WATER PRESSURE IN PROPAGATING CONCRETE CRACKS

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ABSTRACT: Water pressure in propagating concrete cracks is experimentally and numerically investigated. Ultimate application of this study is the uplift pressure in a concrete gravity dam during and after an earthquake. Numerous tests were conducted on wedge splitting specimens with hydrostatic pressure along the crack. Relative velocities of water front versus crack front as well as the effect of sudden crack closure have been investigated. It was observed that, for the tested specimens, the crack opening rate has important consequences on the internal water pressure distribution. If the crack opening rate is slow enough, the water pressure has time to develop, whereas under fast crack openings the water front cannot keep up with the crack front. Furthermore, upon sudden crack closure the trapped water acts as a wedge causing tensile stresses in the specimen. Finally, on the basis of the experimental observations, a model for the conductivity of cracked concrete is developed. Such a model could then be used in the coupled transient finite-element analysis of a concrete dam subjected to an earthquake.

INTRODUCTION

The complex problem of uplift forces in cracked concrete dams under seismic conditions has seldom been experimentally investigated, and as a result a number of simplifying assumptions are made. The most notable one is the lack of uplift pressure inside an earthquake induced crack. But how correct is this assumption, and what about sudden crack closure and opening? Those most important questions play a key role in assessing the ability of a dam to sustain earthquake loads. Furthermore, it should be mentioned that similar problems are also encountered in cracked offshore structures and to a lesser extent in the safety assessment of cracked concrete containments of hazardous material. As part of an extensive investigation on the safety of dams undertaken at the University of Colorado at Boulder, special attention has been given to the cracking of concrete and to the response of cracked concrete structures. In initial tests, the fracture properties of large-scale specimens were determined (Saouma et al. 1991). Subsequently, the response of cracked concrete specimens with internal water pressure was also studied (Brühwiler and Saouma 1995a,b,c). In both cases the load was applied statically. Those preliminary results have in turn been implemented in the finite-element program MERLIN by Reich (1993) and Reich et al. (1997). More recently, the fatigue behavior of cracked concrete was also investigated by Slowik et al. (1996). The work presented here is thus a continuation of these efforts and focuses on the behavior of cracked concrete specimens (where the crack size is at least equal to the aggregate size) subjected to both external dynamic loads and internal water pressure.

In the broader context of static loading, the problem of uplift pressure in concrete dams has been extensively studied for a long time (Fillunger 1915; Terzaghi 1936; Serafim 1964; Bažant 1975). Experiments on the water-fracture interaction in concrete under dynamic loading conditions have not been reported before. A few related works should be mentioned. Brühwiler and Saouma (1995a,b,c) conducted an experimental study in which it was determined that the (static) uplift pressure inside a crack is a function of the crack opening and that, along the fracture process zone, this pressure reduces from full reservoir pressure to zero. Tinawi and Guizani (1994) also developed a numerical model for the hydrodynamic forces inside a crack; however, this model is purely analytical and is not based on experimental observations. Visser (1998) presented an extensive study on extensile hydraulic fracturing of concrete and sandstone. It was shown that permeability and saturation level of the continuum surrounding the crack influence the effect of the hydrostatic pressure in the crack. The work was however limited to slow crack propagation. Fluid flow in the crack was not taken into consideration. The fluid flow through (uncracked) cementitious porous material has been extensively studied (Bjerkeli 1990; Vuorinen 1985); however, only a few investigations of the fluid flow along concrete cracks are reported. Reinhardt et al. (1998), Brauer and Schiessl (1996), and Imhof-Zeitler (1996) investigated the flow of unpressurized (hydraulic head $\leq$1.4 m) fluids in concrete cracks. It was shown that fluid flow and penetration depth strongly depend on the crack width. In addition, the properties of the penetrating fluid and the saturation level of the crack surfaces (Brauer and Schiessl 1996) were found to have an influence. Reinhardt et al. (1998) concluded that the permeability of cracks having an opening of more than about 0.03 mm is higher than in the undamaged concrete. For smaller crack widths the penetration behavior is similar to the one in uncracked concrete. Brauer and Schiessl (1996) investigated the fluid flow in prestressed (closed) cracks and determined that fluid penetration cannot be completely prevented by applying crack closing compressive stresses. Models have been developed to predict the fluid penetration depth (Imhof-Zeitler 1994), the pressure distribution in concrete cracks (Brühwiler and Saouma 1995a; Shinmura and Saouma 1997), and the uplift pressure in concrete dams (Illangasekare et al. 1992; Reich et al. 1994; Tinawi and Guizani 1994; Brühwiler and Saouma 1995b). Finally, models in which the uplift pressure is embedded in a coupled poroplastic approach were also presented (Fauchet and Coussy 1991).

EXPERIMENTS

The concept for the dynamic splitting test apparatus stems from previous experience with the wedge splitting test for quasi-static fracture tests. A loading device similar to the one introduced by Brühwiler and Wittmann (1990) was used (Fig. 1). Wedges were inserted between opposite roller bearings thus inducing a splitting force on the specimen. In the tests with internal water pressure, a rubber membrane was glued to the concrete surface to maintain the pressure in the notch, and two metal clamps were pressing the membrane to the concrete surface. The water was supplied through a steel tube connected

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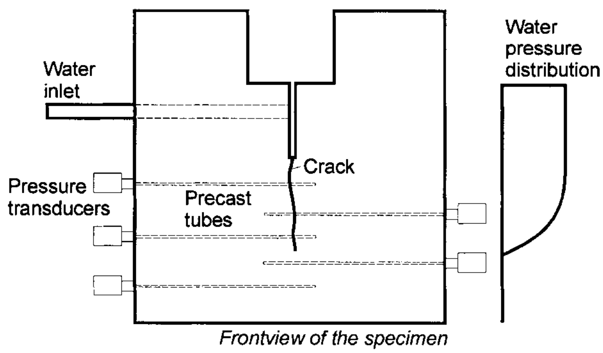

FIG. 1. Experimental Setup for Wedge Splitting Tests

to the notch. To measure the water pressure along the crack path a similar setup as the one used by Brühwiler and Saouma (1995b) was adopted. Piezoelectric pressure transducers were connected sideways to the crack trajectory through small precast tubes (1.5 mm in diameter) (Fig. 1). In addition, parallel wires have been placed across the specimen to electrically detect the water front through the closing of an electric circuit by the saline water. For long-term tests, the water input pressure was controlled by a servovalve, which provided constant head. During the experiments, applied force, crack mouth opening displacement (CMOD), water input pressure, pressure readings along the ligament, output of the electrical water front detector as well as acoustic emission were monitored.

Through the experimental program the following practical questions, often raised by dam engineers, have been addressed:

- Does the crack opening rate have an influence on the uplift pressure distribution in the crack? What is the velocity of the pressure buildup, and how does it compare to the crack velocity?
- Following a sudden crack propagation, what is the water pressure distribution in the crack? Is there a smooth transition between full and zero water pressure along the fracture process zone near the crack tip? Would the fracture process zone be eventually fully pressurized?
- What is the pressure variation during sudden crack closure? If the water cannot be expelled from the crack mouth, would it then act as a wedge with anticipated tensile stresses in the ligament?

These complex questions required different experimental procedures. Displacement controlled wedge splitting tests with different CMOD rates were conducted to address the first question. For the second one, the pressure buildup along the fracture process zone in precracked specimens was investigated through pressure readings along the crack. For measuring the water pressure during sudden crack closure, a fracture process zone was created by preloading prior to crack pressurization. Then, the CMOD was decreased to zero within 0.15 s through an external crack closing force, which could be applied by a modified wedge splitting device (Slowik and Saouma 1994).

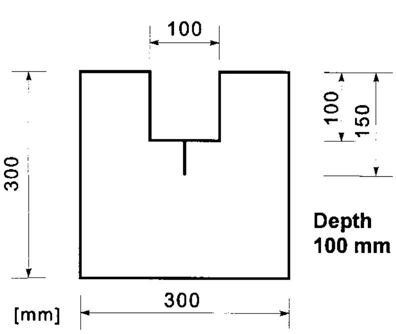

FIG. 2. Specimen Dimensions

TABLE 1. Concrete Composition

Composition (1)	Value (2)
Cement type I	350 kg/m^3
Water	182 L/m^3
Sand (0–5 mm)	761 kg/m^3
Gravel (5–12.5 mm)	614 kg/m^3
Gravel (12.5–25 mm)	538 kg/m^3

The specimen dimensions are shown in Fig. 2. For the sudden crack closure tests, larger specimens have been used (Slowik and Saouma 1994). In Table 1, the concrete mix used for all specimens is given. The average compressive strength was 30 MPa. All samples were stored in a steam room until testing.

EXPERIMENTAL OBSERVATIONS

Effect of Crack Opening Rate

Fig. 3 shows the load-CMOD curves of wedge splitting tests for both slow (2 μm/s) and fast (200 μm/s) crack openings. The following observations could be made:

- The peak load is smaller under quasi-static loading than under fast loading. This can be explained by the loading rate effect on the concrete strength (Slowik et al. 1996).
- There is a substantial difference between the two postpeak responses. More specifically, to maintain a specified (postpeak) value of CMOD, a higher splitting force is required for the fast loading than for the slow one.

Because it was shown earlier that, for dry tests under fast and slow loading, the postpeak responses are similar (Slowik et al. 1996), the observed discrepancy (second observation) can only be explained by the presence of additional water pressure in the slow loading specimen. Thus, if the crack opening rate is small enough, the water pressure has time to develop. However, for fast loading rates this is no longer the case. In Fig. 3 the water pressure readings at different locations along the crack path for both slow and fast loading are also shown. One observes that the hydrostatic pressure reaches its maximum value at a larger CMOD in the fast loading case than in the slow one. This was confirmed by the electric circuit water front detection.

As such, it is concluded that the loading rate indeed plays a dominant role in controlling the internal water pressure distribution within a propagating crack. Hence, the faster the crack propagation, the lower the water pressure inside the crack (as is currently assumed).

Although the location of the water front during the experiment can be determined from pressure readings and the electric water front measurements, there is no experimental technique to reliably determine the crack front. This can only be accomplished numerically. Using the nonlinear fracture model of MERLIN (Reich et al. 1997), along with the experimental CMOD, load, and water pressure readings, one can determine the corresponding crack profile through a simulation of the experiments. Fig. 4 shows the location of the crack and water fronts in terms of the CMOD for two tests performed at 0.21-MPa water pressure but with different loading rates. The curves for the crack front are almost identical for both crack opening rates. A substantial difference, however, can be observed in the water front curves. For slow crack opening, the distance separating the water and the crack front remains con-

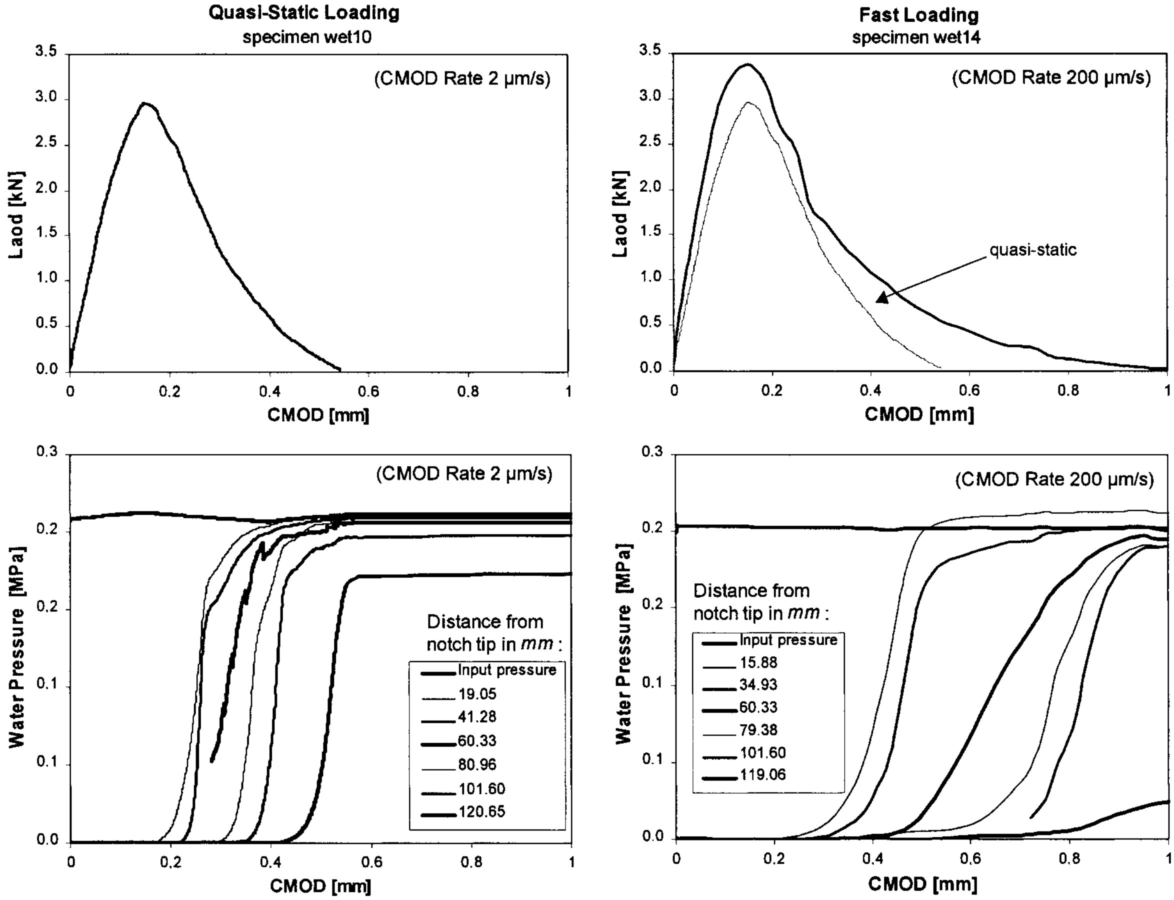

FIG. 3. Load and Water Pressure versus CMOD for Different CMOD Rates

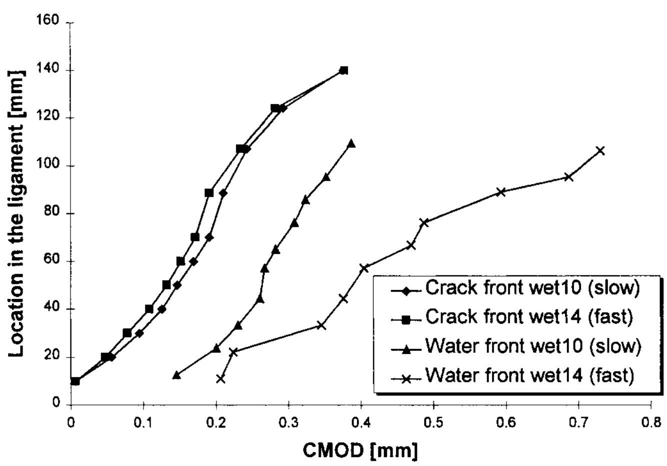

FIG. 4. Crack and Water Front versus CMOD Curves for Slow (Specimen Wet10) and Fast (Specimen Wet14) Loading (Input Water Pressure 0.21 MPa)

stant, whereas it increases for fast loading. As the crack propagates, the ''distance gap'' (vertical distance) between the crack front and the water front increases. This clearly implies that in the case of fast crack opening the water front cannot keep up with the crack front. To investigate the influence of the water input pressure on these findings, the whole analysis procedure was repeated for a pair of specimens tested under 0.62-MPa input pressure. Because of the higher input pressure, the gap between crack and water front for slow loading appeared to be smaller than in the case of 0.21 MPa.

It is possible to derive the local crack opening from the numerical analysis results. For slow crack opening, the results exhibit a parabolic dependence of the water pressure on the crack opening. This confirms the experimental results and the proposed law of Brühwiler and Saouma (1995b,c). However, for fast crack opening, this simplified model is no longer applicable, and a more comprehensive one, which takes into account time, will be presented later.

Effect of Time

It was previously shown that for fast crack opening, the water front lags behind the crack front. Hence, the next question to be addressed is the uplift pressure following crack arrest and closure.

To address this question, a wedge splitting specimen with a height of 300 mm was first loaded into the postpeak region and then unloaded (Slowik et al. 1995). In a numerical backward analysis the distance from the notch to the crack tip was found to be about 110 mm. A constant input water pressure of 0.21 MPa was then applied at the notch of the specimen, and the pressure distribution along the crack path was monitored for about 6 h. It was observed that the pressure increased in time until after about 5.5 h, when the maximum (input) pressure was reached along the entire crack. Water is clearly flowing into the crack, and the flow is unsteady as the pressure varies with time. Given a sufficiently long time, steady flow is reached, implying zero flow and a constant pressure distribution. In a longer crack, such as in a concrete dam, this time period would be longer. Nevertheless, there is no reason for a pressure gradient along the crack after an ''infinite'' amount of time elapses (contrarily to the pressure gradient with steady flow along a continuous joint).

Rapid Crack Closing

Next, we investigated the behavior of a water filled crack when it is subjected to rapid closing (Slowik and Saouma 1994). Of primary concern is the possibility that water rather than being squeezed out is trapped inside the crack. In a dam, this could cause unexpected tensile stresses in the downstream face. To shed some light on this subject, in several wedge splitting specimens a crack was formed, and subsequently a water pressure was applied into it. Then, within a short time period of 0.15 s the crack was forced to close completely (CMOD equal to zero) resulting in a negative load because the water pressure and some residual inelastic crack opening had to be overcome. The pressure readings indicated that during sudden crack closure water is trapped in the crack resulting in a temporary overpressurization. In these particular tests, the hydrostatic pressure was about three times the initial one. It should be noted that the initial pressure in the notch increased as well but not as much as the one measured in the fracture process zone. The trapped water did indeed act as a wedge while the crack was being closed. After the rapid crack closure, the ligament of the wedge splitting specimens was completely broken. This suggests that, in a concrete dam, tensile stresses may develop in the downstream face. The magnitude of these stresses would significantly depend on the geometry, magnitude of the water pressure, and loading rate.

PROPOSED MODEL

From the experimental observations it is concluded that the fluid conductivity of a crack significantly depends on the damage level in the fracture process zone. Furthermore, the pressure time dependency points to the necessity of modeling the fluid flow in concrete cracks as a transient phenomenon. The fracture process zone appears to have a substantial fluid storage capacity, and it is postulated that it in turn depends on the damage level [expressed in terms of crack opening displacement (COD) within the context of this work].

The next step is thus to develop a model for the fluid flow in concrete cracks that could be implemented in a discrete crack representation within a finite-element model. Such a model should lend itself to a coupled nonlinear analysis in which the water conductivity is directly related to the COD of a propagating crack.

A widely used model for concrete cracking is the fictitious crack model by Hillerborg et al. (1976). In this model the fracture process zone is replaced by a fictitious crack that exhibits strain discontinuities and stress continuity. The tensile strength normal to the fictitious crack is a function of the COD as long as the COD is less than a critical (material parameter) value. Then the crack becomes a real one; its opening is not fictitious any more. In a monotonically propagating crack the stress transferred normal to the fictitious crack is equal to the local strength value. For zero crack opening, the tensile strength is equal to the one of the undamaged concrete.

It is postulated that the fluid conductivity and the storage capacity also depend on the COD. The larger the COD, the higher the fluid conductivity and the storage capacity would be. Furthermore, the undamaged concrete surrounding the fracture process zone is considered to be impermeable. This assumption is supported by the fluid permeability of cracks being significantly higher than that of uncracked concrete.

The derivation of the model begins with the conservation of mass equation for a 1D problem

$$\frac{1}{dx}\cdot d\dot{m} = \frac{d(\dot{q}\cdot\rho)}{dx} \tag{1}$$

where $\dot{q}$ = fluid flow (m^3/s); $\dot{m}$ = mass of fluid removed from the flow per unit time (kg/s); ρ = fluid density (kg/m^3); and x = length along the crack path (m). Under the assumption of constant stream tube depth s and fluid density ρ

$$\frac{ds}{dx} = 0;\quad \frac{ds}{dt} = 0;\quad \frac{d\rho}{dx} = 0;\quad \frac{d\rho}{dt} = 0$$

Eq. (1) can thus be rewritten as

$$\frac{d}{dt}\left(\frac{dV}{dx}\right)\cdot\rho = \frac{d(v\cdot d\cdot s\cdot\rho)}{dx} \quad \text{and with} \quad \frac{dV}{dx\cdot s} = W \quad \text{as} \quad \frac{dW}{dt} = \frac{d(v\cdot d)}{dx} \tag{2}$$

where V = fluid volume (m^3); W = volume of fluid displaced from the flow per unit crack length and per unit crack depth (m^3/m^2); v = flow velocity (m/s); and d = width of the stream tube (m). Darcy's law, which relates the velocity to the gradient of the hydraulic pressure head p, is then invoked assuming laminar flow

$$v = K\cdot\frac{dp}{dx} \tag{3}$$

The laminar flow assumption is supported by the low water flow velocity in concrete cracks. K is the permeability (m/s). Capillary forces are not explicitly considered in the model. Such an assumption is based on the fact that for small crack widths, the microcracks are not interconnected. Therefore, only a small portion of the full capillary forces is present. For crack widths >0.07 mm, the additional pressure head would amount to about 0.2 m only. On the other hand, the effective flow resistance parameters that are determined in backward analyses from experiments (see following section) indirectly account for the effect of capillary forces.

From (2) and (3) it follows that

$$\frac{dW}{dt} = (Kd)\,\frac{d^2p}{dx^2} + \frac{d(Kd)}{dx}\cdot\frac{dp}{dx} \tag{4}$$

The permeability K and the width of the stream tube d are both assumed to depend on the fictitious crack opening w. It would be too speculative to consider the width of the stream tube to be equal to w because the crack opening by itself does not account for the connectivity of individual microcracks in the fracture process zone as well as microcracks on each side of the macrocrack. On the other hand, it is not necessary to separate the width of the stream tube from the permeability. Therefore, the crack parameters K and d will subsequently be merged into a single parameter termed crack conductivity, which describes the resistance of the crack against fluid flow. In contrast to the permeability and the width of the stream tube, the fluid conductivity of a crack can be determined through a backward analysis of the flow process (as explained in the following section).

During crack formation, cavities are formed. They are dry and air filled at first, and then they are impounded by water. From the ideal gas law

$$\frac{p{*}V}{T} = \text{const}$$

and for isothermal conditions

$$w_A\cdot p_A = w_f\cdot p \tag{5}$$

where w_A = opening of the crack to be filled with water; p_A = original pressure head in the crack before water penetration; w_f = portion of the crack opening that is occupied by the compressed air after water penetration; and p = actual pressure head after water penetration. This equation implies that if the pressure increases from p_A to p, then the air in the crack is pressurized and will subsequently fill only a portion of the crack opening w_f. Hence, W, which is the volume of fluid removed from the flow per unit length and per unit depth, can be expressed as

$$W = w_A - w_f \tag{6}$$

where the crack opening w_A, which can be filled with water, is further decomposed into two portions: one associated with the opening w and the other with the coalescence of intersected pores. If r is the characteristic pore radius (m) and α the porosity (m^3/m^3), then this additional width would be equal to $2r\alpha$. The portion α of the crack path intersects pores. On one crack surface, the crack width increases amounts to $r\alpha$. Thus

$$w_A = w + 2r\alpha \tag{7}$$

The solubility of air in water is not accounted for. Thus, W is slightly underestimated, and the error introduced by this simplification should be <1%. Furthermore, the compressibility of the water is also neglected since it is very small as compared to the compressibility of the air in the partially filled crack.

Prior to water penetration, the air pressure head p_A in the crack is assumed to be equal to the atmospheric pressure head p_0. During crack propagation and water penetration, an air exchange between the crack and the surrounding material takes place. Simplifying, it is assumed that the volume of air inside the crack is always equal to the one that would result in $p = p_0$ for a dry crack (i.e., not a water filled crack). This implies that after removing the water out of the crack the pressure is equal to the atmospheric one. Consequently, there is air transport into an opening crack and air transport out of a closing crack. If the closing and opening takes place slowly and in a dry crack, then the air pressure would always be equal to p_0. However, under rapid crack closure, the air cannot be squeezed fast enough into the material surrounding the crack resulting in a pressure head higher than p_0. Conversely, during rapid crack opening there may be a sudden air pressure drop. If crack surfaces are moving slowly then and only then would $p_A \approx p_0$. The effect of rapid crack closing and opening during the fluid flow process is taken into account by correcting the original pressure head in the crack p_A. Simplifying, it is assumed that the drop or rise of p_A is linearly dependent on the local crack opening velocity $\dot{w}$. Hence

$$p_A = p_0 - R\dot{w} \tag{8}$$

where R = material constant that accounts for the resistance against the air exchange between the crack and the surrounding material. Combining (5) and (6), we obtain

$$W = w_A \left(1 - \frac{p_A}{p}\right)$$

which in turn can be combined with (7) and (8) to yield

$$W = (w + 2r\alpha)\cdot\left(1 - \frac{p_0 - R\dot{w}}{p}\right) \tag{9}$$

$$\frac{dW}{dt} = \frac{dW}{dw}\dot{w} + \frac{dW}{dp}\dot{p} = \left(1 - \frac{p_0 - R\dot{w}}{p}\right)\dot{w} + (w + 2r\alpha)\cdot\left(\frac{p_0 - R\dot{w}}{p^2}\right)\cdot\dot{p} \tag{10}$$

The derivative dW/dt can be replaced by (4). Solving for $\dot{p}$ gives

$$\dot{p} = C_1 p_{xx} + C_2 p_x + C_3 \tag{11}$$

with $p_{xx} = d^2p/dx^2$ and $p_x = dp/dx$ and the following coefficients

$$C_1 = f(p, \dot{w}, (Kd)) = \frac{p^2(Kd)}{(w + 2r\alpha)(p_0 - R\dot{w})} \tag{12}$$

$$C_2 = f\left(p, \dot{w}, \frac{d(Kd)}{dx}\right) = \frac{p^2\,\frac{d(Kd)}{dx}}{(w + 2r\alpha)(p_0 - R\dot{w})} \tag{13}$$

$$C_3 = f(p, \dot{w}) = \frac{-(p - p_0 + R\dot{w})\dot{w}p}{(w + 2r\alpha)(p_0 - R\dot{w})} \tag{14}$$

For the special case where there is no increase in the crack opening (i.e., $\dot{w} = 0$) and the conductivity Kd is constant along the crack, (11) can be simplified to

$$\dot{p} = C_1 p_{xx} \quad \text{with} \quad C_1 = \frac{p^2(Kd)}{p_0(w + 2r\alpha)}$$

implying that the pressure distribution in a crack with constant conductivity is linear under steady flow conditions.

The application of the proposed model hinges on the experimental determination of the crack conductivity Kd, which will be done through backward analyses of the experiments reported before.

NUMERICAL SIMULATION OF EXPERIMENTS

The wedge splitting tests under monotonically increasing CMOD with internal water pressure in the crack were simulated. In such an analysis, the interaction between cracking and fluid flow cannot be neglected. Hence, coupled nonlinear fracture mechanics and unsteady fluid flow analyses had to be performed to numerically simulate the experiments.

For the crack propagation simulation, the fictitious crack model (Hillerborg et al. 1976) with a bilinear softening curve was adopted. The softening curve describing the stress transfer in the fracture process zone has been determined on the basis of dry tests without water pressure. To investigate the influence of the test conditions, four tests performed under different input water pressure and loading rate were selected for the numerical simulation. The softening curves were slightly adjusted to optimize the fit between experimental and numerical results. Fig. 5 shows the softening curves used in the simulation. The load rate effect in concrete specimens tested under fast loading (200 μm/s) caused slightly higher stresses than in other specimens.

The conductivity-crack opening curves had to be determined

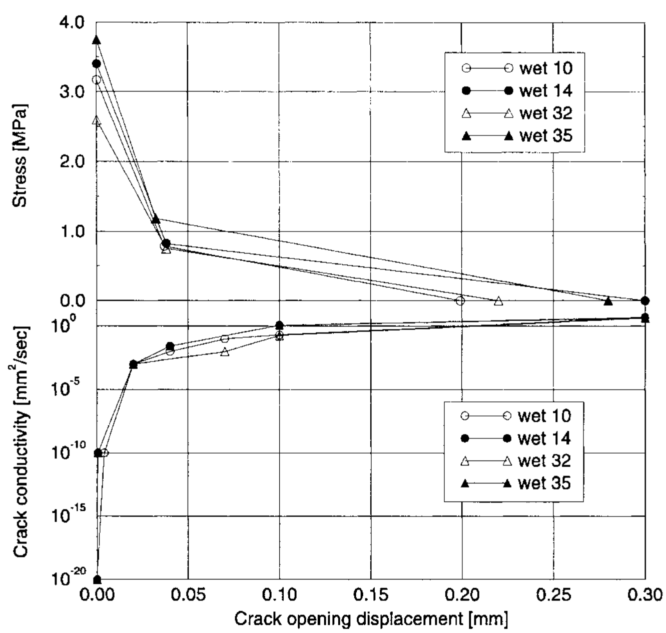

FIG. 5. Softening and Conductivity Curves for Four Simulated Wedge Splitting Tests (See Also Fig. 6)

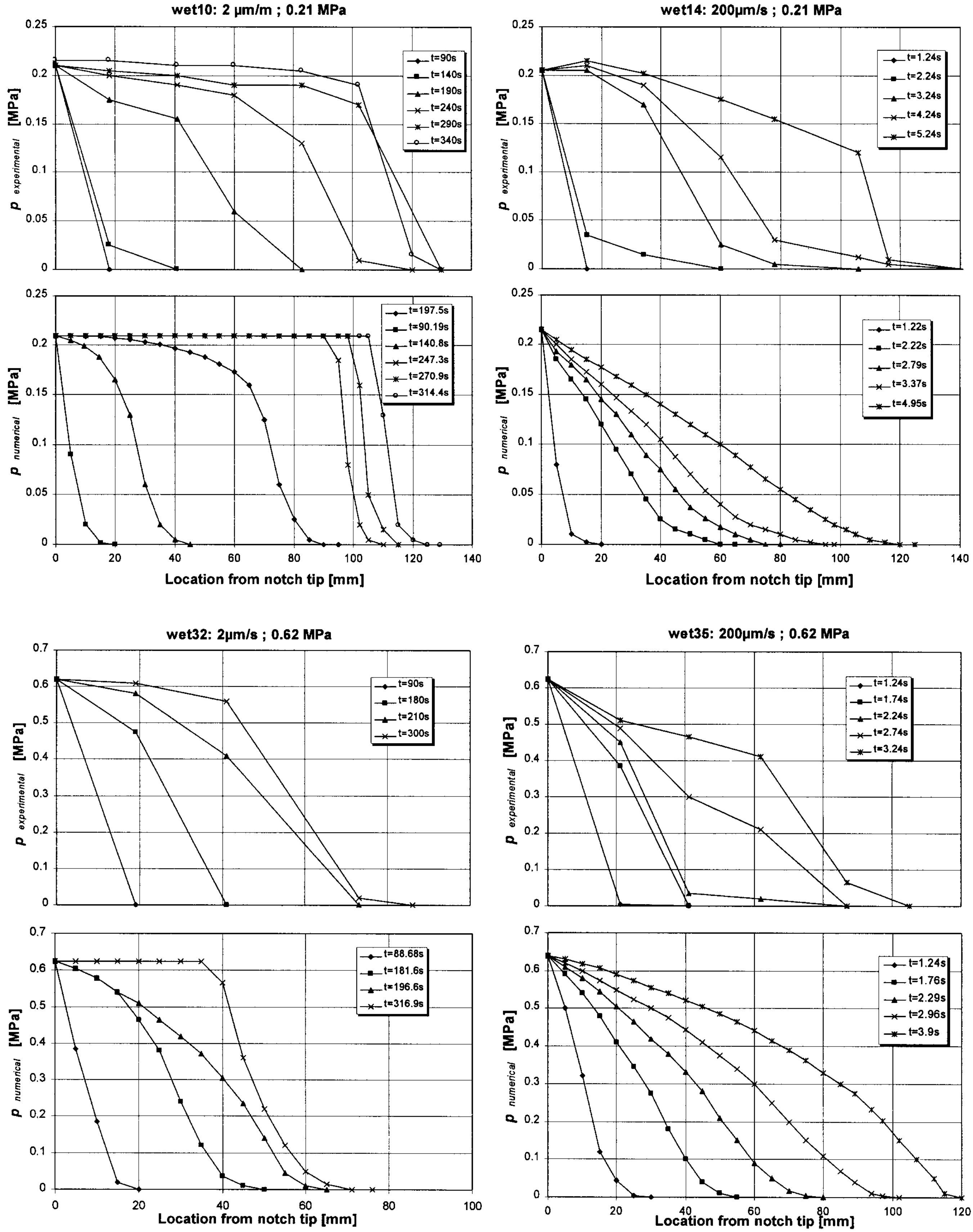

FIG. 6. Water Pressure Distribution Obtained Experimentally and Numerically for All Tests Analyzed (Upper Half of Each Plot: Experimental Pressure Readings for Different Time Steps; Lower Half of Each Plot: Corresponding Numerical Results, Respectively)

through an extensive trial-and-error procedure (Roh 1995). In this curve fitting process the load-CMOD curve, as well as the time-dependent pressure distribution along the crack path, had to be matched. The parameters to be adjusted in the fitting process were the softening curves as well as the conductivity curves showing the crack conductivity *Kd* as a function of the crack width. In all analyses, the air exchange parameter C was set to 10 s. Pore radius r and porosity α were assumed to be 5×10^{-4} mm and 0.1, respectively. Fig. 6 shows the experimentally and numerically determined pressure distributions along the crack path. In the upper half of each plot, the experimental pressure readings for different time steps are shown. The numerical results are shown in the lower half of each plot. Through this observation, one can note the good correlation between experimental and numerical results. However, in the case of 0.21 MPa and 200 μm/s, respectively, the numerical results cannot capture the very last water pressure distribution (at 5.24 s). The reason is that this last water pressure was measured right after the test (i.e., after the specimen had already failed).

It has to be mentioned that in the experiments water flow occurs vertically, whereas in a dam the flow is horizontal. However, the influence of the water weight on the water flow in the experiments is considered to be negligible when compared to the reservoir pressure head.

Fig. 5 illustrates the conductivity-crack opening curves for the best fits. Because the tests, which have been simulated numerically, were performed under very different conditions, the good match would indicate that this curve is truly a material parameter describing the water conductivity of a concrete crack.

SUMMARY AND CONCLUSIONS

1. Dynamic wedge splitting tests with internal water pressure were performed, and the variation of the internal pressure distribution along the crack path was monitored.
2. It was observed that the crack opening rate can have important consequences on the internal water pressure distribution. If the crack opening rate is slow enough, the water pressure has time to develop, whereas under fast crack openings the water front cannot keep up with the crack front. In the context of an investigation on the safety of concrete dams, this implies that during an earthquake induced fast crack propagation there is probably no water pressure acting in the crack. Although this finding is solely based on the preliminary reported tests, additional tests are necessary to further quantify this important observation.
3. As time elapses the pressure inside the newly formed crack will eventually reach the reservoir pressure.
4. If an opened and saturated fracture process zone is forced to close rapidly, then the water is not immediately squeezed back to the crack mouth. It is trapped in the crack and may act as a wedge causing tensile stresses in the ligament. This can have serious implications on the safety of cracked dams during an aftershock. That is, it is safer if the aftershock were to occur right after the major earthquake, than much later (when a long crack has time to become fully saturated).
5. An engineering model for water flow in a fracture process zone was proposed. It embodies most of the experimental results into a simple physical model that can be combined with a finite-element analysis of concrete structures. The fluid flow inside the fracture process zone is considered to be unsteady; the fluid conductivity as well as the storage capacity depend on the COD that can be readily determined from the finite-element analysis.
6. Coupled nonlinear fracture mechanics and unsteady fluid flow analyses were performed to numerically simulate some of the experiments. The simulation of the performed laboratory experiments enabled us to determine the material parameters controlling the fracture process as well as the fluid flow. The conductivity-crack opening curve, representing the material parameter describing the fluid flow in the crack, turned out to be independent of the test conditions indicating that the selected model is both physically sound and objective and that the derived curve is truly a material parameter.
7. The proposed model has not yet been used for simulating sudden crack closure. For such an analysis an appropriate constitutive law for the closing fictitious crack has to be adapted. Furthermore, the influence of the water compressibility on the pressure in an almost completely water filled and closing crack should be investigated. The role of pore pressure in the microcracks that are closing in the vicinity of the fracture process zone will also deserve deeper study.

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