Simulation of hydrofracturing in masonry dam structures

C. König

GKW Ingenieurgesellschaft mbH, Bochum, Markstr. 77, 44801 Bochum, Germany, ck@gkw-gmbh.de

V. Bettzieche

Ruhrverband Essen, Kronprinzenstr. 37, 45128 Essen, Germany, vbe@ruhrverband.de

C. Könke

RWTH, Aachen University of Technology, Mies-van-der-Rohe-Str. 1, 52056 Aachen,Germany, koenke@baustatik-rwth.aachen.de

ABSTRACT: The numerical simulation of stress and pressure fields in fractured porous media presents a highly non-linear coupled problem of structural and fluid mechanics. The stress field depends on the fluid pressure field and the fluid pressure field is influenced by the changing boundary conditions along propagating crack trajectories. This "hydrofracturing" problem, which has been already intensively studied in the area of oil exploitation simulations, can not be appropriately represented by a smeared crack model. The physical boundary condition along the free crack surfaces can only be approximated with a discrete crack model.

An incremental two-step method has been developed to realise a coupled calculation of pressure field and crack propagation. The method will be demonstrated by a hydrofracture-simulation of a masonry dam.

1. INTRODUCTION

Many reservoirs in Germany are dammed up by masonry dams, being established almost 100 years ago. These dams possess a triangular shaped cross-section, which was bricked up by hand using quarry stones sized 0,50 x 0,50 m and larger. The stones were placed particularly careful on the exterior surfaces of the dams and fixed in mortar as waterproof as possible. Within the dam structure itself the stones were partly tilted, but still any existing gaps were filled up and carefully fixed in mortar together with gravel. The dams were founded on an existing bedrock, released from the top gravel revealed down to the stable rock. The proof of stability for these kind of dams can be executed by numerical methods. For a close-to-reality projection of the coupled hydro-mechanical processes, the methods used must be able to illustrate temperature stresses and hydraulic pressures as well as the crack propagation.

The methods used for the calculation of the crack propagation can basically be separated into smeared and discrete crack models. The approach presented here has been based on a discrete crack propagation model. The physical effects are thereby substantially better illustrated. The model supplies a picture of the macroscopically large defects of a numerically stable method without 'stresslocking effects', often obeserved with smeared crack models.

The performance and efficiency of the models is to be demonstrated on the basis of the discrete crack simulation, coupled to a hydraulic pressure calculation for a dam.

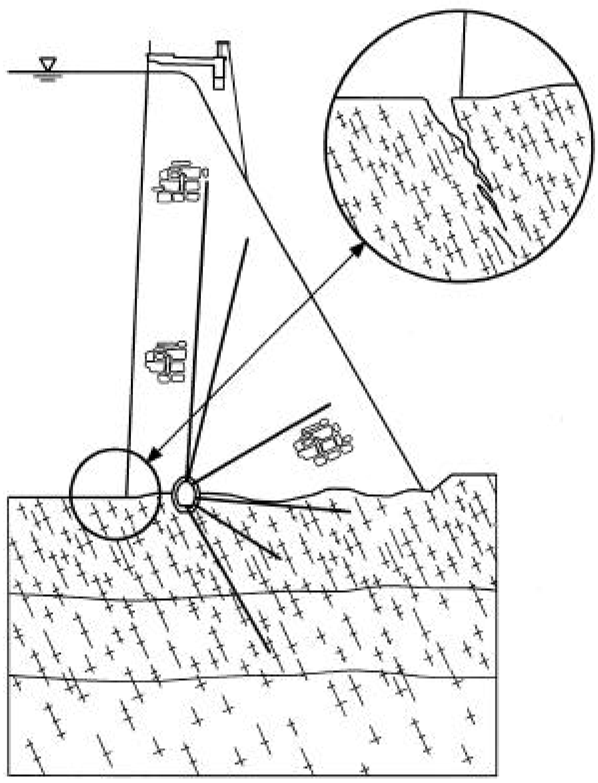

Figure 1. Crack in dam foundation

2. SIMULATION OF DISCRETE CRACK INITIATION

Due to fissures and stratification in the subsoil of a dam as a result of sedimentation and loading history, the rock shows an unisotropic material behaviour. These fissures however only have a small tensile strength, resulting from mineralogization within the fissure surfaces and from cohesion. If this tensile strength is exceeded, then the fissure tears apart and a crack develops.

The dam foundation, which is situated well below reservoir level, usually is the area where structural failures occur (see fig. 1). The inner forces of a crack, resulting from water penetrating into the crack, have to taken into consideration when simulating the propagating crack. These forces depend on the crack aperture. With an open crack the hydrostatic water pressure causes direct pressure loads. The decreasing hydrostatic pressure in the crack propagation zone results in a decrease of the external pressure loads along the crack faces and thus in an increasing stress within the material (see fig. 2). Failure of material occurs, as soon as a critical fracture energy is exceeded.

If the crack propagation has to be calculated for a rock with fissures, then an unisotropic material law (e.g. Mohr-Colomb), defining the failure stress and residual strength in dependence of the main fissure direction, must be taken as a basis.

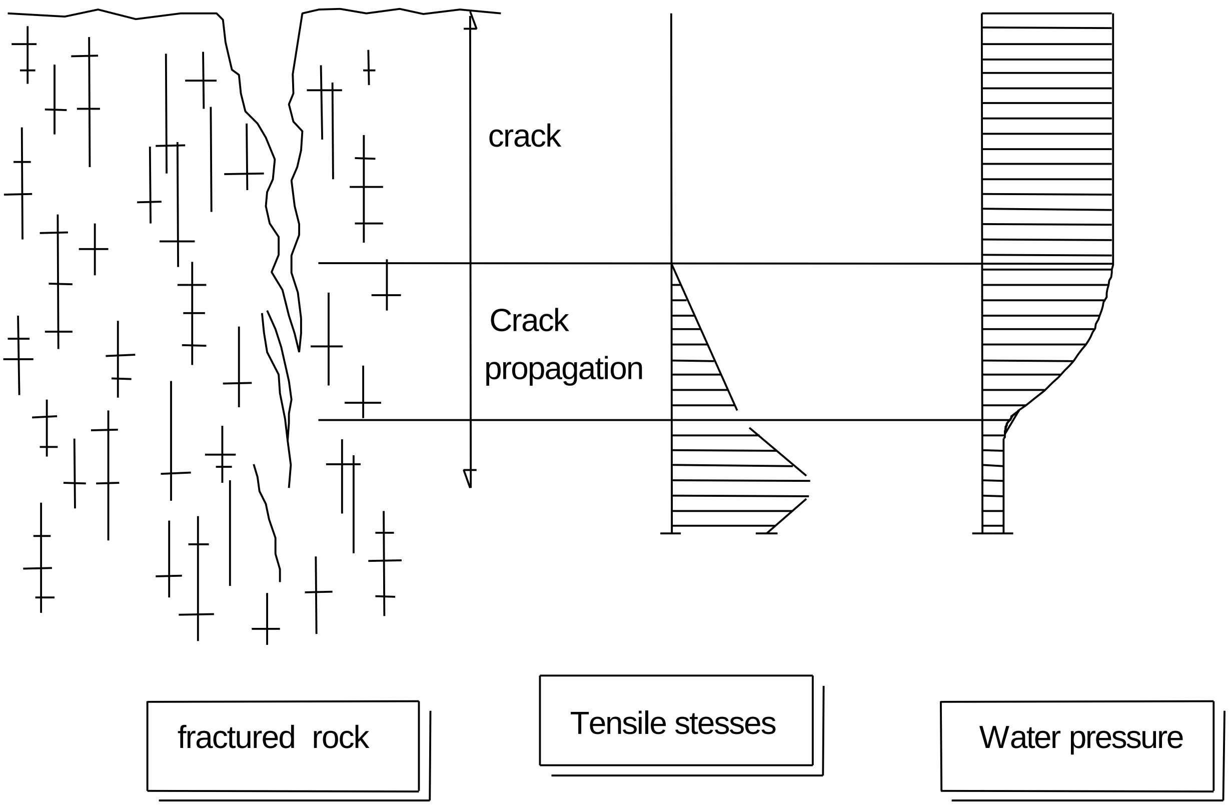

Figure 2: Process of the crack propagation

3. MACRO CRACK PROPAGATION CALCULATION

The modelling of discrete crack propagation problems by means of the finite-element method (FEM) has been presented for the first time at the beginning of the 80's by Saouma and Ingraffea irrespective of an initial discretization. These simualtion algorithms have furtehron developed by Swenson in 1985/87 [3] and Ingraffea/Wawrzynek and coworkers [3]. Today discrete crack propagation simulations have been applied to three-dimensional problems of linear-elastic fracture mechanics [5]. In this method the crack is modelled by discrete crack increments in the structure. However in order to be able to use this procedure for linear-elastic problems, an “initial crack increment” must be given in the model. In many cases the location of the initial crack can be predicted when considering the stress distribution in the undamaged structure.

The initial crack is introduced into the FE model as discrete crack, i.e. the two crack surfaces are considered as free crack surfaces. The crack tip

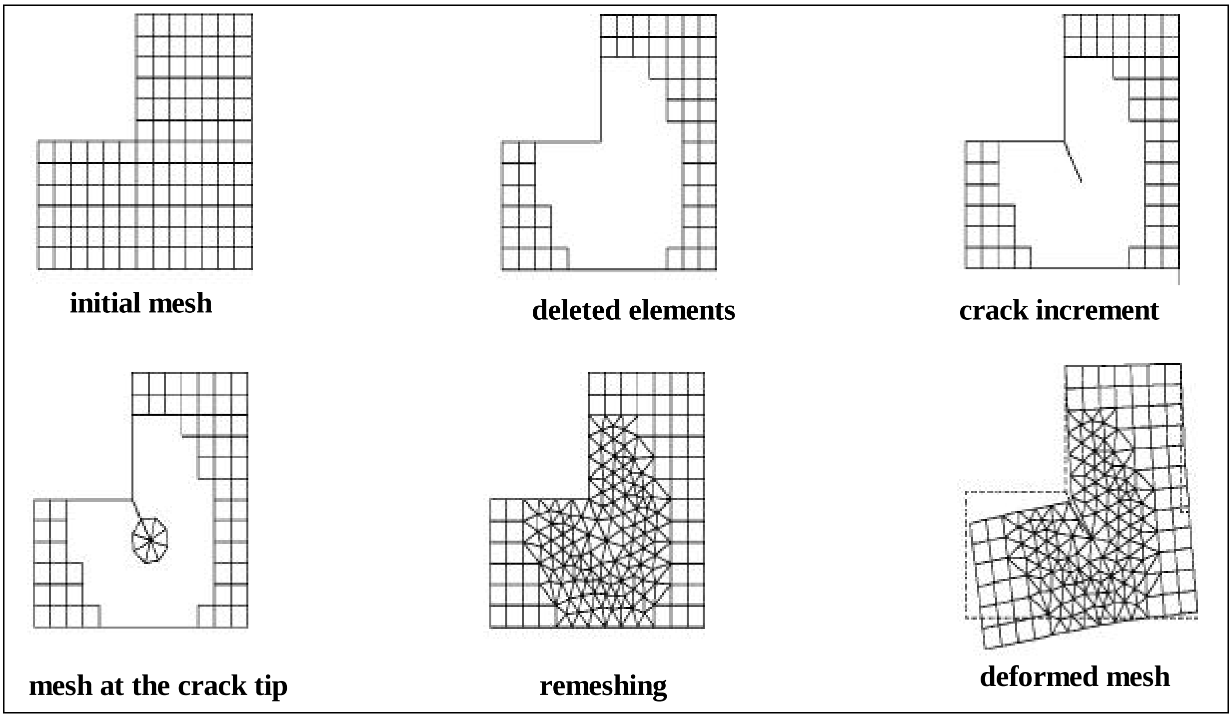

Figure 3: Remeshing Procedure to simulate a discrete crack

respectively the crack front can be modelled with special crack tip features, such as stress singularities in case of linear-elastic fracture mechanics. Therefore special degenerated quarter-node crack tip elements have been developed. Therewith the stress-singularity of linear fracture mechanics can be modelled. For an existing crack, a prediction of the direction and the size of the next crack increment can be made with the help of fracture-mechanic characteristics, such as the stress intensity factors or the J-integral calculus.

For problems of durability the appropriate phenomenological crack propagation laws - Paris or Foreman laws – can be analysed [6].

The basic procedure of the discrete crack propagation simulation is prototypically represented in fig. 3. It shows that the FE mesh, as well as the geometrical model must be adapted to the new crack geometry after every crack increment. The crack propagation due to quasistatic loading is incrementally pursued. The direction of the crack propagation is thereby determined as perpendicular to the main tensile stress.

4. COUPLING OF CRACK AND FLOW CALCULATION

In case of "hydrofracturing" problems the forces, which are responsible for crack expansion and which result from water penetrating into the crack, must be considered. A new flow computation with altered boundary conditions must be done for every crack increment, which supplies the new compressive forces effecting the crack for the further crack propagation calculation. This two-step procedure has been automatized for the FEM calculation within the software SPRING [8].

At first there is a flow computation and a further calculation based on the undamaged state of tension. An initial crack is then determined according to this calculation. This initial crack is placed in the area of the largest main tensile stress, perpendicularly to it. As described in the previous chapter, the area of the initial crack is again supplied with a new mesh. Subsequently a flow computation is executed with newly defined boundary conditions along the crack trajectory. It supplies the compressive force for the following step of stress calculation. The new crack increment is the result of this stress calculation. After remeshing the area of the crack increment another flow computation with changed boundary conditions is performed. This iteration is continued until the crack no longer expands, i.e. the critical fracture energy will be no longer exceeded.

5. APPLICATIOIN

The efficiency and stability of the algorithms presented above are examined in an exemplary application. The dam represented in fig. 4 possesses a drainage gallery and drainage boreholes. The complex flow area in the dam and the effect of cracks, which can not be excluded for extreme loading conditions, may be illustrated close-to-reality only with the methodology of a coupled flow and crack calculation.

The flow problem has been considered in the undamaged status at the beginning of the calculation. A boundary condition for seeping on the downstream face of the dam and the drainage installations inside the dam were set, as well as a fixed potential boundary condition for the upstream face of the dam. The resulting flow area and its resulting side issuer is illustrated in fig. 4.

The result of the mechanical problem shows large horizontal tensile stresses at the upstream base of the dam. This result has been confirmed by results from literature. The position of the initial crack is selected at the transition between dam base and fissured subsoil (fig. 5). The following iteration of the flow and crack propagation calculation results in a crack, which propagates diagonally under the base of the dam into the bedrock. Fig. 6 illustrates the principal stress trajectories and the vertical stress component along horizontal lines at the end of the calculation. Green colour is showing negative vertical stresses and red colour is showing areas of tension stresses.

The crack with a final length of several meters led to a stress redistribution within the dam base area. The tensile stresses at the crack tip have been reduced and the fracture energy criterion now detects an arresting crack. Even for this final situation the dam does not fail.

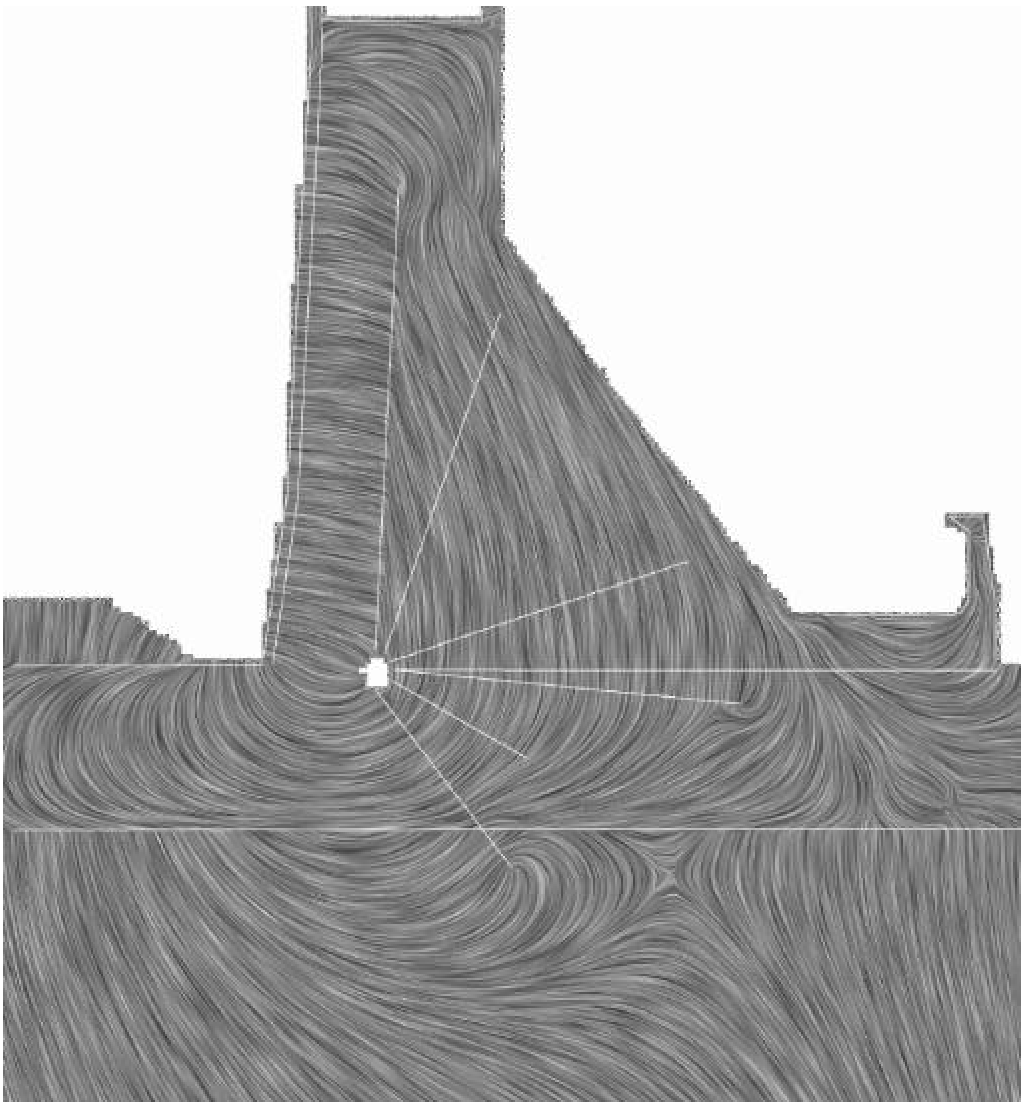

Figure 4. Seepage within the dam

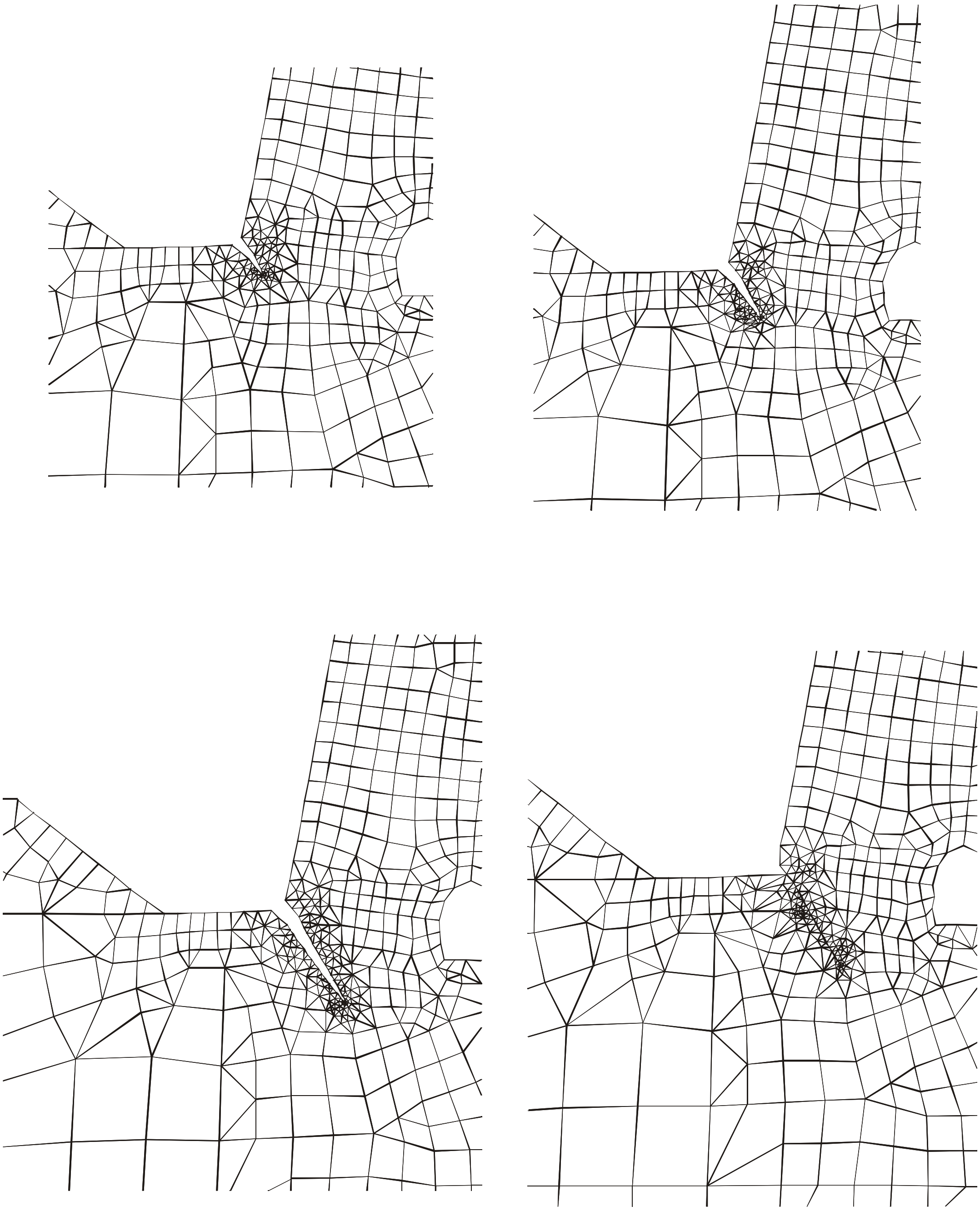

Figure 5. Displacement conditions during crack propagation

6. SUMMARY

A coupled flow-crack-model with a discrete crack propagation simulation has been presented for the proof the load carrying capacity of a masonry dam. The crack propagation calculation has been influenced by the complex migrating water load and changed local flow pressure conditions.

As known from literature, horizontal tensile stresses result in vertical relief cracks within the rock at the upstream base of the dam. The direction and expansion of these cracks are defined by the material properties of the rock. The history of rock origin as well as disintegration have developed separation layers, such as stratification and fissures, within the rock. The material is thereby weakened, since no tensile stresses can be transferred perpendicularly to these separation layers and a possible shearing force is reduced in direction of the fissure. The crack trajectory follows the separation layers beginning at the base of the dam, propagating into the subsoil, until the crack until the stress redistribution leads to an arresting crack.

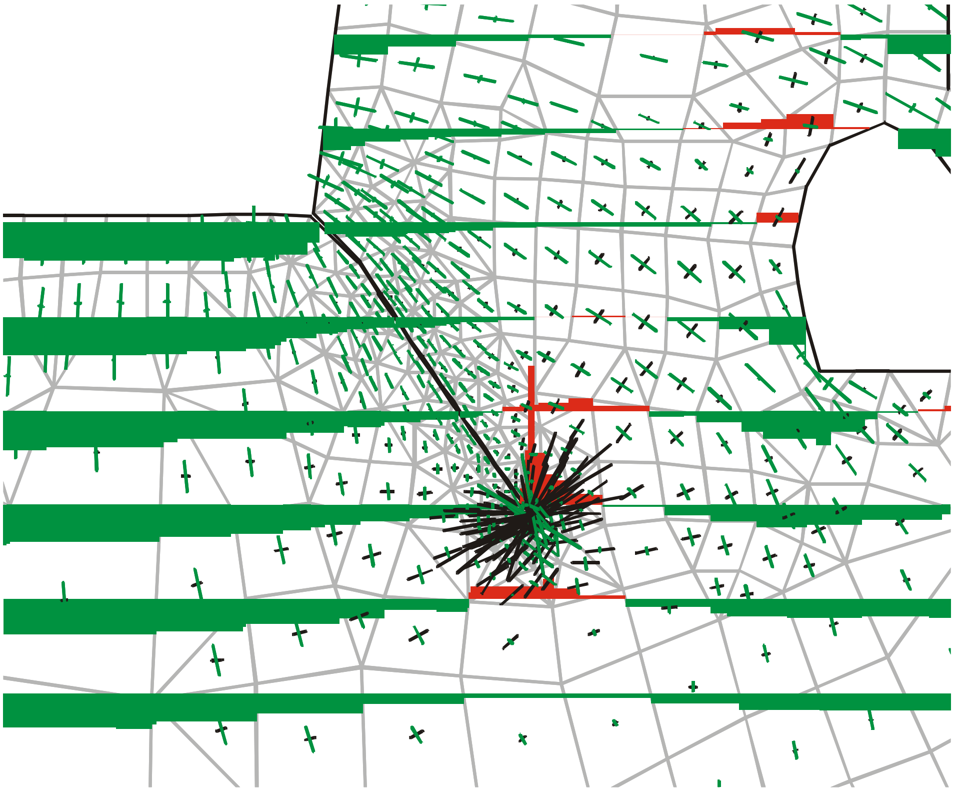

Figure 6: Stress trajectories for final crack state

7. REFERENCES

[1] Rashid, Y.R.: Ultimate Strength Analysis of prestressed concrete pressure vessels, Nuclear Engineering and Design 7 (1968), 334-344.

[2] Rots, J.G.: Computational Modeling of Concrete Fracture, PH.D. Thesis, University Delft, 1988.

[3] Wawrzynek, P.A., Ingraffea A. R.: Discrete Modeling of Crack Propagation. Theoretical Aspects and Implementation Issues in Two and Three Dimensions, Department of Structural Engineering, Report Number 91-5, Cornell University, Ithaca, New York, 1991.

[4] Cervenka, J.: Discrete Crack Modeling in Concrete Structures, Ph.D. Thesis, Department ofCivil, Environmental and Architectural Engineering, University of Colorado, Boulder, 1994.

[5] Potyondy, D.O.: A Software Framework for Simulating Curvilinear Crack Growth in Pressurized Thin Shells, School of Civil and Environmental Engineering,Report Number 93-5, Cornell University, Ithaca, New York, 1993

[6] Broek, D.: Elementary engineering fracture mechanics, Noordhoff International Publishing, 1974.

[7] Bettzieche, V.; Temperaturmessungen und -berechnungen am Beispiel einer alten Gewichtsstaumauer, Wasserwirtschaft 87 (1997); www.ruhrverband.de.

[8] SPRING; SPRING User's Manual Version 1.1 (1999) GKW Ingenieurgesellschaft, Bochum.