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TRANSIENT FLUID FRACTURE INTERACTION

V. Slowik,
Hochschule für Technik, Wirtschaft und Kultur Leipzig (FH), Germany
V.E. Saouma, Y.-S. Roh,
Department of Civil, Architectural and Environmental Engineering,
University of Colorado at Boulder, USA

Abstract

Wedge splitting tests under dynamic loading with internal water pressure in the crack were performed, and it was observed that the crack opening rate has a significant effect on the water pressure distribution along the crack. Combined nonlinear fracture mechanics and fluid flow analyses were performed in order to numerically simulate the experiments. The fictitious crack model was adopted, and unsteady flow along the fracture process zone (in which both the fluid conductivity and storage capacity depend on the crack opening) was assumed.

1 Introduction

Over the past couple of years at the University of Colorado, an extensive investigation on the safety of concrete gravity dams has been undertaken. Special attention was given to concrete cracking and its interaction with internal water pressure. This fluid fracture interaction has a significant impact on the proper numerical modeling of cracked concrete dams for both static and dynamic loads. Furthermore, similar problems are encountered in cracked offshore structures, the containment of hazardous materials, and concrete pavement cracking.

In initial static tests performed by Brühwiler and Saouma (1994), the fluid fracture interaction was investigated by performing wedge splitting tests with internal water pressure in the crack. In addition to load and displacements, the water pressure distribution along the crack path was monitored. It was found that within the fracture process zone, the water pressure decreases from the full reservoir pressure at the crack mouth to zero pressure at the fictitious crack tip. The results of the tests were used to formulate a numerical model which was implemented in MERLIN by Reich (1993). In these tests the load has been applied statically. Cracking of concrete under dynamic loading conditions was subsequently studied by Slowik, Plizzari and Saouma (1995).

The experiments documented here represent a natural evolution of both the investigation into the water-fracture interaction under static loading and the „dry“ tests under dynamic loading. Currently, it is commonly assumed that the full reservoir pressure acts along a crack in a concrete dam. Whereas this is a rather conservative estimation for static loading, there is a big uncertainty involved in the estimation of the water pressure distribution for the case of seismic loading. Under seismic loading, it is commonly assumed that the propagating crack is not subjected to water pressure, in other words the crack front velocity is assumed to be much higher than the water front velocity. This fundamental assumption has never been experimentally validated and it may be unconservative, should there be an uplift pressure in the crack.

Experimental investigations into fluid flow in continuous joints have been performed primarily by the rock mechanics community. Usually, for joints in solid rock the laws of the steady flow allow to describe the investigated phenomena. To the best of the authors knowledge experimental results on the water-fracture interaction in concrete under dynamic loading conditions have never been reported before.

2 Experiments

A wedge splitting device similar to the one introduced by Brühwiler and Wittmann (1990) was used, Fig. 1. Wedges are pressed between roller bearings imposing a splitting force on the specimen. A rubber membrane is glued to the concrete surface in order to maintain pressure in the notch. The water is supplied through a steel tube entering the notch. In order to

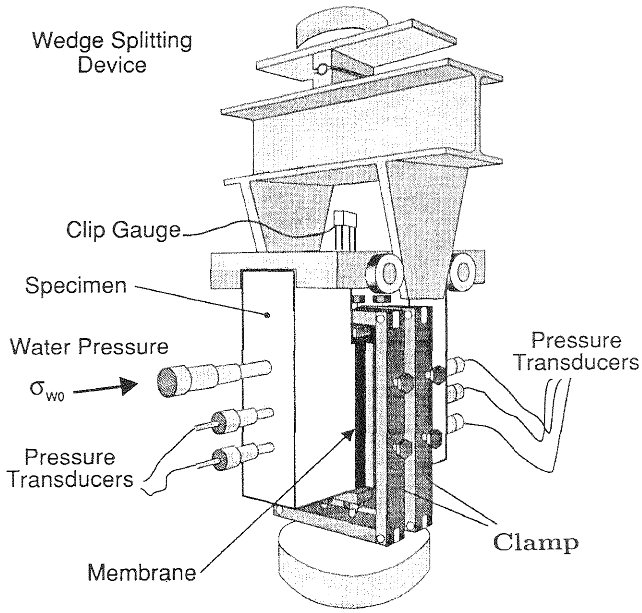

Fig. 1. Experimental set-up

measure the water pressure along the crack path a similar setup as the one used by Brühwiler and Saouma (1994) was adopted. Small channels (1.5 mm in diameter) were introduced in the concrete during casting. Outside the specimen piezoelectric pressure transducers were assembled, connected to the crack path by the precast channels, see Fig. 1. In addition to the setup used by Brühwiler and Saouma (1994), parallel wires were placed across the specimen to detect the water front when water connected the wires. As such, a special water front detector was built. For long term tests, water input pressure was controlled by a servo valve in order to provide constant boundary conditions.

In the experimental program the following practical questions raised by dam engineers were addressed:

- Does the crack opening rate have an influence on the pressure distribution in the crack? Under seismic loading, is there water pressure along the crack?
- Following an earthquake, what is the pressure variation? Would the fracture process zone be eventually fully pressurized?

These questions require more than one experimental procedure. Wedge splitting tests with different CMOD rates were conducted in order to address the first question. For the second one, involving the long term water pressure build-up, specimens were first preloaded, i.e., a fracture process zone was formed, then unloaded, and then water pressure was applied. The pressure build-up along the fracture process zone was recorded for several hours.

3 Experimental results

3.1 Effect of crack opening rate

Fig. 2 shows the load-CMOD curves for both slow (2 μm/s) and fast (200 μm/s) crack opening. The following observations can be made:

- The peak load is smaller under quasistatic loading than under fast loading. This can be explained by the loading rate effect on the concrete strength, see Slowik, Plizzari and Saouma (1995).
- There is a substantial difference in the two post-peak responses. More specifically, to maintain a specified (post-peak) value of CMOD, a higher splitting force is required for the fast loading than for the slow one.

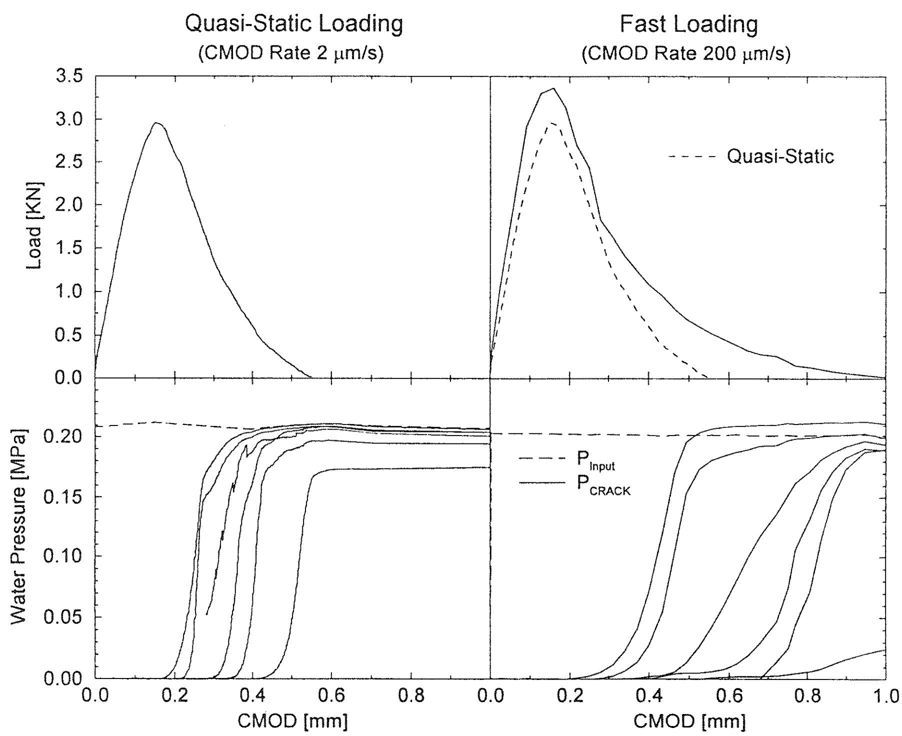

Fig. 2. Load and water pressure versus CMOD for different CMOD rates

Since it was earlier shown that for dry tests under fast and slow loading, the post-peak response is similar, see Slowik, Plizzari and Saouma (1995), the observed discrepancy (second observation) can only be explained by the added presence of water pressure in the slow loading specimen. If the crack opening rate is slow enough, the water pressure has time to develop; however for fast loading this is not the case. In Fig. 2 the water pressure readings at different locations along the crack path for both slow and fast loading are also shown. They show that the hydrostatic pressure reaches its maximum value at a larger CMOD in the fast loading case than in the slow one. Finally, the electric circuit water front detection has confirmed these findings.

On the basis of all the above, it is concluded that the load rate plays a dominant role in controlling the internal water pressure distribution within a propagating crack and that the internal uplift pressure is inversely proportional to the rate of crack growth. Hence, the faster the crack propagation, the lower the water pressure in the crack. Whereas the location of the water front during the experiment can be obtained from pressure readings and electric water front measurement, there is no experimental technique to reliably determine the crack front. This can be accomplished numerically. Using the results of a nonlinear fracture mechanics analysis, along with the experimental CMOD, load, and water pressure readings, it is possible to determine the corresponding crack profile. The experimental and numerical load-displacement curves for specimen wet10 (slow crack opening: 2 μm/s) and specimen wet14 (fast crack opening: 200 μm/s) are shown in Fig. 3. The applied water pressure was 30 psi (0.21 MPa) for both specimens. For the numerical simulation the program MERLIN has been used. With a satisfactory numerical model, we now have the means to determine the crack tip location at various stages, and compare it to the water front location.

Fig. 4 shows the location of the crack and water fronts in terms of the CMOD. The curves for the crack front are about equal for both crack opening rates. That means that for a pressure of 30 psi (0.21 MPa) the crack profile is not significantly influenced by the pressure distribution. A major difference, however, can be seen in the water front curves. Under slow crack opening (wet10) the distance separating the water and the crack front remains constant. This distance increases under fast loading (wet14). As the crack propagates, the "distance gap" (vertical distance) between the crack front and the water front is getting larger. This clearly shows that in the case of fast crack opening the water front can not follow the crack front.

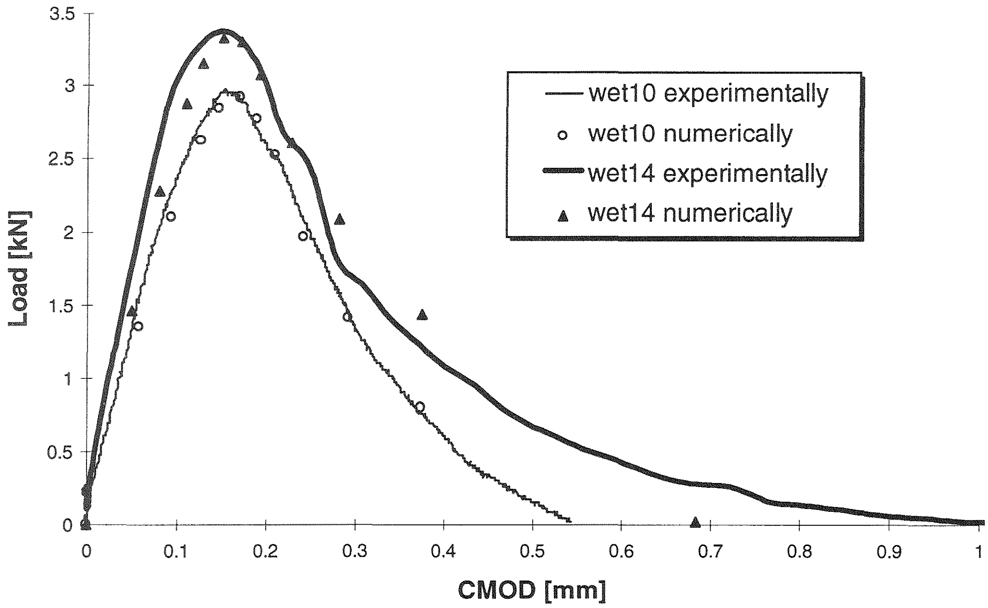

Fig. 3. Experimental and numerical load-CMOD curves for slow (wet10) and fast (wet14) loading

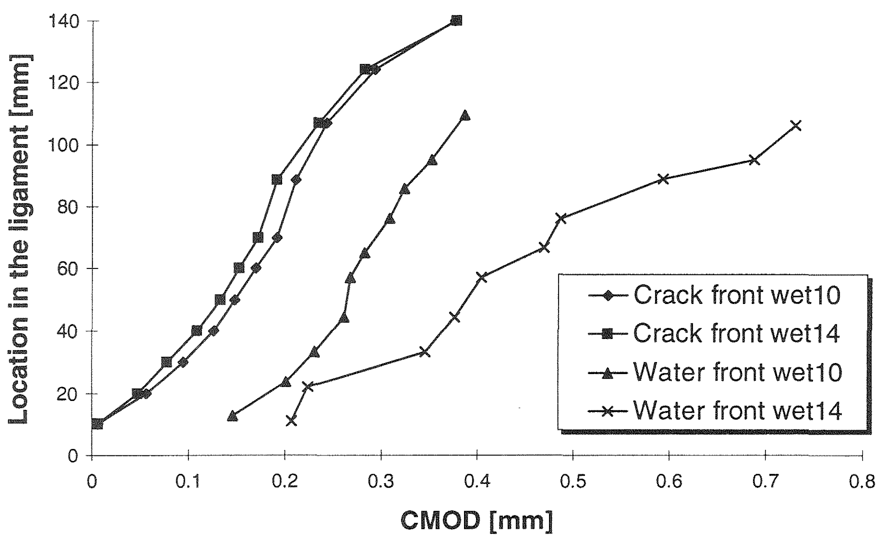

Fig. 4. Crack and water front versus CMOD

In order to investigate the influence of the water input pressure on the findings outlined above, the whole analysis procedure was repeated for a pair of specimens tested under 90 psi (0.62 MPa) input pressure. As in the case of 30 psi (0.21 MPa), it could be shown that the distance between the crack and water front remains constant for a slow crack opening and increases for a fast crack opening.

3.2 Effect of time

It could be shown that in the case of fast crack opening, the water front can not follow the crack front (section 3.1). But what happens when the earthquake is over and the crack is closed?

A wedge splitting specimen was loaded into the post-peak region and then unloaded. The equivalent crack length after this loading amounted to about 85 mm. From this it was concluded that the fictitious crack length was about 100 mm. After applying a constant input water pressure to the notch of the specimen, the pressure distribution along the crack path was monitored for about 6 hours, Fig. 5 (where the location of zero corresponds to the notch tip). We observe that the pressure increases in time until the maximum (input) pressure is acting along the entire crack. Water is flowing in the crack. The flow is unsteady because the pressure varies in time and water remains in the crack, i.e. "disappears" from the flow. After a very long time, steady flow is reached, which means in this case zero flow and constant pressure distribution. In a longer crack, such as in a concrete dam, this time period will be longer; but still, there is no physical justification for a pressure gradient in a concrete crack after an "infinite" amount of time elapses. In the case of a continuous joint, there can be a pressure gradient under steady flow conditions.

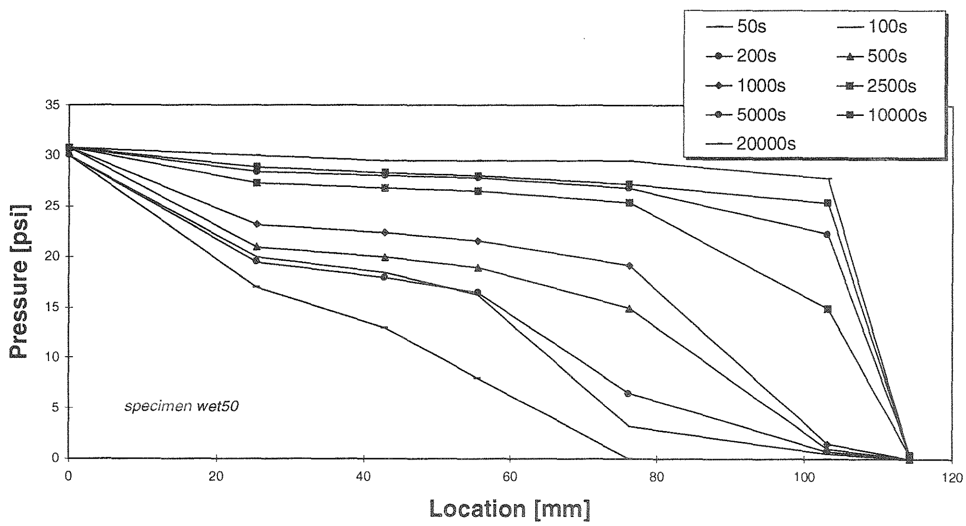

Fig. 5. Water pressure distribution within the fracture process zone (30 psi = 0.21 MPa)

4 Numerical Model

From the experimental results it is concluded that a model describing an unsteady fluid flow in the fracture process zone would be appropriate for simulating the experiments described above. In such a simulation, the interaction between the cracking process and the fluid flow can not be neglected. An increasing water pressure forces the crack to propagate resulting in a wider crack opening which in turn accelerates the water pressure increase. Henceforth, a combined nonlinear fracture mechanics and unsteady fluid flow analysis has to be performed in order to numerically simulate the experiments.

The discrete crack model, as implemented in MERLIN for the nonlinear fracture mechanics analysis of concrete dams, Cervenka (1994), was used. Similarly, a discrete crack model was adopted in the computational model which describes the one-dimensional unsteady fluid flow. The fluid conductivity and storage capacity depend on the discrete crack opening.

The conductivity is the product of the material permeability and the width of the stream tube. Both depend on the assumed discrete crack opening. Because the permeability of the undamaged concrete is much smaller then that of the cracked concrete it is assumed that there is no flow out of the fracture process zone.

The storage capacity per unit crack area is given by the discrete crack opening and the pores intersected by the crack. The air in the crack is considered to remain there when the water penetrates and the pressure rises. Hence, because of the compressibility of the air, the local saturation level in the fracture process zone depends on the local pressure.

Fig. 6 shows the water pressure along the crack path, measured during a wedge splitting test with monotonic crack opening. The different curves correspond to different times. The results of the numerical simulation of the test are also shown. We observe the excellent correlation achieved.

Several experiments performed under different conditions for the crack opening rate and the water input pressure were simulated. 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 physically sound and the derived curve is truly a material parameter. Fig. 7 schematically shows the conductivity-crack opening curve as obtained from the best fits of the experimental results.

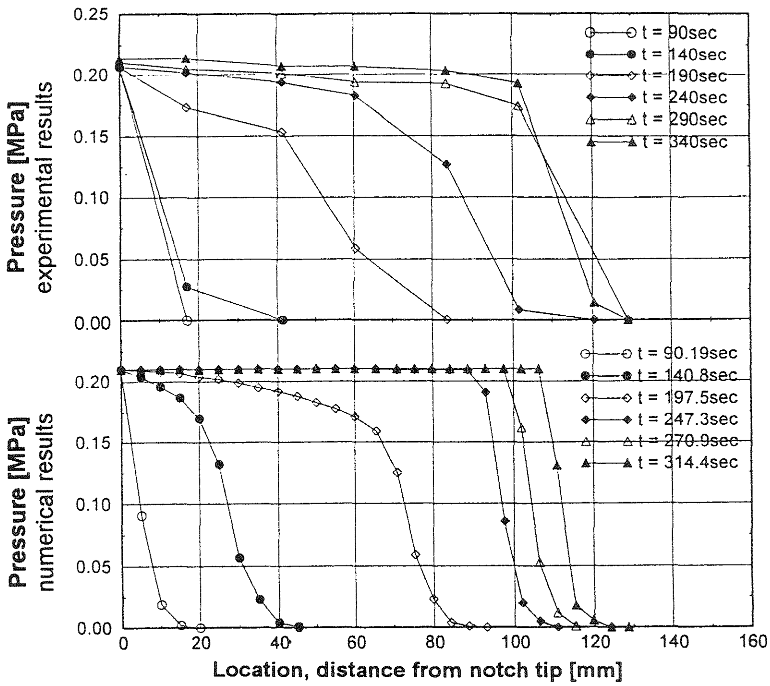

Fig. 6. Water pressure along the crack path for specimen wet10

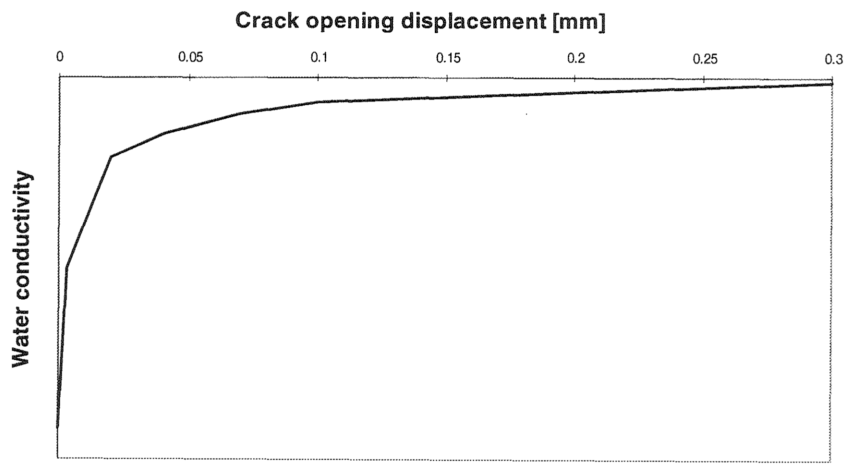

Fig. 7. Schematic conductivity-crack opening curve

5 Conclusions

1. In Wedge splitting tests under dynamic loading with internal water pressure in the crack the water pressure distribution along the crack path has been monitored. A significant crack opening rate effect on the water

pressure distribution within an opening crack was observed. If the crack opening rate is slow enough, the water pressure has time to develop, whereas in the case of fast crack opening the water front can not follow the crack front. In the context of the concrete dam design that implies, that during an earthquake induced fast crack propagation there is probably no water pressure acting in the crack. However, as time elapses the pressure inside the newly formed crack will eventually reach the reservoir pressure, and this indeed may have some serious implications on the dam response to after shocks.

2. A fluid-mechanical model for the water flow in a fracture process zone is proposed. It embodies most of the experimental results into a simple physical model which should be coupled with a finite element analysis of dams. Combined nonlinear fracture mechanics and unsteady fluid flow analyses were performed in order to numerically simulate the experiments. The fluid flow in the fracture process zone is considered to be unsteady; the fluid conductivity and storage capacity depend on the discrete crack opening following the fictitious crack approach. The simulation of the performed laboratory experiments allows to obtain the material parameters controlling the fracture process as well as the fluid flow.

5 References

Brühwiler, E. and Saouma, V.E. (1993) The effect of hydrostatic pressure on the fracture of concrete. technical report, EPRI, Palo-Alto, CA, U.S.A.

Brühwiler, E. and Wittmann, F.H. (1990) The wedge splitting test, a new method of performing stable fracture mechanics tests. **Engineering Fracture Mechanics**, 35, 117-125.

Cervenka, J. (1994) Discrete crack modeling in concrete structures. Ph.D. thesis, University of Colorado at Boulder, U.S.A.

Reich, R. (1993) On the marriage of mixed finite element methods and fracture mechanics: an application to concrete dams. Ph.D. thesis, University of Colorado at Boulder, U.S.A.

Slowik, V., Plizzari, G. and Saouma, V.E. (1995) Fracture of concrete under variable amplitude fatigue loading. submitted to **ACI Materials Journal**.