
International Conference on Dam Fracture
GS-7491
Proceedings, September 1991
Denver, Colorado
September 11–13, 1991

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Prepared for
Electric Power Research Institute
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RATE AND SIZE EFFECTS IN CONCRETE FRACTURE: IMPLICATIONS FOR DAMS

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ABSTRACT

This paper reports the results of reduced-scale fracture tests of concrete with reduced-size aggregate and the results of large-scale fracture tests of dam concrete with large aggregate. In the latter, very large fracture specimens, up to 72 in. in dimension, have been tested. Static tests with times to the peak load ranging from 1 s to 260,000 s have been carried out. The size effect method, recently published as a RILEM Recommendation, has been used to determine the fracture energy, fracture toughness, effective length of the process zone, brittleness number and critical crack-tip opening displacement. The conclusions are: (1) The size effect law proposed by Băzant appears to be valid for various loading rates; (2) As the loading rate decreases, the response shifts closer to linear elastic fracture mechanics and the brittleness number increases; (3) there is a strong load relaxation in the post-peak states which is due to additional creep in the fracture process zone, the relative relaxation being about the same for all the post-peak states and about 1.7-times stronger that the basic relaxation due to linearly viscoelastic creep outside the fracture process zone. The results are of considerable interest for the fracture of concrete dams because the fractures in dams often develop over a very long period of time. Fracture properties obtained in normal-rate tests cannot be used for such analyses unless they are adjusted for the rate effect.

INTRODUCTION AND NATURE OF PROBLEM

The purpose of this paper is to briefly report the main experimental results of a collaborative project of Northwestern University and University of Wisconsin, concerned with the rate effect and size effect in concrete fracture, with particular focus on dam concrete. Both problems are of keen interest for concrete dams.

The large size of aggregate used in dam concretes dictates the use of very large fracture specimens, whose study has already been pioneered by Swiss Federal Institute of Technology, Lausanne, and University of Colorado, Boulder (Brühlwiller and Wittmann, Saouma, Broz, Brühlwiller and Boggs). An effective approach in this regard is the new size effect method for testing fracture properties, proposed by Băzant and recently published as a new RILEM Recommendation (1990). This method implies extrapolation to infinite size and thus enables using smaller fracture specimens than would otherwise be required to obtain size-independent fracture properties.

Large fractures in dams often grow very slowly, over long periods of time. But the existing experimental results of fracture have been obtained under normal loading rates, with time to peak load of 10 min. or less. All the information on the effect of loading rate pertains to the dynamic range, for which the time to peak ranges from $10^{-8}$ s to $10^{-2}$ s. It is not clear if and how this information can be extrapolated to the static loading range. The preliminary results of the present investigation of the rate effect in the static range on reduced-scale specimens have already been briefly reported.
(Bažant and Gettu, 1989, 1990, Bažant 1990), but the present paper gives the first report after completion of the experiments.

**REDUCTED-SCALE FRACTURE TESTS**

Wedge-splitting compact tension specimens of various sizes up to 6 ft., with 3 in. maximum aggregate size, as well as reduced-scale three-point-bend fracture specimens with 13 mm maximum aggregate size, have been used. The size effect method proposed by Bažant and recently published as a new RILEM Recommendation (1990) (cf. also Bažant and Cedolin, 1991) has been employed to determine the fracture energy \( G_f \), the effective length of the fracture process zone \( c_f \), and the brittleness number \( \beta \) at various loading rates, chosen so that the time to peak load \( t_p \) varied from 1 s to 260,000 s (72 hours) (this represents a range of over five orders of magnitude of the loading rate).

Table 1 summarizes the results of the tests of geometrically similar three-point bend fracture specimens of three different depths \( d \), made of concrete with reduced aggregate size. The main results are the peak loads \( P_{\text{max}} \) for various loading rates, from which the material fracture properties have been evaluated using the size effect method. In this evaluation it has been assumed that, despite creep, the material outside the fracture process zone can be treated as elastic. This means that creep has been taken into account according to the effective modulus method, well known from the theory of viscoelasticity. The use of the effective modulus for creep is in fact implied in all fracture studies of concrete, because the deformation of concrete in the usual static test (about 1 to 4 min. to peak load) contains about 30% creep. For the slowest rates used in the present tests, creep constitutes about 50% the total deformation, which is not that much different from the normal test. Thus the effective modulus method ought to be an acceptable approximation for handling creep.

The material fracture properties obtained for the reduced-scale tests are listed in Table 2.

The values of the nominal strength \( \sigma_N \) for various rates and various specimen sizes are plotted in figure 1 (\( \sigma_N = \) maximum load divided by specimen depth and thickness, \( \beta = d/d_0 = \) brittleness number = relative specimen size, \( B_f \) and \( d_0 \) are the constants of the size effect law, obtained by data fitting). It is seen that the results of these carefully controlled reduced-scale laboratory tests agree with the size effect law proposed by Bažant (1984) (solid curves) quite well and that the scattered is about as low as one can expect from such a heterogeneous material as concrete. The results for all the rates and sizes are replotted as one graph in figure 2. This graph yields an important conclusion: With decreasing rate of fracture, the response shifts in the size effect plot to the right, i.e. closer to linear elastic fracture mechanics (LEFM). This means that the brittleness number of concrete increases as the rate of fracture decreases. Consequently, the long-time fracture behavior of concrete dams is even closer to LEFM than the short-time behavior. This result has significant implications for the analysis of dam fracture.

It is interesting to note that a parallel study of the rate effect in static fracture of limestone showed no such shift toward LEFM at decreasing rate of loading. This is probably explained by the fact that limestone, in contrast to concrete, exhibits no significant creep (at these rates). Thus it seems that the shift toward LEFM is caused by relaxation of the stresses near the fracture tip, caused by creep of the surrounding concrete.

Figure 3 shows the dependence of apparent fracture toughness \( K_{\text{fc}} \) and the effective length of the fracture process zone \( c_f \) on the loading rate, as determined by the size effect method. That the former increases with the loading rate is already well known, but that the latter decreased is a new...
result, which corresponds to the increasing brittleness number. (For the method of calculation of $c_f$, see Bažant and Kazemi, 1990a,b).

To understand the creep effects and the change of brittleness, the crack mouth opening displacement CMOD of some fracture tests has been arrested at various points of the load-deflection curve, both before and after the peak, and the subsequent load relaxation and constant displacement has been measured. Unlike for limestone, this relaxation has been found to be very strong for concrete. The measurements are shown in figure 4, which reveals a rather interesting new property. The relative relaxation is about the same for all the post-peak states, shortly after the peak as well as after considerable softening. Moreover, the relaxation is long-lived, just like creep, with the relaxation curves being approximately straight lines in the log-time plot. The downward slope of these lines is about 1.7-times larger than that for the relaxation at very small displacements, or the relaxation measured on companion unnotched specimens at small deformation, which falls into the realm of linearly viscoelastic creep. These observations are confirmed by the relative relaxation curves in figure 5, where the dashed line at bottom is the common post-peak relaxation, and the lines of smaller slopes are pre-peak relaxations. The fact that the slope of the relative relaxation curves is about the same for all the post-peak states is in agreement with a previous observation by Bažant, Gettu and Kazemi (1991) that the size of the fracture process zone of a propagating crack remains approximately constant for the post-peak states.

LARGE-SCALE FRACTURE TESTS

A second series of tests, carried out at the University of Wisconsin, explored similar responses for a typical dam concrete with maximum aggregate size 3 in., using wedge-splitting compact tension specimens of square size with heights 12, 30 and 72 in. (the latter is probably the largest-size fracture specimen ever tested). The specimen geometry is shown in figure 6. After casting, specimens were allowed to cure in their molds for 5 days after which the molds were removed and the specimens were wrapped in plastic for an additional 28 days of curing. In view of the very large specimen size, and the need to use heavy equipment to move the specimens, these tests could not be carried out in a laboratory room with environmental controls. Furthermore, because of the difficulty in handling as well as some of the very slow load rates, testing of all specimens from one batch of concrete typically required one week's time to complete which exacerbates the effect of age on strength. It is no doubt for these reasons why the scatter of the results of these tests has been larger. One way to avoid contamination of the results by random scatter would be to further increase the size range, the rate range and the number of specimens within a particular batch of concrete, but this would be prohibitively expensive.

Nevertheless, a similar size effect was confirmed by these tests, and a similar trend with regard to the loading rate has been observed, as revealed by the results in figure 7, and the basic data which are summarized in Table 3. In figure 7, we see a large shift toward LEFM (i.e. to the right) between the fast rate and the medium rate, but no further shift for the slow rate. Based on the reduced-scale tests, further shift has been expected. Its absence might well be merely one manifestation of statistical scatter. That the scatter is large is confirmed by figure 8, which shows the results of a greater number of tests in which the specimens were cast from four different batches of concrete. Note that results within a particular batch of concrete are more consistent than the average of all batches indicates.

CONCLUSIONS
1. The fracture behavior of dam concrete agrees reasonably well with the size effect law proposed by Bažant, and testing of geometrically similar fracture specimens of various sizes makes it possible to determine nonlinear fracture parameters of dam concrete quite easily.

2. The size effect law appears to be valid over a wide range of loading rates, spanning over five orders of magnitude (provided the effective modulus method is used to take creep into account).

3. The fracture toughness, effective length of the fracture process zone, and effective critical crack-tip opening displacement decrease with decreasing rate of loading.

4. The load relaxation in the post-peak range at constant CMOD tends to a straight line in the logarithm of the elapsed time and is about 1.7 times stronger than the relaxation in unmatched specimens. This difference is explicable by additional creep in the fracture process zone and possibly also time-dependent crack growth.

5. There is no doubt strong interaction between fracture and creep in concrete, and prediction of long-time fracture behavior must take such interaction into account.

Remark: Development of a mathematical model describing the present results is under way and will be reported in a separate study.

ACKNOWLEDGMENT

NSF Support under coordinated grants BCS-8818230 and BCS-8819068 to Northwestern University and University of Wisconsin is gratefully appreciated. Partial support for the underlying basic studies of size effect was obtained from the Center for Advanced Cement-Based Materials at Northwestern University. The cooperation of Lycon Concrete Company of Southern Wisconsin is gratefully appreciated.

REFERENCES AND SELECTED BIBLIOGRAPHY


Table 1: Fracture Test Data

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<th>age at loading (days)</th>
<th>peak load (N)</th>
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$f'_c =$ 28-day compressive strength of 76mmx152mm cylinders

$\omega =$ coefficient of variation of $f'_c$
Table 2: Material Fracture Parameters

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<tr>
<th>series</th>
<th>avg. ( t_p ) (sec)</th>
<th>avg. age (days)</th>
<th>( B_{fu} ) (MPa)</th>
<th>( d_0 ) (MPa)</th>
<th>( \omega )</th>
<th>( K_{IC} ) (MPa√mm)</th>
<th>( c_f ) (mm)</th>
<th>( E ) (GPa)</th>
<th>( G_f ) (N/m)</th>
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\( \omega \) = coefficient of variation of the deviations of the fit from test data

Table 3: Material Fracture Parameters of Large Aggregate Concrete

<table>
<thead>
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<th>C (in)</th>
<th>do (in)</th>
<th>( G_f ) (lb/in)</th>
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<td>0.975E-5</td>
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<td>34.154</td>
<td>0.885</td>
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Figure 1. Optimum size effect curves for the test data.
Figure 2. Change in mode of failure with loading rate.

\[ \log \left( \frac{\sigma_N}{B f_u} \right) \]

\[ \log \beta \]

Strength Criteria

LEFM SLOW

FAST

USUAL

- Fast, \( t_p = 1.45 \) s
- Usual, \( t_p = 500 \) s
- Slow, \( t_p = 13650 \) s
- Very Slow, \( t_p = 253000 \) s

\( t_p = \) average time to peak

Figure 3. Effect of time to peak load on (a) fracture process zone size and (b) fracture toughness

\[ c_f = c_0 \left( \frac{t_0}{t_p} \right)^{0.22} \]

\[ K_{ic} = K_0 \left( \frac{v}{v_0} \right)^{0.041} \]

421
Figure 4. Relaxation tests of fracture specimens on post-peak state, for various CMOD rates: (a) load-CMOD curves before relaxation of specimens loaded beyond the peak, (b) load-CMOD curves before relaxation of specimens at and before peak. (c) Load relaxation.
Figure 5. Rate effects on (a) load-CMOD response and (b) load-deflection response.
Figure 6. The specimen used in the large aggregate concrete tests.

Figure 7. Size effect plot of large aggregate concrete test data from all specimen sizes, and all loading rates of batch 4 concrete.
Figure 8. Size effect plot of large aggregate concrete test data from all specimen sizes, and all loading rates for all the four batches concrete tested.