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# Cracks in Arch Dams and repair works

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## Summary

A noticeable number of arch dams suffer worldwide under a more or less extensive cracking. Only cracks caused by a clear structural reason will be dealt with, disregarding cases due to volume changes of the concrete. A typology of the most common cracking patterns is then given.
It appears that generally the cracks start at a dam face and are due to bending efforts. They may then deflect under the effect of transverse forces and turn to be dangerous for the structure. A good design criterion for a concrete dam should therefore consists in avoiding tensional stresses in the sections where transverse forces are to be transferred.

From some observations it appears that the rupture of the concrete mass is mainly of the brittle type. The big amount of elastic energy released at the cracking time might even lead to a crack overpassing the final no-tension point.

A number of cracked dams were or are to be repaired.
Few example will be shown as: Zeuzier, Kölnbrein, Zillergründl and Flumendosa dam.

# CRACKS IN ARCH DAMS AND REPAIR WORKS

seen from the engineer practice

## 1. INTRODUCTION

During the last decades a noticeable number of problems arose worldwide in connection with cracking of concrete dams.

For the engineer, the logical flow-chart of the problem is condensed in figure A. The main question is whether the cracked dam is still sufficiently safe and if not, whether it can be repaired or must be given up /1/.

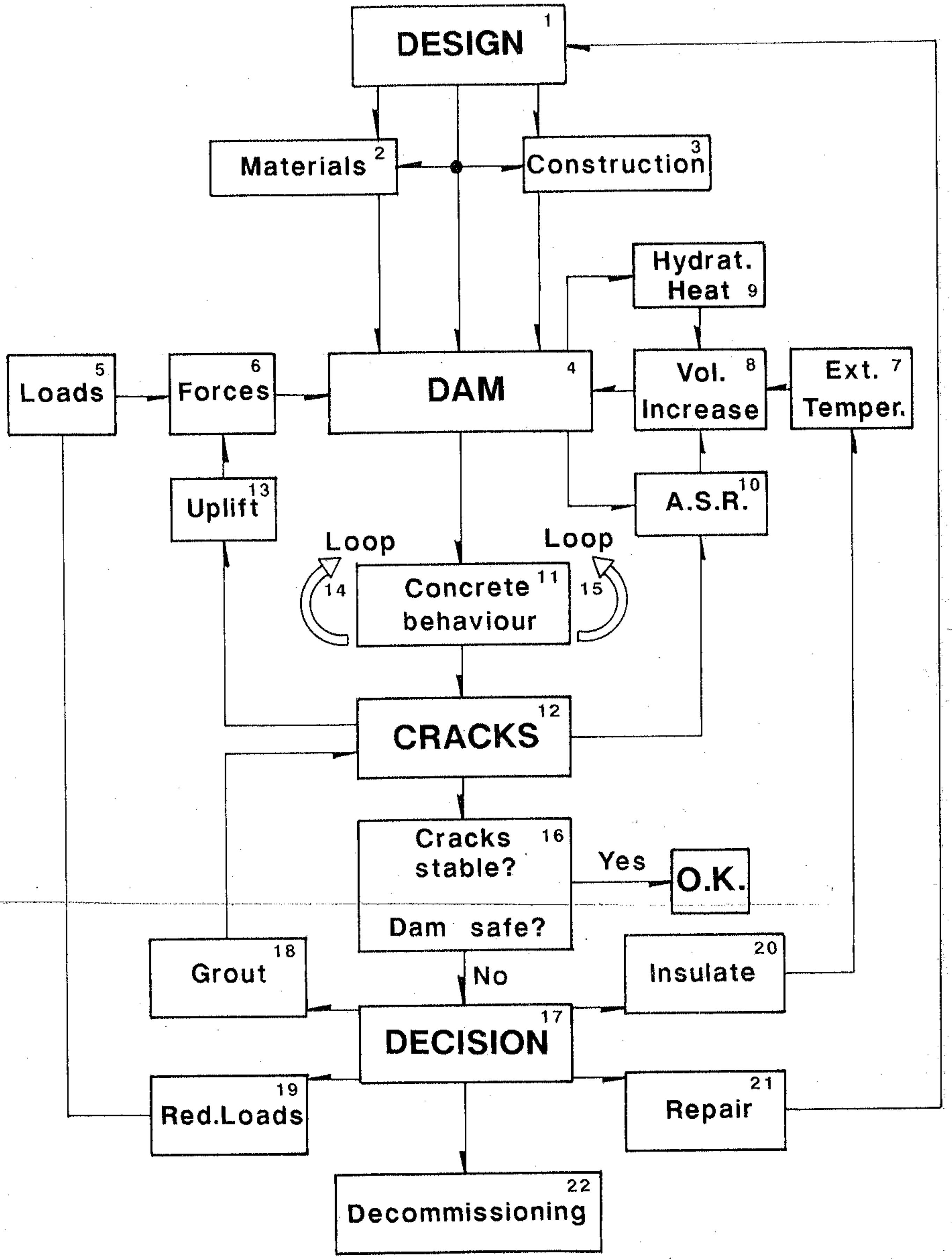
A statistically important case is the one of cracks due to a volume increase related e.g. with an alkali-silicate reaction; where a self-feeding process may take place. (Figure A. Point 10)

The shrinking and the contraction of the concrete mass is generally accounted for in a correct way at design stage, so only few problems are related with these effects. (However an exception will be mentioned later on.)

While the over-all effect of thermal changes on the dam may be easily taken into account in the design, it is seldom possible to avoid a fine surficial cracking due to sharp temperature peaks or thermal shocks like strong solar radiation followed by a cold wind.

During the initial cooling of the concrete, an insufficient curing of the surface may also lead to heavy cracking in connection with rapid temperature changes.

In some cases, constructional procedures - like grouting of contraction joints -, and external impacts - like movements of the foundation -, may have similar consequences as the ones due to a volume change of the concrete.




**<u>Figure A.</u> Diagram of the cracking of a concrete dam.**

In all these cases, however, a clear distinction has to be made between a distributed, locally induced, often surficial, fine cracking and well defined main cracks of the structural type even if the latter have finally been caused by a volume change of any type.

For the sake of simplicity, only well defined "structural" cracks in arch dams will be dealt with in the following, regardless of their origin.

## 2. GENERAL CONSIDERATIONS ON CRACKS IN ARCH DAMS

In studying the cracking of arch dams, it has to be taken into account that the structure is not a simple, ideal, elastic body. Vertical contraction joints subdivide the dam in blocks. Even after grouting they will represent a discontinuity in as much as they cannot be grouted to the dam faces but only to the water-stops. Additionally, the grouting is seldom carried out in a completely satisfactory manner.
Furthermore, the concrete is placed in layers and lifts making weakness planes possible at frequent elevations, and inhomogenities and anisotropies - which can hardly be detected - are likely to exist in the concrete mass.
The randomly scattered, anisotropic permeability of the concrete leads to an irregular field of water pressures in the dam body and to a complicated pattern of its gradient and consequently to quite unpredictable flow-induced internal forces.

From the structural point of view, it has to be duly taken into consideration that, as a rule, the sections of an arch dam are not submitted to pure tensile forces nor to a simple bending but to a combination of compression and bending that is to eccentric compressive forces. Therefore, accordingly to figure B, families of cracks are not infrequent.

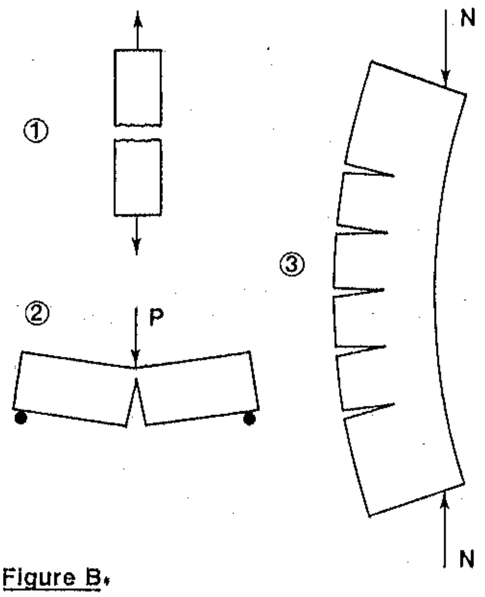



Figure B.

① and ② : single crack
③ crack family

As a rule, twisting moments and the membran shear will deflect the principal stresses, so their direction will coincide with the mentioned weakness surfaces only in certain few cases.

Cracks in arch dams are feared both for the structural consequences they may produce and for the water outflows they may permit. In spite of the fact that only in few cases outflows can present by themselves any danger, they often deeply impress the people involved so to lead them to plug, as fast as possible, the waterways disregarding sometimes more important structural problems.
Such a plugging may make difficult or even impossible to conveniently repair the dam later on and to restore the complete integrity of the structure.
A structural analysis and a safety check, or at least some thinking, must therefore be carried out in any case before tempting to plug any important waterway.

## 3. LOADING HISTORY OF THE DAM

Along its life, the dam is subjected to a great number of different states of stress: construction sequences, dead loads, temperature changes, shrinkage, water load of varying intensity, earthquakes and so on.

A crack may also start under certain loadings, develop along with increasing loads, stop because of a changed temperature field, close, reopen and progress again under different conditions. Meanwhile it might have been plugged or even healed by some material e.g. calcium carbonate.

As a rule, the entire loading history of the dam - including the construction procedures - must therefore be known to correctly interpret a crack and to explain it. However the complete information is seldom available, so that more or less extensive assumptions are often required.

## 4. TYPOLOGY OF CRACKS IN ARCH DAMS

A frequent type of crack forming is the one described in the following. /2/

1) Under certain load conditions (e.g. empty reservoir) an important bending moment produces high tensile stresses at the one of the dam faces.
2) A crack starts perpendicularly to it as soon as the tensile strength is reached.
3) Due to changed loading conditions a transverse force may appear in that section while the crack is still open or only partially closed.
4) The induced inclined tensile stresses will then lead to an extension of the crack in a deflected direction. This change of direction may happen in a sharp or in a smooth progressive way, depending of the history of the loadings.

Figure C presents the typology of common cracks in arch dams of usual design. In sections where important transverse forces will never develop, the cracks may be considered to be of the stable type. But, where such forces may arise and reach a high intensity, the cracks are potentially unstable and need a more detailed investigation.

A simple good design criterium consists therefore in avoiding cracks - that means in avoiding any tensile stress - in sections across which important transverse forces are to be transferred. These sections are obviously the ones perpendicular to the trajectories of the transverse forces. It is in fact believed that the tensile strength is in no way a reliable property of the concrete mass. In no way therefore the safety of the dam has to depend on the tensile strength of the concrete mass.

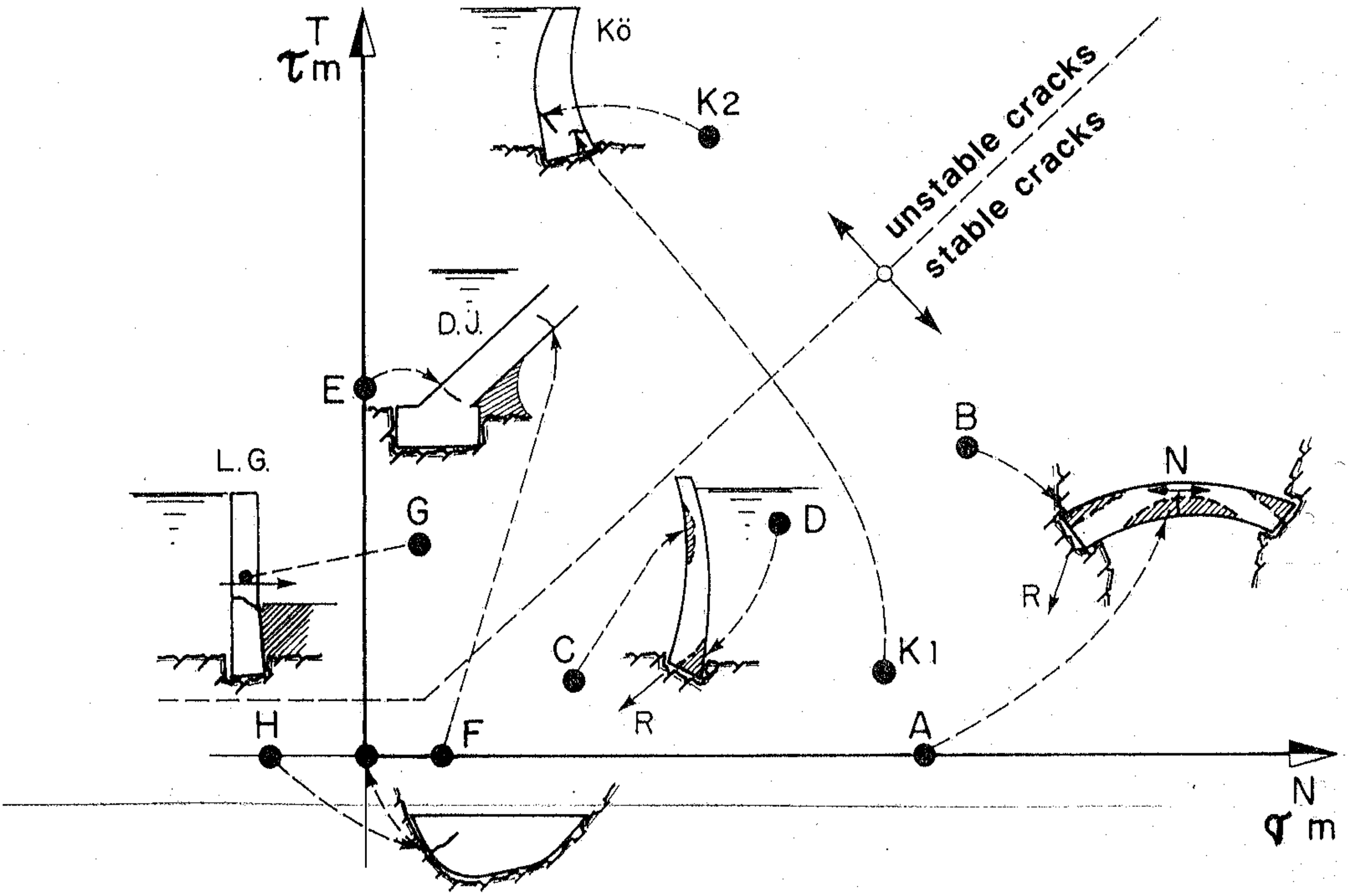
Obviously in interpreting cracks in existing dams, a different approach has to be followed than at the design stage.

## 5. IS CRACKING IN ARCH DAMS OF THE BRITTLE TYPE?

Any arch dam, especially if thin, is in fact an extremely soft testing machine. So, the amount of energy released at the moment of cracking may be very important, much bigger than the fracture energy.

At least, under certain circumstances, the rupture due to tensile stresses has therefore to be considered as sudden.

The cracking of a single concrete block at the Kölnbrein dam during the grouting of the contraction joints is told to have produced a loud blow and a strong shaking of the entire dam, so to make the workers escaping the site. A similar information was also received from the Zillergründl dam.




<u>Figure C.</u> **Typology of cracks in arch dams.**

**N = Normal force, T = Transverse force;**

**$\sigma$ m, $\tau$ m = respective stresses**

**Kö = Kölnbrein, D.J. = Daniel Johnson, L.G. = Le Gage**

The inertial swinging of the dam around its statical point of equilibrium might extend the crack over the corresponding limit eliminating, that way, any tensile stress at the tip of the fissure.

In such a situation, where no tensile stresses can be taken into account, a simple structural analysis may suffice to define the shape and the final extension of the crack. One may refer to the concept of "voûte active" introduced by Coyne.

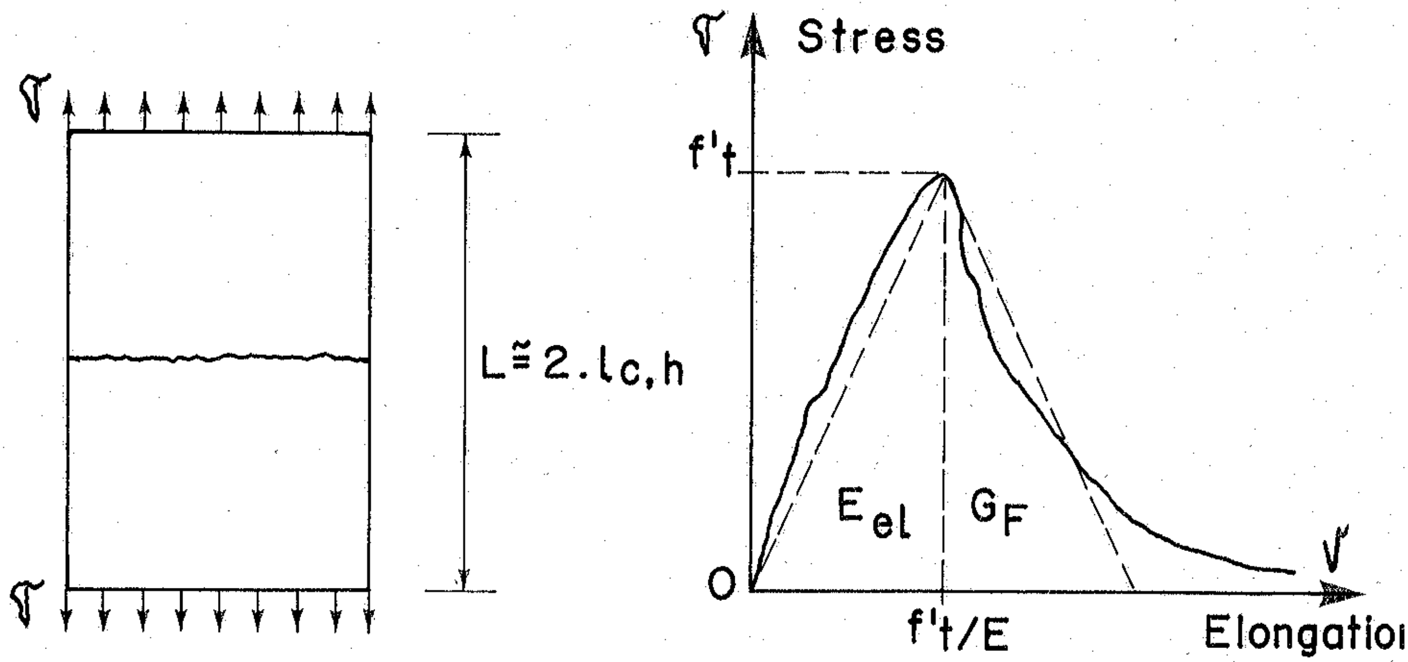
It seams that while the first cracking is very sudden, the extension of the crack may be a continuous smooth process.
A difference has also to be made between a crack interesting the whole structure and more local fine fissures, for which the concrete mass around the crack tip can be considered to act like a stiff testing machine.

A length about double of the one proposed by Hillerborg seams to assume a physical meaning and to steer the process. In fact the elastic energy stored in a concrete zone of that length may be of the same order of magnitude as the fracture energy of the crack. Figure D. So this length may be seen as a divide between a stiff and a soft testing device.

It is believed that a discussion on this point could be of very interest.

## 6. REPAIRING CRACKED ARCH DAMS

In spite of the simple typology shown, and because of the great number of intervening factors, each arch dam presenting one or more significant cracks has to be studied by itself as a single case requiring special investigations, careful studies and specific techniques to be repaired.




$$E_{el} = \frac{\sigma^2 . L}{2 . E}$$ **= Elastic Energy**

$G_F$ **= Fracture Energy**

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$$G_F = \frac{f'_t{}^2 . L}{2 E}$$ **= at fracture time**

$$L \cong \frac{2 . E . G_F}{f'_t{}^2} \cong 2 . l_{c,h}$$ **= twice Hillerborg characteristic length**

<u>**Figure D**</u> **Equalizing elastic and fracture Energies**

A first possible way to ensure a sufficient factor of safety may consist in a modification of the structure itself or of the intensity of the applied loads like a reduction of the operational reservoir level.

The strengthening may also consist in trying to restore the global continuity of the structure e.g. in grouting the cracks. Obviously, the state of stress has been modified by the cracking as a certain amount of deformation energy was released and the state of internal stresses was modified.

Grouting the cracks in the right way and at the right time may allow a more favorable future stress pattern. In doing so, one has however to take into consideration that "dislocations" are introduced in the structural continuum and that the stress distribution along a grouted section may no longer be a linear one.

## 7. SHORT CASE HISTORIES

### Zeuzier arch dam

During fall 1978 the settlement of the dam foundation, caused by the drainage of the rock mass through an exploratory adit, produced a narrowing of the valley. An important cracking was the result. Structurally speaking, this movement has the same consequences as an hypothetical volume increase of the concrete.
As the imposed deformation was not a reversible one, an acceptable state of stress could be found at the new dam position. In doing so, any open crack could be interpreted as a zero stress boundary condition and the epoxy-resin (150'000 Liters) grouting could be understood to fix the new state of stress, making it to a starting point for the future loadings of the dam. The repaired Zeuzier arch dam is operating as before since 1988, without any restriction /3/.

Kölnbrein arch dam

An excessive grouting and the consecutive wide opening of the contraction joints - which may also be understood as a volume increase of the concrete - produced a deflection of the blocks towards upstream and high tensile stresses at the downstream toe causing there a deep cracking.
The sound upstream part of the cross section was no longer able to resist the high transverse forces due to the impounding and cracked also.
The solution for the repair was finally found in placing a big downstream buttress block to back the arch dam and to reduce the acting transverse forces in the lower part of the cantilevers.
Additionally, the cracks will be resin grouted.

Zillergründl arch dam

A special concrete slab was designed to act as a blanket along the upstream toe in order to eliminate the uplift pressure in the foundation joint, which was permanently drained.
Due to the anisotropic permeability of the concrete, downwards oriented hydraulic forces in connection with the concrete weight produced an important crack in one of the dam blocks. The crack was resin grouted and the loading conditions were modified in reintroducing a partial uplift pressure in the foundation joint.

Flumendosa arch dam

At crest elevation the dam is strongly leaning towards downstream, so that during construction the independent blocks were not stable by themselves. Consequently, the upper part of the contraction joints could never open.
During the cooling of the concrete, the upper arches contracted and pulled the blocks towards downstream, so far as to produce a

great number of cracks at the upstream face. Most of them coincide with the weak lift joints.
The continuity of the structure will be restored in grouting the cracks at winter time by a low water elevation.

## 8. CONCLUSIONS

Summarizing the above comments, one may state the following:

- The concrete mass is by far not an elastic ideal body.
- Tensile strength is not a reliable property of the concrete.
- In no way the safety of the dam can depend on it.
- Cracking can happen suddenly.
- Each arch dam is a special case to be dealt with.
- However, "standard" types of cracks can be recognized.
- Nowadays the repair techniques - especially resin grouting - improved significantly.
- Designing a new dam and repairing a cracked one are two different problems, for which different approaches are adequate.

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