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Slot cutting response of compressed concrete structures

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ABSTRACT: Expansion joints have been introduced using diamond wire saws in several concrete dams to control deformations and release accumulated compressive stresses due to concrete swelling induced by alkali-aggregate reaction. Slot cuts have also been used to reduce the detrimental effects of cyclic seasonal thermal loading of dams located in northern regions. However, it was found that it is very difficult to estimate a priori the elastic rebound and long term closure of slot walls. This paper reports field observations from cuts in two gravity dams. A complementary experimental study on four 1.5m long compressed concrete specimens is then presented. Measurements of elastic rebounds and long-term responses are compared with elastic and viscoelastic finite element analyses. The laboratory tests have shown that it is difficult to model accurately the long term slot closure response, even in the controlled environment of the laboratory where differences from experimental measurements and numerical analyses ranging from 10% to 30% have been observed. This could be mainly attributed to sensitivity to the creep law adopted.

1 INTRODUCTION

Several concrete gravity dams, powerhouses and spillways subjected to alkali-aggregate reaction (AAR) and severe seasonal temperature variations have developed irreversible displacements and major cracks either along lift joints or across monoliths. The built-up of compressive forces along the axis of these structures is introducing differential displacements in weak components jamming gates, impairing turbine operation, and inducing damage. For gravity dams, the critical zones are usually located near geometric discontinuities along the longitudinal axis of the dam.

One possible action to reduce compressive forces and control deformations is to cut open vertical slots (≈10mm to 20mm in width) in the dam introducing joints being able to absorb further volumetric growth. However, in several cases it was found that it is very difficult to predict the short-term elastic rebound and the long-term closure of slot walls. This is due to several phenomena such as the difficulty to evaluate the initial stress state, and the rheological laws of decompressed material where delayed elastic recovery is taking place in conjunction with creep of the compressed part of the section considered. It would therefore be useful to develop and validate appropriate modeling strategies to evaluate, on a more accurate basis, the transient slot closure in hydraulic structures.

To address this problem, this paper first briefly reports field observations related to slot closures of two gravity dams. Experimental results related to slot cuts performed on four small precompressed concrete specimens are then presented. The objective of the tests was to measure the displacements of slot walls as well as the stresses at the slot base. Additional tests on standard cylinders have also been performed to obtain creep data. These results have been used to assess the performance of elastic and transient viscoelastic finite element analyses to simulate elastic rebounds and delayed slot closure responses.

2 REHABILITATION OF CONCRETE DAMS BY SLOT CUTS

2.1 *Dams where cuts have been made*

Caron (2000) made a comprehensive review of dams where slot cuts have been performed to improve the structural behavior. Problems related to these dams are due to: (a) cracking, (b) cumulative displacements, (c) increasing leakage, and (d) operation of mechanical equipment. It is important to outweigh advantages and inconveniences that are brought by a cut from a prognostic established by appropriate structural studies considering serviceability and safety limit states (Veilleux 1995, Curtis 2000, Gocevski 2000). The advantages of a cut are: (a) stress releases, (b) closing of cracks and joints, (c) reduction of leakage, (d) correction of deformations impairing gate and turbine functionality, and (e) recuperation of accumulated displacements. The inconveniences of a cut are: (a) the restart of high swelling rate due to release of beneficial restraints, (b) the formation of a zone of high stress concentration near the cut tip, and (c) the occurrence of secondary deformations that have sometimes been found detrimental to the functionality of electromechanical equipment.

Case studies have shown that structural modeling of the short and long-term responses to slot cuts is a difficult task. It requires accurate evaluation of the initial stress (strain) state and its post-cut evolution that is a function of the loading (particularly temperature), AAR expansion, material strength, stiffness and creep properties, as well as boundary conditions.

2.2 *Chute-à-Caron and La Tuque dams*

Increasing water leakage has been observed in a drainage gallery at Chute-à-Caron dam (Fig.1) from 1992 to 1995 (Batta et al. 1998). The longitudinal geometric discontinuity at this location (147° angle) combined with seasonal thermal variations (~ -30°C to + 30°C) induced cyclic opening of a lift joint at the bottom of the upstream face. There is no AAR at this dam. In 1997 a partial slot cut was performed near the discontinuity to improve the behavior of the dam in this problematic zone (Fig.2). The 13m high cut, that was 15mm wide (δ_{MAX}), closed almost instantaneously by 10mm whereas the prediction from finite element analysis (FEA) was 4.5mm. Following this observation, concrete temperature measurements were gathered as well as laboratory measurements of the thermal expansion coefficient. The corrected closure according to the updated data was 7.9mm, that is slightly smaller than the measured closure. Moreover, an irreversible drift was also observed in the transient closure response (Fig.3).

Of somewhat similar geometry to Chute-à-Caron dam, La Tuque gravity dam (30m high, Canada) presents a more complex problem because of internal openings (a transfer bay) near the discontinuity forming a flexible structural component (Veilleux 1995). Moreover, concrete swelling due to moderate AAR is taking place in addition to seasonal temperature variations. Major cracks developed in the transfer bay. After performing FEA, a 50mm cut was recommended to release accumulated stresses and to absorb thermal expansion cycles as well as future concrete swelling. However, for practical reasons a 12mm slot cut was performed in 1993 and closed completely in short time. The irreversible displacement rate, observed before the cut, reestablished itself after a year. It was estimated that the cut allowed to absorb two years of deformation.

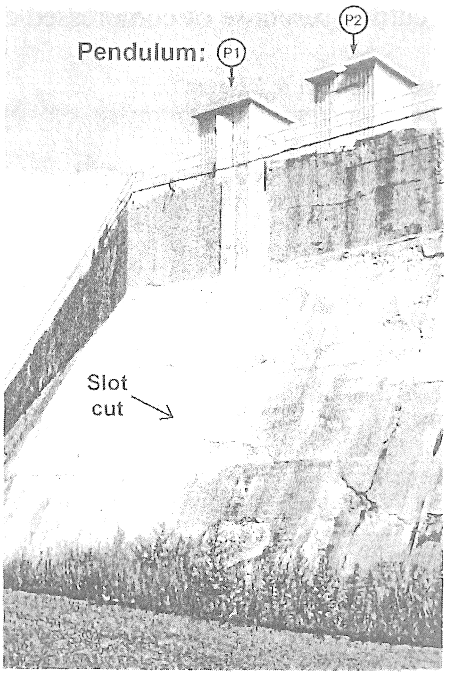

Figure 1. Chute-à-Caron dam (Canada).

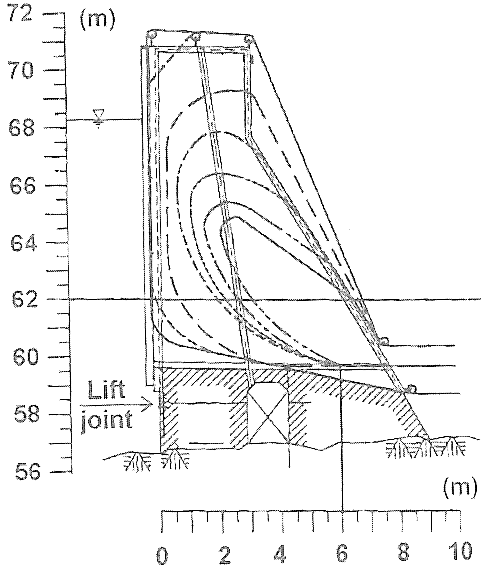

Figure 2. Chute-à-Caron dam slot cut.

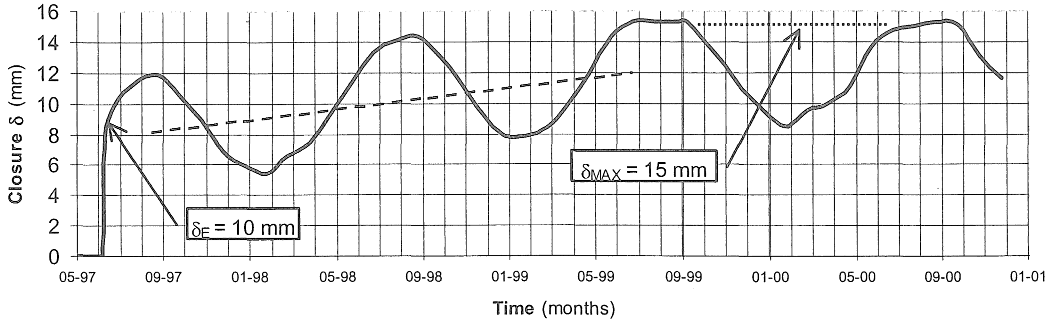

Figure 3. Chute-à-Caron dam slot closure.

3 NUMERICAL PREDICTIONS OF THE STRUCTURAL RESPONSE TO SLOT CUTS

3.1 *Constitutive model and finite element analysis of dams affected by AAR*

Various constitutive models have been proposed to study concrete structures affected by AAR (Curtis 2000, Gocevski & Pietruszczak 2000, Léger et al. 1996). The strain superposition principle is generally retained in these mass concrete constitutive models:

$$\varepsilon_{TOT} = \varepsilon_{ME} + \varepsilon_{CR} + \varepsilon_{TH} + \varepsilon_{HY} + \varepsilon_{AAR} \quad (1)$$

The total strain ε_{TOT} is computed as the sum of strains due to mechanical (ME) (applied loads producing elastic strains, cracking), creep (CR), thermal (TH), hygroswelling or shrinkage (HY), and alkali-aggregate reaction (AAR) effects. Although additions are used, it must be recognized that AAR swelling strains are coupled with temperature, moisture, and compressive stresses (restraints). A basic problem is how to convert strains into stresses when micro-cracking associated with AAR is reducing the elastic modulus, compressive and tensile strengths, while enhancing concrete creep. In that regard, laboratory testing on concrete cores and calibration of numerical models against in situ stress measurements have shown to be very important (Curtis 2000).

3.2 *Short term slot-cut response – elastic rebound*

In a homogeneous concrete specimen, the elastic slot closure can be estimated from $\delta_E = (L_{ch})\ (\varepsilon_0)$ where L_{ch} is a characteristic length and ε_0 is the initial strain before the cut (Caron 2000, Lupien 1991). The closure can thus be estimated from:

$$\delta_E = (\beta\, h_c)\ (\sigma_0 / E_0). \quad (2)$$

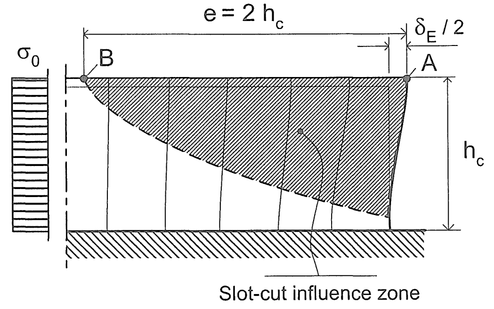

Figure 4. Fixed boundary condition below a cut.

The closure is directly proportional to the initial stresses, σ_0, and slot depth, h_c, and inversely proportional to the elastic modulus E_0, where β is a constant that depends on the boundary conditions. For a fixed boundary condition below the cut (Fig.4) parametric finite element analyses have shown that $\beta \approx 4/3$. The zone where decompression is taking place can be delimited by the length $e = 2h_c$ at the top of the structure. The displacement at point B is then negligible compared to the displacement at A. In an actual dam with a cut intersecting cracks and joints, small rigid body motions are also possible as the cut proceeds. Moreover, the cut introduces a new thermal boundary condition allowing penetration of cold (warm) air. The hydraulic conditions are also modified by the cut, which could drain intercepted lift joints.

3.3 *Long term slot-cut response – mechanical, creep, thermal, AAR effects*

If a cut must stay open for a time period t_e, the necessary width could be estimated by :

$$\delta = [\gamma_{ME}\ \delta_E]+[\gamma_{CR}\ \delta_{CR}(t_e)]+[\gamma_{TH}\ \delta_{TH}^{max}(t_e)]+[\gamma_{AAR}\ \delta_{AAR}(t_e)] \quad (3)$$

where γ_{ME}, γ_{CR}, γ_{TH}, and γ_{AAR}, represents magnification factors to account for uncertainties in mechanical, creep, thermal, and AAR responses; δ_E is the "elastic" closure, δ_{CR} is the creep closure at time t_e, δ_{TH}^{max} is maximum thermal closure, δ_{AAR} is the AAR closure at time t_e. The values of the γ factors are tributary to the reliability of the input parameters as well as the modeling and calibration procedures adopted. From previous field experiences, initial estimates could be based on γ values of the order of 2 to 3. The challenge being to develop and implement a structural analysis methodology able to minimize relevant uncertainties.

4 EXPERIMENTAL STUDY ON SMALL CONCRETE SPECIMENS

Slot cutting experiments were performed on four pre-compressed concrete specimens (1500 x 500 x 250mm) as shown in Figure 5. Complementary creep tests were performed on standard concrete cylinders subjected to similar stress states as the concrete specimens. The experiments were performed on relatively young concrete that is not affected by AAR. The main objectives were: (a) to obtain experimental closure and strain data in a controlled environment, and (b) to assess the performance of a viscoelastic modeling procedure using creep data obtained from standard material testing.

4.1 *Description of test specimens and instrumentation*

Table 1 presents the compressive strength f'c, the elastic modulus, E_0, the applied initial compressive stress before the cut, σ_0, and the cut depth, h_c, for each specimen. The effects of variations in cut depths (167mm or 1/3 of the total depth, and 196mm) and the initial stresses (5MPa and 2.5MPa) were investigated. The first two tests used the same σ_0 (5MPa) and h_c (167mm) values to assess the repeatability of the experiments. In Test 3, h_c was increased to 196mm with σ_0 = 5MPa, while in Test 4 σ_0 was reduced to 2.5 MPa with h_c=196mm. Mechanical properties (E_0, Poisson's ratio ≈ 0.18) were obtained from tests on standard cylinders performed just prior to the cuts. The initial stress was applied by post-tensioning four instrumented steel bars. The bars were then locked in place by bolts (Fig.5). Concrete deformations due to cut stress releases and creep reduce the tensile forces in the bars that were continuously monitored. Slot closure was monitored from measurements made from a pair of 50mm gage points located on the top of the specimen, and 3 additional pairs of gages located along the cut on both sides of the specimens (Figs. 5, 7). The corresponding experimental measurement error was ±0.0013mm. Three strain gages (Fig.5) were also used on both sides of the specimens to monitor concrete deformations, ε_x, on the residual section below the cut, and to estimate the corresponding stresses ($\sigma_x = E_0\ \varepsilon_x$).

Table 1. Test specimens and elastic closures.

Test	f'c (MPa)	E_0 (GPa)	σ_0 (MPa)	h_c (mm)	$\delta_E^{(Exp)}$ (mm)	$\delta_E^{(FEM)}$ (mm)
1	34.4	32.7	5.0	167	0.18	0.20
2	34.1	33.6	5.0	167	0.20	0.19
3	30.4	31.5	5.0	196	0.33	0.26
4	30.9	30.4	2.5	196	0.16	0.17

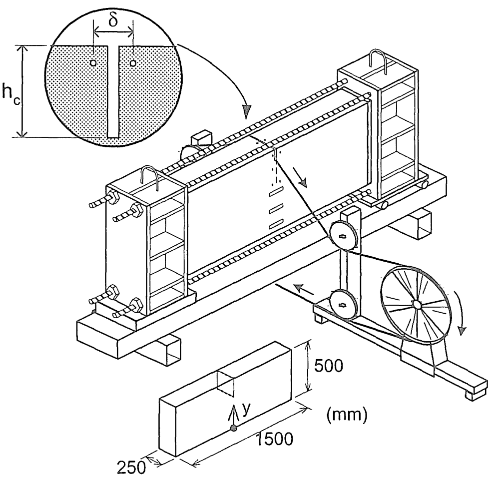

Figure 5. Concrete specimen and cutting procedure.

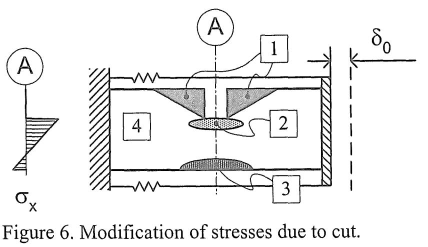

Figure 6. Modification of stresses due to cut.

Prior to the cut, an initial deformation δ_0 inducing a uniform initial stress field σ_0 was applied to the specimen. Figure 6 illustrates changes in concrete stresses due to the cut. The influence zone [1] is decompressed. A zone [2] of high compressive stresses is induced at the cut tip due to stress concentration and the flexural component introduced in the system. Tensile stresses could be generated at the bottom fiber of the specimen [3]. Finally, stresses in the bulk of the specimen [4] will not be affected significantly by the cut. The long-term deformation of each zone is controlled by relevant rehological viscoelastic laws (creep, relaxation), strain compatibility requirements, and the time varying induced forces (deformations) by the steel bars.

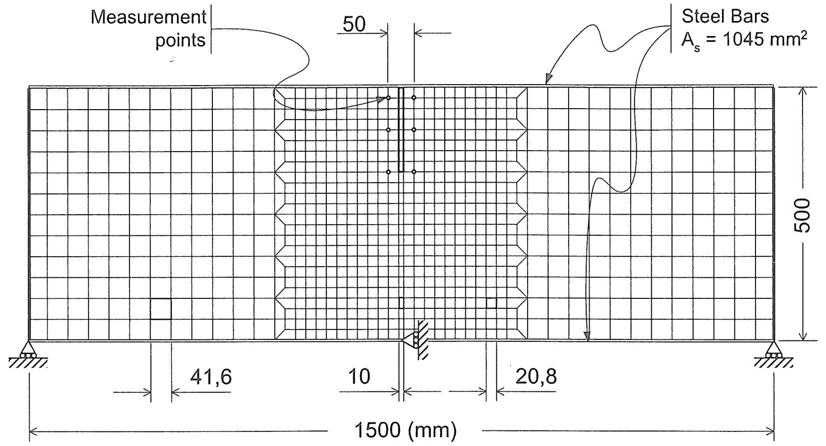

Figure 7. Plane stress finite element model (FEM).

4.2 *Testing procedure and experimental results*

A 10mm diamond wire saw was used to perform the cut (Fig.5). Table 2 presents the age of concrete when the cut was made and the time required to do it, t_c. The slot closure, tensile forces in the bars, and concrete deformations were measured periodically while performing the cut. The slot closure and the forces in the bars were then subsequently monitored for 28 days.

Table 2. Age of specimen and time to perform the cut (t_c).

Test	Age (days)	t_c (min)
1	71	91
2	114	33
3	56	70
4	83	104

4.2.1 *Short-term elastic response*

Table 1 presents the experimental short-term "elastic" closure responses $\delta_E^{(Exp)}$ at the top of the specimens. The elastic closure profiles are nearly linear with maximum values at the top of the specimens (Fig.8). When σ_0 is doubled (Test 4 vs Test 3) the closure is nearly doubled (Table 1). When the cut depth is increased by 29mm (Test 3 vs Test 2) the closure is increased by 65%.

Figure 8 indicates the experimental stress distributions before (Exp-be) and after (Exp-af) the cuts obtained from the strain gages. For all tests, σ_0 prior to cuts is uniform. After the cuts, the stress distributions become roughly trapezoidal. Tests 3 and 4 for which h_c=196mm induced tensile stresses at the bottom of the specimens. However, concrete cracking was not observed in the tensile zone.

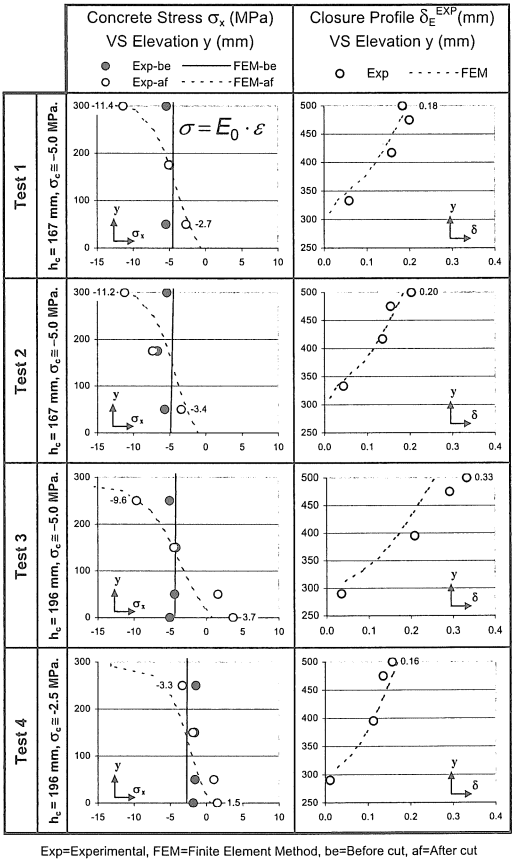

Figure 8. Short-term elastic responses.

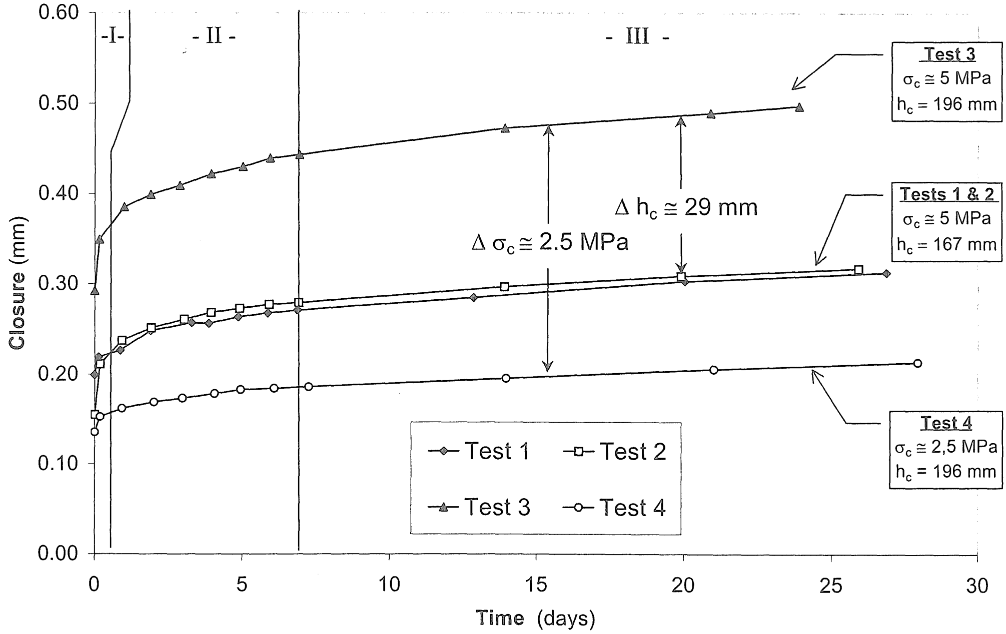

Figure 9. Long-term experimental closure responses.

4.2.2 *Long-term response*

Figure 9 presents the measured long-term closure responses $\delta(t)$ for the four specimens. The data are based on gage points located 25mm below the top of the specimens using average measurements from both sides. The closure-time relationships can be divided into three regions (I, II, III) in Figure 9. The first region, lasting approximately one day, presents a very rapid rate of closure that is slowing down with time in regions II and III. For Test 1, the value $\delta(1\text{day}) = 0.23\text{mm}$ increased to $\delta(28\text{days}) = 0.31\text{mm}$. This represents a 34% increase indicating the importance of transient phenomena. Overall, the transient increases in slot closures could be estimated using an average sustained elastic modulus, E_S, equals to 0.71 E_0.

Observations made earlier for the short-term experimental response are still valid. The 29 mm increase in cut depth (Test 3 vs Test 2) induces a 60% additional long-term closure. Doubling the applied stresses (Test 4 vs Test 3) produces a proportional increase in slot closure. The similarity in short-term and long-term experimental responses from Tests 1 and 2 have indicated repeatability of the results within a reasonable confidence interval.

5 COMPARISONS BETWEEN EXPERIMENTAL RESULTS AND NUMERICAL SIMULATIONS

Figure 7 shows the plane stress finite element model that was developed to carry out numerical simulations using the computer program ANSYS. A Ross model was used for creep with:

$$\varepsilon_{CR}(t) = \frac{\sigma_0}{E_0} + \frac{\sigma_0}{E_t}(1 - e^{-t/t_1}) \tag{4}$$

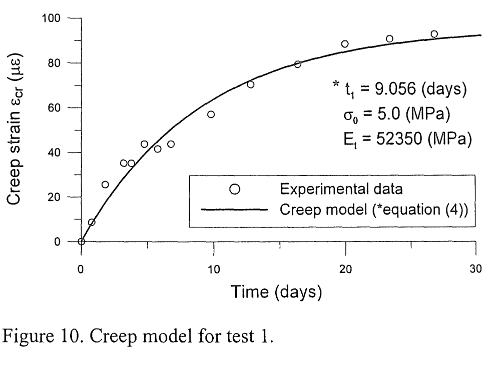

Figure 10. Creep model for test 1.

Creep test data on cylinders loaded simultaneously with specimens were used to determine the constants E_t and t_l. An excellent correlation was obtained between the subsequent 28 days creep test data recorded and the Ross model (Fig. 10). Shrinkage was estimated from measurements taken on unloaded reference specimens. Shrinkage was then introduced in the finite element analyses as a negative thermal deformation varying linearly in time.

5.1 *Short-term elastic response*

Table 1 presents the top short-term "elastic" closure estimated by finite element method (FEM), $\delta_E^{(FEM)}$. Considering a simplified analysis, Equation (2) does not produce good result in this case because significant bending deformations are developed from the experimental setup after the cut.

The computed closures $\delta_E^{(FEM)}$ are generally in fairly good agreement with experimental measurements with an average error of 10.8% (0.028mm). Finite element analyses based on elastic material properties (E_0 and Poisson's ratio) produce the initial conditions for viscoelastic transient analyses.

5.2 *Long-term response*

Figure 11 shows the FEM computed long-term (viscoelastic) closure responses. In contrast with elastic analyses, transient analyses did not yield as precise correlation between experimental measurements and computed results. For Test 1 a -11% (-0.033mm) difference was obtained for the final closure. For Tests 2 and 3 differences of –26% (-0.082mm) and –27% (-0.133mm) were respectively obtained. Moreover, the +30% (+0.062mm) difference observed for Test 4 is of opposite tendency as compared with the other tests. For the four tests, the average error is 23.5% (0.078mm).

Several causes could contribute to differences between the experimental and computed closures such as: temperature effects, variations in elastic material properties, measurement errors, and the validity of the uniaxial creep model derived from cylinder specimens. A careful review of these possible effects suggests that the creep model is most likely responsible for the differences between experimental and computed results. Correction of creep data for scale effects considering the test specimen section to perimeter ratio as compared to the similar ratio for the cylinder suggested a 20% reduction in computed final closure. This trend is not in agreement with experimental observations. Creep data were experimentally obtained for compressive stresses equal to 5MPa or 2.5MPa. However, after the cut, the stresses are no longer uniform across the specimens, which even develop tensile zones in some cases. A small inaccuracy in the creep model appears to produce a significant error in final closure.

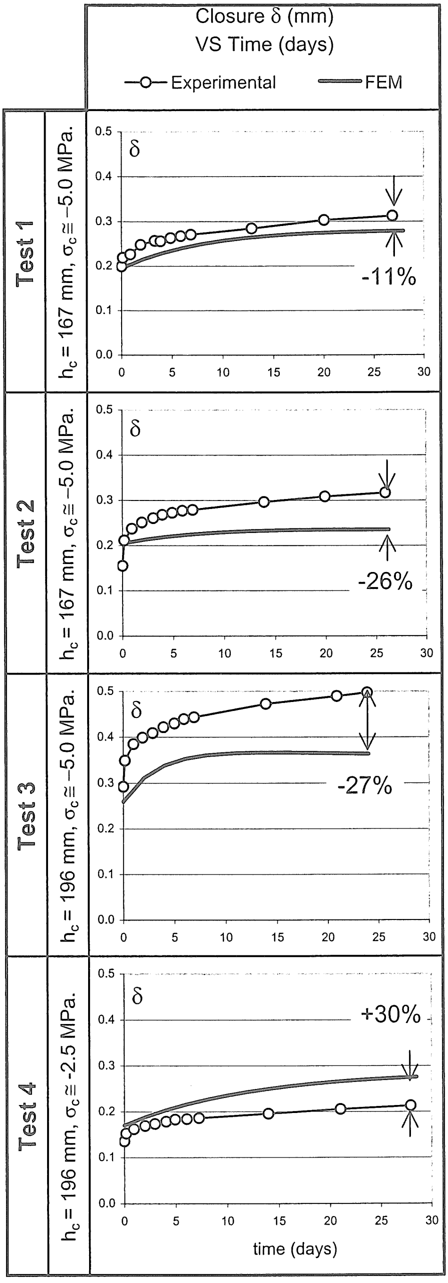

Figure 11. Long-term closure responses.

It is not appropriate to do a direct transposition of these observations to an actual dam. Creep is less for old concrete and for concrete with a high aggregate content. Nevertheless, introduction of a cut in a dam induces an important perturbation in the internal stress field that will also induce differed recovery of elastic and creep displacements and may alter the ongoing creep rate in zones where compressive stresses are modified.

6 CONCLUSIONS

Slot cuts have been performed in several dams to introduce expansion joints to alleviate detrimental effects related to the built-up of compressive forces and related displacements. The long-term efficiency of a cut is directly related to its initial width that will be reduced in time for dams suffering from AAR. Differed slot closure has also been observed for a dam subjected to seasonal temperature variations but where no AAR has been identified. The experimental tests have shown that to properly estimate a slot closure, one must have a good knowledge of the initial stresses, the geometry of the cut, and viscoelastic concrete properties.

For an existing dam, there are high uncertainties in these parameters. A cut intercepting a crack and a network of joints will also induce rigid body displacements that are difficult to anticipate. A priori calibration of numerical models from in situ displacements (crack pattern), temperature measurements, and stress measurements by overcoring techniques, as well as laboratory evaluation of thermal and viscoelastic properties should be considered to assess the transient effects of a cut on a rational basis. The purpose is to attempt to reduce uncertainties on most significant modeling input parameters.

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