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Propagation of Initial Crack in Concrete Gravity Dam

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ABSTRACT: This paper presents the result of numerical investigation on initiation and extension of cracks in a concrete gravity dam caused by the temperature change in the body during one year after finish of the dam concrete work. Information on the thermal crack for concrete, especially on the extension, is very scarce. In this investigation, therefore, authors use a criterion that a crack extends only in the case when the energy release rate at the moment of extension exceeds that at initiation of the crack, and for this end adopt the concept of the virtual crack extension method. Three different cases of the finish time of concrete placing are compared.

1. INTRODUCTION

During the last two decades various problems concerning the fracture of concrete and concrete structures were elucidated from the viewpoint of nonlinear fracture mechanics. But investigations relating to the thermal crack in massive concrete structures are few. Consequently problems, such as dependence of concrete fracture parameter on temperature, remain unsolved. Authors revealed after presentation of their paper (Irobe et al. 1998) at the FRAMCOS 3 that eigenvalues of a gravity dam were practically unchanged for occurrence of short thermal cracks along its downstream face. Results of their numerical study for eigenvalues of a gravity dam are summarized in Section 2. The thermal crack extension in a gravity dam and the resultant change of its dynamic property were matters of concern for them since then. The thermal crack extension is brought into focus in this paper. The problem is examined by the linear fracture mechanics theory, because the linear theory is considered to be applicable to fracture of massive concrete. The solution is obtained by 2-dimensional FEM with the discrete crack model. The randomness of concrete tensile strength, finish of the construction work before cold season, and daily change of water level of the reservoir are assumed to simulate the actual dam with power station. In Section 4 results of temperature analysis, in Section 5 results of crack analysis, and in Section 6 conclusion are given.

2. EIGENVALUES OF GRAVITY DAMS

Eigenvalues of a concrete gravity dam without any crack are compared with those of cracked gravity dam in Table 1. The shape and the discretization pattern of dam used for the calculation are written in Figure 1. Crack generation order obtained in the abovementioned paper is also written. Mode shapes are derived for skeleton line with black circles. The first mode shapes of 4 cases normalized by the displacement of node at 5 meter high are shown in Figure 2. Solutions in Table 1 and Figure 2 are obtained by the generalized Jacobi iteration method. Eigenvalues of cracked dam and the shapes of the first mode also differ little from each other irrespective of number of cracks. These data suggest that dynamic characteristics of the gravity dam are

Table 1. Eigenvalue ω_r^2 (rad^2/sec^2) of concrete gravity dam with thermal cracks along downstream face.

Number of cracks	Mode number (r)		
	1	2	3
0	8640	50400	75600
1	8400	48900	69000
2	8220	48900	68700
3	7980	48600	68400
4	7830	48300	68400
5	7770	48000	68100
6	7620	45600	67800

E-modulus of concrete=30GPa
Density of concrete =225kg/m^3

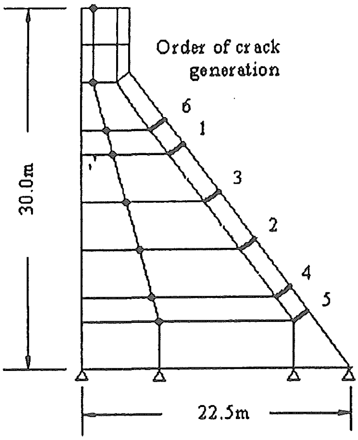


Figure 1. Shape and discretization pattern of gravity dam and skeleton line for mode shapes.

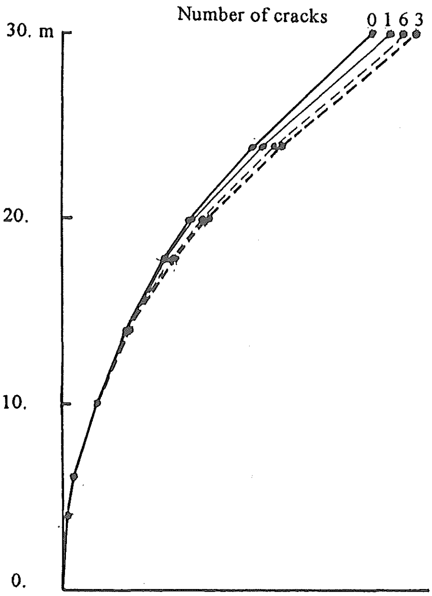


Figure 2. Natural mode shape of gravity dam without and with cracks along downstream face.

stable for a few surface cracks along its downstream face, if they are short. These facts motivate the authors to continue the investigation on the development of the thermal crack in gravity dam and the resultant influence on its dynamic characteristics.

3. MATERIAL CONSTANTS

The strength of field concrete scatters usually around the strength of design concrete. Using the uniform random number the random distribution of the tensile strength of concrete is introduced in the analysis. The obtained mean value and standard deviation were 2.502 and 0.141 MPa respectively, so the scattering modulus is 5.6%. The other material constants are the same as those in the previous paper. The dependence of E-modulus of concrete on temperature is considered, so the problem to be solved is a material nonlinear problem.

4. INITIAL AND BOUNDARY CONDITIONS AND RESULTS OF TEMPERATURE ANALYSIS

Three different cases are analyzed. The initial temperature of concrete is assumed as constant 20℃ in every case. In the first case concrete placing ends on the 1st of November, and storage of water continues day by day after the end of concrete work. The water influences the temperature of the upstream face of dam. Temperature of the water is expressed by the Fourier series with reference to an observation for a lake in the north Japan The temperature of exposing surface to the air is treated to be equal to the atmospheric temperature. Two kinds of loads, dead weight and water pressure to upstream face, act concurrently on dam on the 1st of next January. The temperature of downstream face on the day is -0.86℃. The above process is put forward by 21 days in the second case.
Then the downstream face temperature is the lowest

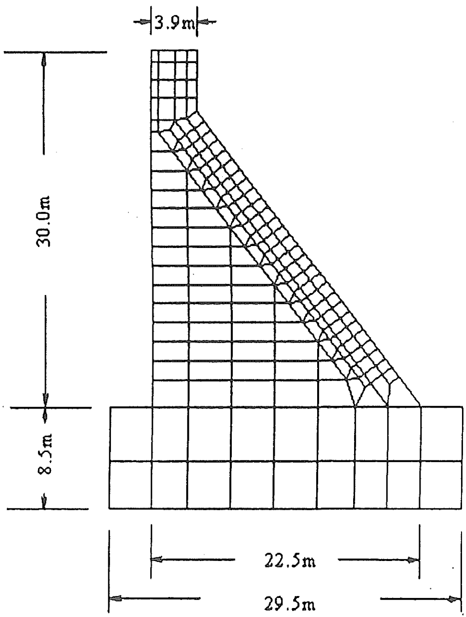


Figure 3. Finite element discretization of investigated dam and monitoring points for temperature analysis.

in a year, that is -1.58℃. In the last case the time lags of end of concrete placing and start of loading are extended from 21 days to 43 days and to 64 days respectively. Then the downstream face temperature is 0℃.

The dam temperature was analyzed by using the FEM under the above initial and boundary conditions. Computational domain is' discetized by 9-nodes quadrilateral elements and 6-nodes triangular elements as shown in Figure 3. 1meter square elements are arranged in two layers along the downstream face. Monitoring points for the temperature analysis are shown in Figure 4. The computational results of the dam temperature for three cases are shown in Figure 5a-c together with the starting point of loading. Numbers given for curves mean the monitoring points.

5. RESULTS OF CRACK ANALYSIS

The analysis was carried out with use of the same finite element discretization as shown in Figure 4. In addition to the initial and boundary conditions the

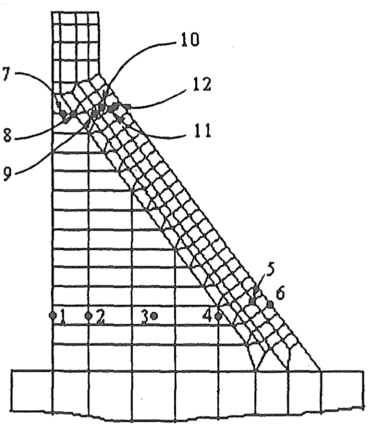


Figure 4. Monitoring points for temperature analysis.

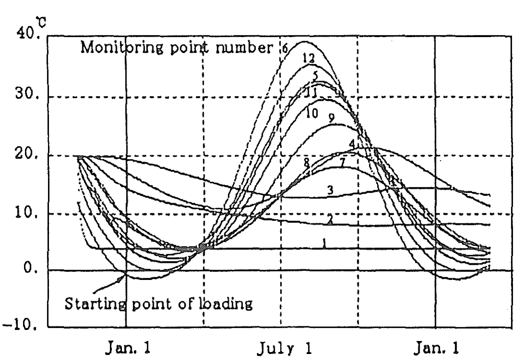


Figure 5a. Dam temperature in Case1.

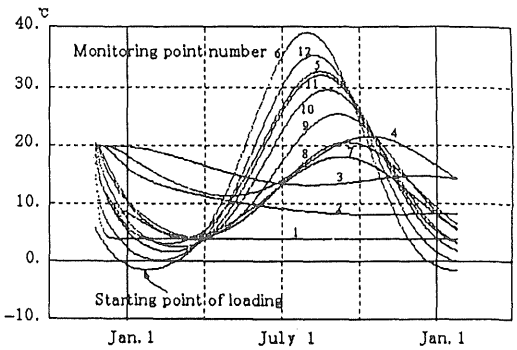


Figure 5b. Dam temperature in Case 2

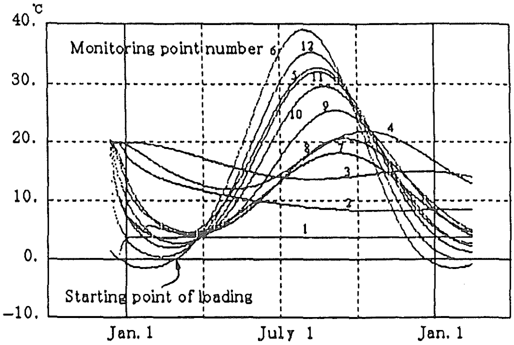


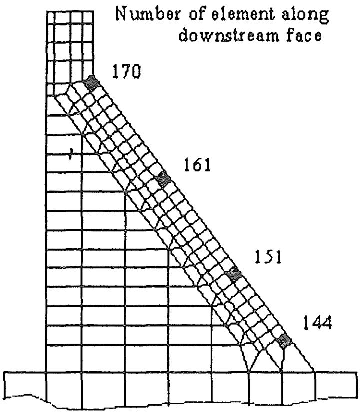
Figure 5c. Dam temperature in Case 3.

following assumptions were introduced: (1) if the primary principal stress at a Gauss point in a certain element along the downstream face reaches the concrete tensile strength of the element, a crack is generated perpendicular to the principal axis from the downstream face along the nearest mesh line from the Gauss point, (2) a crack extends, when the dependent energy release rate exceeds the energy release rate at the generation of the crack. The second assumption is unconfirmed. It is an unavoidable choice, because authors have no reliable criterion for thermal crack propagation in concrete.

Scattering of the tensile strength f_{ct} of concrete described in the section MATERIAL CONSTANTS is represented by the tensile strength of elements from toe to corner in a downstream face layer in Figure 6. This is one of governing factors for the crack generation order.

In this analysis actual daily change of the reservoir water level is replaced with rise and fall of every other day.

Figure 7 shows the sequence of the tension crack generation obtained from the first assumption. Thick lines represent cracks. Cracks are generated while the water level is lowered. Crack generation place and date are written in the figure. The computational



Number of element	f_{ct} (MPa)	Number of element	f_{ct} (MPa)	Number of element	f_{ct} (MPa)
		151	2.365	161	2.281
		152	2.470	162	2.605
		153	2.354	163	2.531
144	2.615	154	2.333	164	2.676
145	2.437	155	2.356	165	2.458
146	2.582	156	2.635	166	2.626
147	2.543	157	2.284	167	2.561
148	2.453	158	2.465	168	2.632
149	2.288	159	2.292	169	2.307
150	2.516	160	2.747	170	2.457

Figure 6. Tensile strength of elements

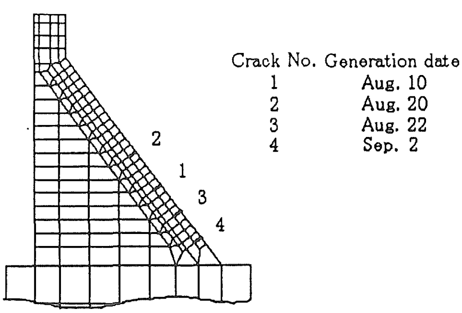


Figure 7a. Tension crack generation place and order in case 1.

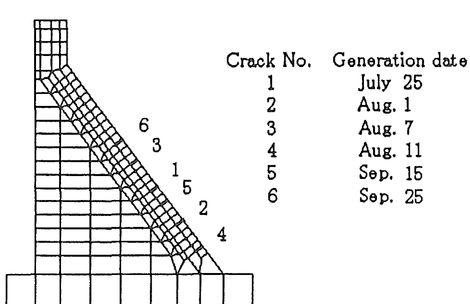


Figure 7b. Tension crack generation place and order in case 2.

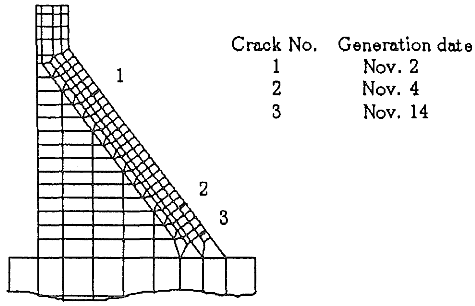


Figure 7c. Tension crack generation place and order in case 3.

results of the third case are most intelligible in the light of dam concrete practice.

The energy release rates are estimated from the work to release the nodal forces equivalent to stresses in a pair of elements along a tension crack for generation, and a virtual crack for extension. The equivalent nodal forces are determined by numerical integration of stresses at integration points.

Energy release rates for crack generation and extension are compared in Table 2. The energy release rates of Case 3 are lowest. Discrepancies between the first two cases and the third case are remarkable. The initial temperature at loading date for the stress calculation is considered as the source of the discrepancy. The energy release rates for virtual crack extension are lower than for the crack generation in every case. The computational results afford a basis for inferring that thermal cracks along downstream face due to atmospheric temperature change will not extend more than 1 m.

Table2. Comparison of energy release rates between two kinds of cracks.

Case-crack number	Crack generation (N/m)	Crack extension (N/m)
1-1	359	297
2-1	354	294
3-1	183	153

6 CONCLUSION

Based upon the linear fracture mechanics theory extension of thermal cracks in a gravity dam initiated by atmospheric temperature change was analyzed by 2-dimensional FEM. Energy release rate is adopted as criterion for the crack extension. The crack extension analysis was performed for three cases of different starting date of loading to the dam. The difference influenced computational results. The initial thermal crack was estimated not to extend in every case. Used size of elements in initial crack zone was 1 m square. Despite of considerably large size element this conclusion is notable, because it is considered thermal crack does not develop more than 1 m long in a gravity dam. .

7 ACKNOWLEDGEMENT

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8 REFERENCES

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