $m^{1/2}$ respectively. These values exceed the fracture toughness of concrete (0.2 MPa $m^{1/2}$) and initiations of cracks due to small surface flaws at these locations are hence justified.

Even though the visible cracks appeared in the concrete surfaces during initial hydration they will get healed towards the end of the hydration period and with the maturity of concrete.

The results obtained in this study mainly depend on the mesh size used, aspect ratios of elements and the boundary conditions. The results would be slightly different slightly if a finer mesh having better aspect ratios for elements is used or different boundary conditions are used for the analysis.

This analysis has provided a reasonable understanding of the process of initiation of surface cracks and their location in mass concrete during the initial hydration period.

References

SAP2000 Non-linear, Version 10.0.1 (1998) *Analysis Reference User's manuals,* Computers and Structures Incorporation (CSI), Berkeley, California, USA.

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