Numerical Models in Fracture Mechanics of

CONCRETE

Folker H. Wittmann
Editor

PROCEEDINGS OF THE 1ST BOLOMEY WORKSHOP ON NUMERICAL MODELS IN FRACTURE MECHANICS OF CONCRETE / ZÜRICH / SWITZERLAND / 16-17 JULY 1992

Numerical Models in Fracture Mechanics of Concrete

Edited by

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Preface

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A variety of methods to numerically predict crack formation and crack propagation in concrete structures have been proposed in the last years. These powerful tools, however, cannot be applied in a general way, unless the entering parameters are identified and methods for their experimental determination are specified in all details.

The fictitious crack model can be considered to be a good example of the parallel development of a numerical method and the corresponding experimental techniques. At least four parameters are needed for the complete description of the model, namely the fracture energy, the tensile strength and two parameters characterizing the shape of the strain-softening diagram. A RILEM Recommendation for the determination of the fracture energy was published in 1985 (50-FMC). Different procedures to assess material parameters can be found in the literature.

In order to define and to discuss the characteristic material parameters for other numerical mehods available at present and to outline the most salient features of their experimental determination, a workshop was organized at the Institute for Building Materials of the Swiss Federal Institute of Technology (ETH) Zürich, July 16 and 17, 1992. In order not to widen the scope of the workshop unduly, the discussion was limited to the simplest case of crack formation under local uniaxial tension.

It was the intention to bring together a small group of inivited experts in the fields of advanced numerical methods and modern experimental techniques. The rôle of the relevant material parameters in different numerical models should be clarified during structured discussions following short presentations.

All contributions to this workshop are compiled in this volume. Summary reports on the discussions written by the session recorders are also included.

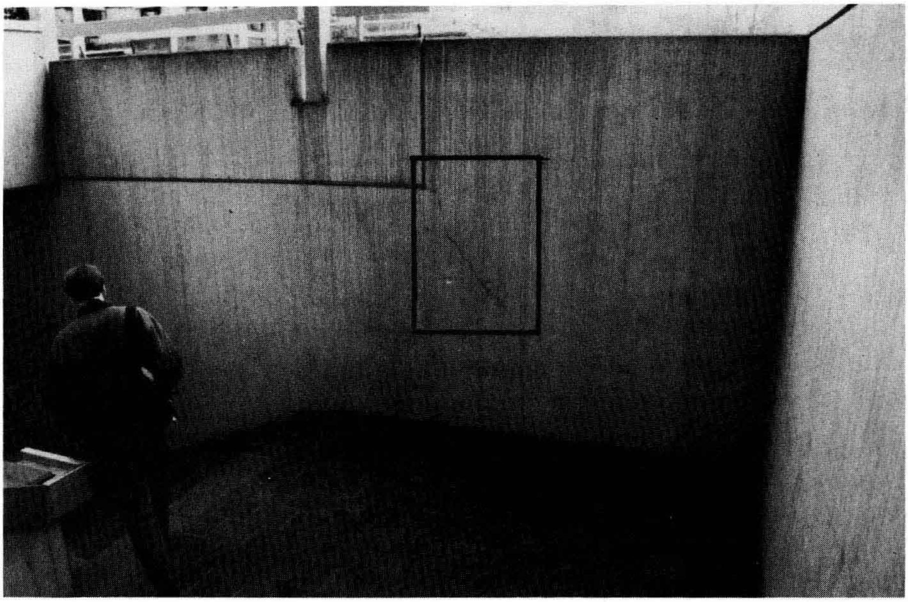
This workshop was substantially sponsored by the Swiss Association for Structural Mechanics (ASMES). This association intends to organize or sponsor in irregular intervals workshops on the behaviour of building materials in real structures. In commemoration of the eminent Swiss concrete scientist Professor Bolomey, this series of workshops has been named Bolomey workshops. For the proceedings of the first Bolomey workshop, Mr. Fermin Alou has written a concise article on major achievements of Bolomey.

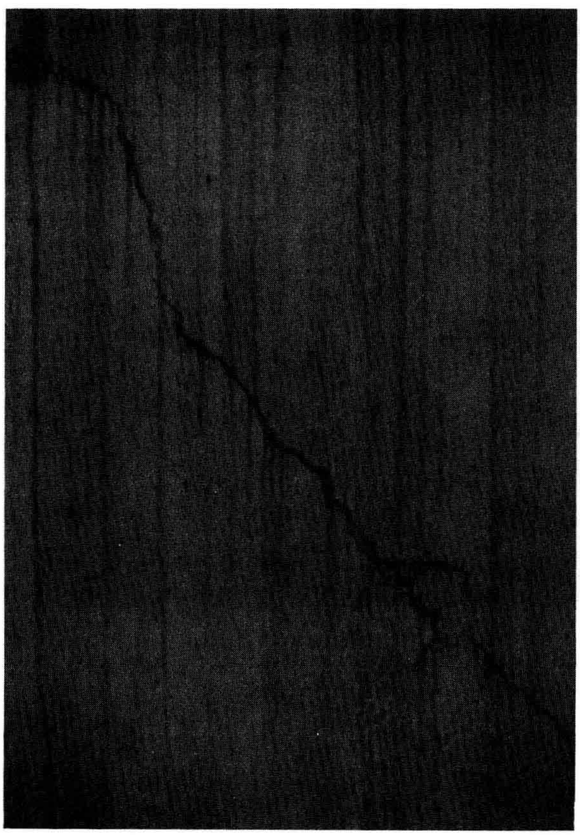
During the discussions, it was clearly pointed out that fracture energy is a material property just as elastic modulus or strength and this means that its numerical value depends on a multitude of parameters, such as rate of loading, stress gradient, size of the specimen, temperature, and humidity content. Once these influences are known, they can be taken into consideration in a detailed analysis. In addition, fracture energy and strain softening show a considerable scatter. This obviously complicates a realistic analysis but, on the other hand, if correctly represented, it overcomes problems of localisation.

Some aspects and problems of existing numerical models and test methods were discussed in depth during the workshop. As could have been anticipated, not many problems were solved during these two days. However, I hope that all participants have gained a better insight into the mutual interdependencies of numerical models and the corresponding test methods to determine the necessary material parameters. This type of discussion sometimes has a dangerous tendency to become too academic and to lose contact with practical problems to be solved. All too often, we content ourselves with a simulation of a laboratory test result. In this context, we must not forget that the major objective of all these efforts must be to provide a better understanding of materials' behaviour in real structures and to provide reliable solutions to practical problems. In Fig. 1, a few cracks in concrete structures arbitrarily chosen are shown. Can we apply non-linear fracture mechanics to simulate failure under these conditions and more important, can we provide ways to avoid such cracks in the future?

During the workshop, it became quite clear that some positions of different research groups are still far apart. This fact is not surprising, as non-linear fracture mechanics is still a young and quickly developing discipline. We will have to listen to each other for quite some time and study all conflicting arguments in detail before we can teach this challenging new approach to students and structural engineers. In 1335, Luca della Robbia symbolically sculptured the different branches of science. These sculptured reliefs originally decorated the campanile of the cathedral of Florence. Today, they are shown in the cathedral's museum. In Fig. 2, two examples are reproduced. At this moment, we find ourselves in the state "la Logica and la Dialettica". A few more successful workshops and more cooperative work will be needed to reach the state of "la Grammatica". By then, all fundamental problems will be solved and fracture mechanics as well as its application in structural enginering will be taught in standard courses.

With gratitude I would like to mention the efficient help by Alejandra Alvaredo and Dr. Volker Slowik during the preparatory work of the 1st Bolomey workshop. For the generous financial support I express my thanks to ASMES.





Some arbitrarily chosen cracks in concrete structures

Fig. 1 a : The staircase leading to the lecture room on which the 1st Bolomey workshop took place shows a crack which is due to differential settlement.

Fig. 1 b : A sustaining wall shows vertical cracks; the upper half is exposed on both sides to environmental conditions (drying and temperature variations)

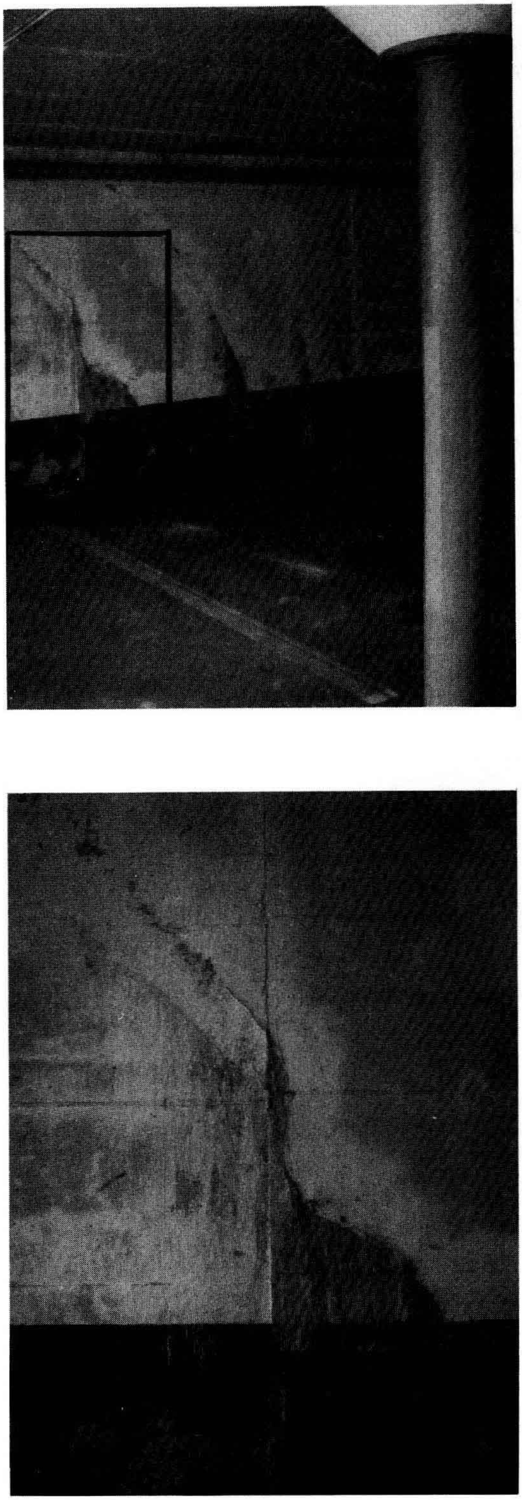


Fig. 1 c : The outer wall of a two-level parking deck shows cracks through which considerable quantities of water penetrate.

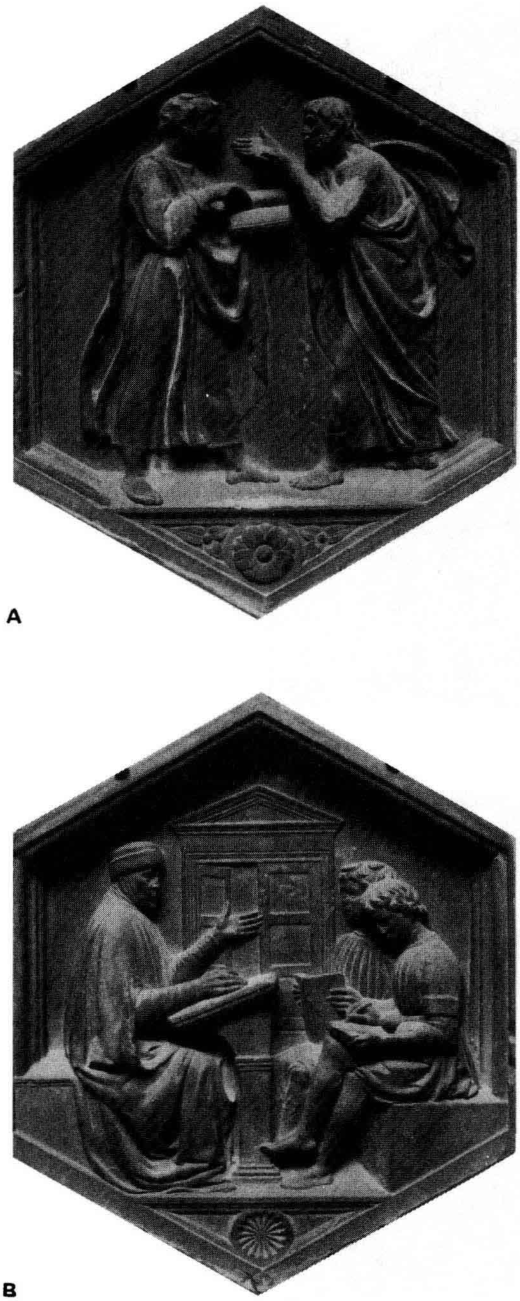


Fig. 2 : Two reliefs sculptured by Luca della Robbia (ca. 1335)

(a) : "La Logica e la Dialettica and (b) : "La Grammatica"

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Professor Jean Bolomey

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1 INTRODUCTION

Jean Bolomey gave renown to the Laboratory for Building Materials (formerly the EPUL Laboratory for testing of stone-like materials) with works started at the Barberine dam work site laboratory in Châtelard and which he continued and finished on the premises of EPUL (Polytechnical School of the University of Lausanne). His work had a worldwide reputation, as shown by R. Dutron, a Belgium specialist, who in an undated publication some time before 1950 wrote the following: "How to make concrete, continuous and discontinuous grading: Bolomey's work has caused in Europe a stir as big as that of Abram's in the United States."

Numerous papers and articles from several countries (Australia, Hungary, United States, South America) which quote Bolomey's work can be mentioned As an example, M.S.A. Mironov's book entitled "Concreting in winter", published in French in 1958, says: "There is an advantage in using the Bolomey's system, improved by S.I. Gortchakov and B.S. Skramtaiev, for cements used in construction..."

Studying the achievements of a researcher like Bolomey, who worked for 30 years on materials such as cements, mortars and concretes, and to highlight his contributions in this field, implies performing a retrospective analysis of the last 50 years of technical development linked with the construction of the large Swiss dams.

2 BACKGROUND

Jean Bolomey was born in St-Légier/Vevey in 1879. He carried out his secondary studies at Vevey College and the Scientific Secondary School in Lausanne. After this, he attended the Engineering School (presently EPFL), where he obtained his Diploma in Construction Engineering in 1901.

From 1901 until 1919, Bolomey studied the doubling of the railway tracks in the first district of the CFF, the Swiss Railway (at that time the Jura-Simplon Society), after which he took part in the construction of the Ricken tunnel for two years. Following this, he became director of works of the Navizence and Rhône Power Units and chief of construction of the Gorgne Power Unit on behalf of the Society for the Aluminium Industry. In 1919, he returned to the CFF, which engaged him as director of works of the power units in Barberine and Vernayaz. It was then that he realized that the knowledge of concrete behaviour concerning the choice of aggregate and binder (neat cement or cement mixed with stone powder or hydrated lime) was not sufficient for the construction of a structure of 210 000 m^3. A problem he was confronted with was placing without segregation a very fluid concrete, called flowing concrete, which circulated by gravity on gutters. Every time the link between two successive gutters was at an angle, the risk of overflowing appeared. He also realized at that time that standards and rules "...are only useful when they are not followed to the letter".

The Barberine dam, 79 m high, was put into service in 1925, one year after the 90 m high Schräh dam of the Waggital Power Unit. These two dams performed similarly, as did three others constructed at about the same period. They proved to be susceptible to freeze-thawing cycles and needed repairs which, in Bolomey's own words, were "...very expensive."

The Barberine dam would undoubtedly have needed new repairing some years ago, had it not been flooded by the 80 m high Emosson dam.

During a conference in Lausanne, organized by the Old Students Association of the EPFL and the SIA, Bolomey gave a lecture on 17th February, 1945, entitled: "Surprises and problems experienced while working at the Barberine Dam".

In 1927, Bolomey was named extraordinary professor of the Engineering School of the University of Lausanne, where he lectured on the construction of railways and on building materials. He was also in charge of the stone-like materials section of the materials test laboratory, which had been founded in 1918 by Professor Marius Lacombe.

In 1947, 20 years later, he was finally promoted to ordinary professor. Such promotions were rare in cases where a professor had never had an "important" chair. In his speech, he said: "In this domaine, which consists of perfecting test methods and apparatus for the rapid and economical control of concrete in the laboratory and on the worksite, the Lausanne laboratory has obtained a lot of success. Unfortunately, this research work has been slowed down by difficulties in finding qualified personnel and especially due to the lack of space, which hinders the location of new machines, very necessary to keep the laboratory at its level of research... "Extraordinary as it may seem, the laboratory does not have a cement mixer at its disposition, nor a place suitable for washing, sorting and drying ballast, nor a saw for concrete."

Professor Bolomey retired at the age of 70 in 1949 and died in 1952.

3 BOLOMEY'S WORK

In the field of cement, mortar and concrete technology his papers are countless.

As a member of the SIA Standards Commission, he collaborated with the Commission for Binder Standards, which published its report in 1933, and also with the Commission for Constructions in Concrete and Reinforced Concrete.

In his first article (1925), he quoted, among others: R. Feret: "On the capacity of hydraulic mortars", 1892; F.W. Taylor and S.E. Thompson: "A traitise on concrete, plain and reinforced", whose chapter XVIII was by R. Feret: "The resistance of concretes to sea water": D. Abrams: "Design of concrete mixtures", 1920; O. Graf: "Der Aufbau des Mörtels im Beton", 1923; Fuller and Thompson: "The laws of proportioning concrete", 1907. It can be said that since his first publication he was always well informed about the state-of-the-art in concrete technology. For this reason, he wrote: "The numerous comparative tests we have carried out have led us to recommend the use of Feret's slightly modified formula in preference to that of Abrams". In this way, he put into practice the thoughts of Belidor (about 1735): "It is better to start where those preceding us have finished."

For example, Feret himself, as soon as he became acquainted with Bolomey's work, showed him respect. During a conference in December 1926 in Zurich, where he had been invited by Professor Ros, Director of the EMPA, Feret stated: "Nevertheless, I think that it is worth examining Bolomey's grading formula, especially if we also take into account the very interesting observations carried out by Mr. Bolomey on the rôle of fine sand particles and on the difference between fluidity and actual plasticity."

A year earlier, in 1925, Ros had given a conference on the strength of mortar and concrete (EMPA Report N° 7) where he quoted Bolomey's formula for calculating the amount of mixing water. According to his opinion, his formula was simpler than that of Abrams and gave values of practical applicability and easy to obtain. He also stated something which was new at that time: that the presence of cement considerably modifies the properties of sand and gravel mixes. To our knowledge, Bolomey remains the first to have included cement in the grading law.

The following subjects were treated by Bolomey in his publications:

a) Influence of curing conditions on the strength of mortars and concretes.
b) Shrinkage, although he did not yet make a distinction between the different types: intrinsic, early, drying and carbonation shrinkage.
c) Creep, large field of study started due to the slow deformations observed in concrete arches and due to the importance of prestressed concrete (Freysinnet in France and Glauville in England).
d) Resistance of concrete to freezing and thawing, which particulary proccupied Bolomey because of the problems he encountered at the Barberine Dam.

It is worth mentioning at this point that it was Bolomey's observation that aggregate particles were cracked and not pulled out of the mortar matrix which led Professor Daxelhofer, Bolomey's sucessor at the Polythechnical School of the University of Lausanne, to devise the JPD (Jean-Pierre Daxelhofer) freeze-thaw test, still used at the laboratory for Building Materials of the EPFL.

Going back to the resistance of concrete to freezing, the results of tests which should have allowed to decide if a concrete was frozen or not were discovered to bear no relation with reality, as was revealed during a conference in 1947 organized to celebrate the fourth centenary of the University of Lausanne.

It is worth mentioning that, at that time, hardened concrete was thought not to be attacked by freezing.

- In 1925, O. Graf wrote: "we know that freezing has practically no effect on concrete that is suitably hardened."
- In 1928, in an EMPA publication on Holderbank-Wildegg's cements, Ros wrote: "The resistance of concrete to freezing is not different to that of stones used in natural constructions (tests of 25 freeze/thaw cycles by weight or evaluation in g/dm^2 of the surface of the broken, crumbled pieces)."
- In 1940, Ros published a note-book on the resistance to freezing. He declared that tests of 50 cycles were very severe and, therefore, on the safe side.
- In 1950, in the issue of "Einflüsse auf Beton", we find "...concrete which is well hardened and which has already reached a strength of 150 kg/cm^2 (15 MPa), and which, as a consequence, is reasonably impervious, is practically not influenced by freezing and thawing."

For this reason, during the above mentioned conference, Bolomey declared:

- "We now know that any work exposed to humidity and freezing risk will be destroyed after a certain time if certain precautions during mixing and placing have been omitted and this is valid both in the mountains and in the plain".
- "The best reasoning does not hold true compared with reality."

e) Control of cement, the main ingredient of concrete. He improved a test method to determine the cracking time. He also developed a small dynamometer which measures the tensile strength of mortar obtained by sieving of concrete, using small prisms 20/20/120 mm (this test method was standardized in France about 1950 after a request by Mr. Lazard, the chief of service of the SNCF = French Railways Society).

The latter test method was not very precise because the obtained tensile strength had to be converted into the compressive strength, but the device allowed to carry out the testing of a great amount of specimens at very low cost. Curing conditions could also be varied.

f) Influence of temperature on strength and its development with time. This is an important question in precasting. During the tests performed between 1926 and 1927, Bolomey made an interesting discovery: the loss of strength experienced by aluminate cement if it was kept at temperatures higher than 30^{0}C. We know today that this drop in strength is due to the allotropic transformation of hydrated tricalcic aluminate within the hexagonal crystalline structure into a cubic crystalline structure.

He showed that the strength at 28 days of a concrete kept a6 75^{0}C could drop to 91 kg/cm^2, whereas it attained nearly 400 kg/cm^2 when cured at room temperature.

g) Vibration, which now is part of everyday's techniques, was invented or at least first used between 1925 and 1930.

h) Influence of "grading" or "granulometric composition of aggregates" and its two main approaches: continuous and discontinuous grading curves.

i) Permeability of mortar and concrete by devising and using an instrument which, although it does not allow the direct measurement of the coefficient of permeability, makes it possible to evaluate permeability by the depth of penetration of water under a given pressure measured immediately after failure of a splitting specimen.

It can be seen that Bolomey addressed all subjects related to concrete technology except that of admixtures. The reason for this is that admixtures were rare at that time. The oldest company producing admixtures in Switzerland was founded in 1920; its name SIKA derives from SI = silicate and KA = calcium.

Most of the points enumerated above deal with parameters exerting an enormous influence not only on the compressive strength of concrete but also on another property to which we always assign a great deal of importance: the resistance of concrete to time, that is, durability.

4 BOLOMEY'S FORMULAE

In his many publications (see chapter 5), Bolomey proposed several formulae on the concrete subject.

We quote here just a few of his most relevant ones

a) **On grading composition**

$$P = A + (100 - A)\sqrt{d / D}$$

where

P = cumulative percentage in mass of grains smaller than or equal to d, binder included

A = parameter depending on the desired workability of concrete and on the shape of the aggregate: A = 8 to 10 for gravel and 10 to 12, or even 13 or 14, for crushed aggregate