Fracture Mechanics of Concrete Structures,
Proceedings FRAMCOS-2, edited by Folker H. Wittmann,
AEDIFICATIO Publishers, D-79104 Freiburg (1995)

APPLICATION OF NON-LINEAR FRACTURE MECHANICS TO THE SEISMIC ASSESSMENT OF CONCRETE GRAVITY DAMS

M. Galli, G. Feltrin and H. Bachmann,
Institute of Structural Engineering, Swiss Federal Institute of Technology, Zurich, Switzerland

Abstract

The seismic assessment of concrete gravity dams is a dynamic structural problem that requires advanced numerical methods which account for all involved interaction phenomena and the strongly non-linear behaviour of cracking concrete. The methods must be working in the time-domain and be very efficient in order to keep computation time and data storage in reasonable orders of magnitude.

This paper describes the non-linear fracture mechanics model implemented in the 2D-FE-program DUCS (Dynamics of Unreinforced Concrete Structures). Based on a discrete crack approach, the strain-softening behaviour of micro-cracked concrete and aggregate interlock are taken into account.

Some computational examples give evidence of the influence of material parameters (tensile strength, aggregate interlock, fracture energy) and model parameters (mesh).

1 Introduction

Concrete dams are very important structures. On the one hand side they are economicly crucial, on the other hand, their potential risk at failure under extraordinary loading is huge. It is therefore evident that the safety assessment of such concrete dams requires advanced and sophisticated methods.

This paper focuses on the non-linear dynamic analysis of concrete gravity dams under earthquake excitation which is carried out using a 2D-model. Since many dams are built in seismicly active regions, a reliable determination of their dynamic behaviour under these conditions is deciding.

Concrete gravity dams are very large and they can't be analysed as isolated structures: The influences of the adjacent reservoir and foundation are too important to be neglected. As a result, a multi-part system comprising the dam body, the reservoir and the foundation must be analysed (Fig. 1). The main problems in such an analysis are listed below:

1. *Interaction phenomena:* The three parts constituting the overall model interact with each other. The interfaces between the dam body and the reservoir, between the dam body and its foundation and between the reservoir and the underlying foundation must be able to correctly deal with incident waves: Reflection and transmission of waves and of their energy must be in accordance with the characteristics of the different media.
2. *Boundary conditions:* In order to take into account the influence of the reservoir and the foundation both of them need to be included in the model. But as their extensions are very large compared to those of the dam, they cannot be modelled explicitly in their full length and depth. Accordingly, only a near-field part of the reservoir and of the foundation can be treated. This means that the "ends" of both, the reservoir and the foundation, are cut off at arbitrarily defined boundaries. Without further precautions these artificial boundaries reflect waves and their energy. This means that the phenomenon of "radiation damping" would be neglected, although it is thought of as being of great importance for the response of the overall system, see Chopra et al. (1980). Hence, we need to impose special boundary conditions which do not prevent energy from being radiated to farther parts of the reservoir and foundation. Many different kinds of boundary conditions have been devel-

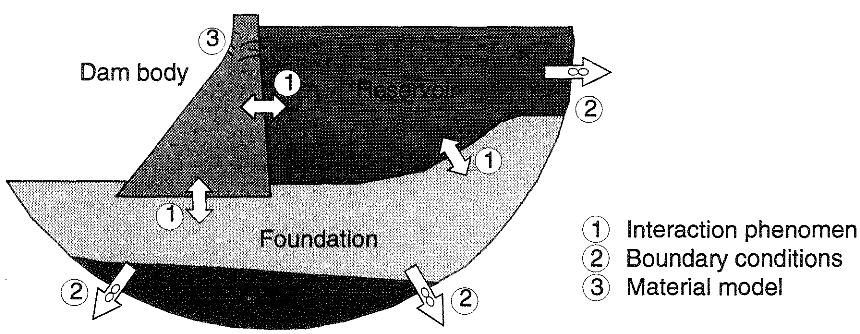

Fig. 1. System of dam body, reservoir and foundation

oped. Exact solutions have mainly been applied to analyses in the frequency-domain and are not very efficient in time-domain analysis. Exact boundary conditions were formulated by Wepf et al. (1988); much more efficient approximations to exact boundary conditions are currently proposed by Weber (1994) and Feltrin et al. (1995).

3. *Material model:* To determine a gravity dam's behaviour reliably, cracking of unreinforced mass concrete has to be considered. This highly non-linear phenomenon must be treated with some kind of fracture mechanics model. Problems arise because of the large size of the structure: The very local phenomenon of cracking would require a very fine mesh whereas the large structure itself entails a mesh with relatively large elements. This makes it practically impossible to use too sophisticated fracture mechanics concepts which assume element dimensions in the order of the aggregate size. Such meshes would contain much too many degrees of freedom and would be computationally too expensive.

It is most important to realize that the seismic assessment of dams is not solely a problem of non-linear material behaviour. Many intricacies stem from the size of the overall model consisting of the dam body, the reservoir and the foundation, from the size of the concrete body relative to the interesting zone of non-linear phenomena and from the fact, that a dynamic analysis is necessary. Therefore, the applied material model should be as simple as possible, but it must be able to capture all essential features of cracking.

2 Overall model of the FE-code DUCS

The FE-program DUCS has especially been designed for the non-linear dynamic analysis of concrete gravity dams. Its main features are listed below:

- DUCS is a 2D-program: A cross-section of the system is modelled and analysed, which is the state-of-the-art procedure for the analysis of concrete gravity dams. 3D-effects are completely ignored.
- The dam body is modelled by four-node isoparametric solid elements.
- A discrete crack approach is used to model the non-linear behaviour of mass concrete: Cracks are represented by special one-dimensional crack elements which are built in the mesh as soon as a new crack develops or an existing one propagates; see Skrikerud et al. (1986).
- Three phases of cracking are distinguished: A phase of crack formation, a phase of micro-cracked concrete with strain-softening and a phase of concrete with macro cracks, whose rough crack borders interact due to aggregate interlock; see Galli et al. (1994).
- The reservoir is split in two parts: The near-field is arbitrarily shaped and modelled with boundary elements. The far-field - a semi-infinite

channel of constant depth - is attached to the upstream boundary of the near-field. Its exact solution can be condensed into boundary conditions of the near field; see Wepf et al. (1988).

- The foundation is supposed to be rigid. Interaction phenomena due to the flexibility of the foundation and due to "radiation damping" into the foundation cannot be considered.
- The time integration is based on the central difference algorithm. As this procedure is explicit, the allowable maximum time step of the time integration is directly proportional to the smallest element in the mesh.
- All steps in connection to the creation of new crack elements - remeshing, build-up and update of system matrices - are carried out automatically.

There are several drawbacks of the existing version of DUCS: The exact boundary conditions for the reservoir are not efficient enough and the influence of the foundation should be taken into account. Therefore, a successor of DUCS, called STRATUM2D is under development. In a first step, new boundary conditions for the reservoir and the foundation were developed and implemented by Feltrin et al. (1995). In the second stage an improved material model will be implemented.

3 Crack model

Under high loading, unreinforced mass concrete starts to crack. Normally single, broad cracks develop. A natural representation of such cracks in an FE-mesh are discrete cracks: one-dimensional crack elements, that are built in the mesh, as soon as a new crack is created or an existing one propagates. DUCS uses such a discrete crack approach, it is able to adapt the mesh and the element matrices accordingly. During crack formation and propagation, three phases can be distinguished. Their respective models are discussed in the following sections.

3.1 Crack initiation

Starting with an uncracked dam body, there has to be a criterion to decide when a new crack element must be created. This criterion can also be used to determine the moment at which an existing crack extends. The criterion implemented in DUCS is "element-based",which is to say that we look at one element at a time and that we decide whether this element is about to crack regardless of what is going on in neighbouring elements. A new crack element is created, if three conditions are satisfied (Fig. 2):

1. *Principal tensile stress:* The principal tensile stress in one of the integration points of the element examined exceeds the tensile strength of concrete (bi-axiality is considered).

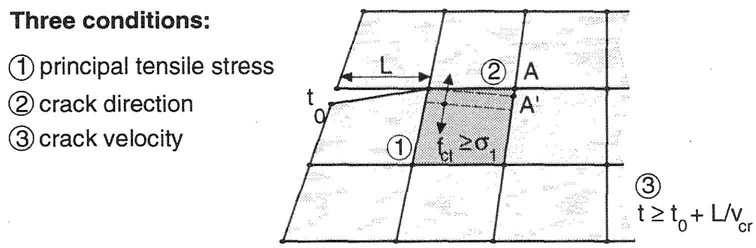

Fig. 2. Crack initiation criterion

2. *Crack direction:* The direction perpendicular to the decisive principal tensile stress is such that a crack element with the same direction can be created within the element and that it starts either at the dam's surface or at an existing crack tip (bifurcation is impossible).
3. *Crack velocity:* It must be ensured that an existing crack doesn't propagate with a velocity that is completely unrealistic. Since the cracks are created in one time step, their apparent crack velocity is determined by:

$$\overline{v_{crack}} = L_{crack}/\Delta t \tag{1}$$

Δt in turn depends on the speed of longitudinal waves in concrete (stability criterion of the central difference method). It turns out that the apparent crack velocity is always greater than the longitudinal wave speed, which is much greater than realistic values of the crack velocity:

$$\overline{v_{crack}} > c_p \gg v_{crack,\,eff} \tag{2}$$

Therefore, the crack is stopped and cannot propagate for a certain period of time ($L_{cr}/v_{crack,\,eff}$), during which the crack could have propagated through the element supposing a realistic crack velocity.

3.2 Micro-cracked concrete exhibiting strain-softening

As soon as the crack initiation criterion is triggered, a new crack element is created perpendicularly to the decisive principal tensile stress. These crack elements are built in the mesh, which means that the neighbouring solid elements have to be adapted accordingly: Their edges must be parallel to the new crack element. This adaptation may entail the deformation of four-node elements (compare Fig. 2 to Fig. 3) and/or the splitting of an existing four-node-element in two three-node elements.

The strain-softening process is implemented as a fictitious crack similar to the one developed by Hillerborg et al. (1976). In this phase, limited tensile stresses may still be transmitted across the crack. Their magnitude de-

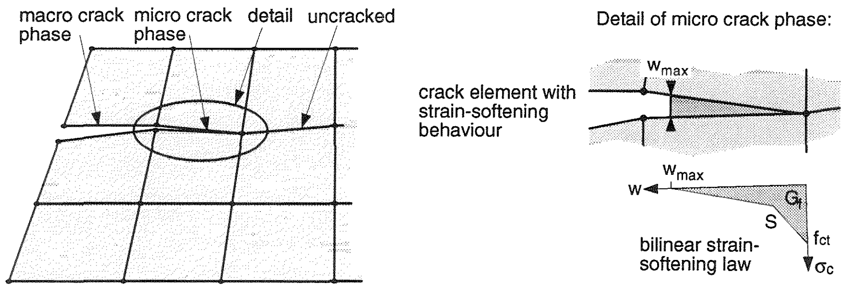

Fig. 3. Fictitious crack (Hillerborg); strain-softening law

pends on the crack opening w as given by the strain-softening law in Fig. 3. The area under the curve is equal to the fracture energy G_f.

Compression stresses are transmitted as in uncracked concrete and cyclic loading with closing and reopening of cracks is considered as shown by Chappuis (1987).

3.3 Concrete with macro-cracks; aggregate interlock

The transition from micro-cracked concrete to a single macro-crack which doesn't transmit any tensile stresses, is triggered by the crack opening w. As soon as the crack opening exceeds the highest permissible opening for stress transmission w_{max} in all integration points of the crack element, the crack opens completely. At this point transmission of tensile stresses across the crack stops and the model of aggregate interlock is activated.

Aggregate interlock is modelled by a series of springs parallel to the crack surface as shown in Fig. 4. It accounts for the non-linear stiffness properties of rough crack surfaces as well as for dilatancy effects. A set of closure conditions assures full transfer of compression stresses as soon as the two crack surfaces are in contact. This can even be the case if the crack is not fully closed: If one surface of an open crack is displaced relatively to the other, the aggregates will not fit any more into the original place, they interlock and the crack doesn't close completely, see Skrikerud et al. (1986).

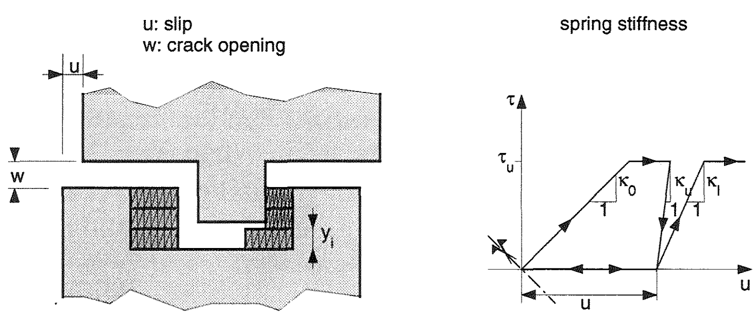

Fig. 4. Model of aggregate interlock

3.4 Advantages

Discrete crack approaches in general and the one used in DUCS specifically have certain advantages:

- Discrete cracks are very perceptual. The interpretation of what happens in and around the cracks is straightforward, because there are no smeared results that need to be translated to the real cracks.
- Processes in and around the crack tip (e.g. aggregate interlock, water pressure in cracks) needn't be translated into solid element or material properties, but, on the contrary, can be modelled directly at the discrete crack.
- The fracture energy G_f is explicitly considered in the material law. This way we don't need to correct the fracture energy to account for different element sizes.
- As we model the cracking process itself, we do not have to consider size effect when choosing our material parameters. In fact, the model should be able to reproduce size effect results: Different sizes of a structure analysed with the same material properties result in size-dependent nominal strength.
- Excessive mesh sensitivity due to the orientation of the mesh can be avoided, as the direction of the cracks is independent of the mesh and because the mesh is gradually adjusted to the crack pattern.

4 Results

The following sections will discuss the influence of several material and model parameters.

4.1 Influence of tensile strength

The influence of tensile strength is examined by means of three different cases: The Pine Flat dam with full reservoir meshed as shown in Fig. 5a) undergoes a horizontal excitation defined by the S69E "Taft" component of the Kern County 1952 earthquake (Fig. 5c) scaled to a peak ground acceleration of 18% of g. The material properties are given in Table 1 (column 2). The evolution of crack pattern is given in three sequences in Fig. 6.

In the first case (f_{ct}=2.5 MPa) the heel crack develops at about 3.7 s, i.e. at the time the first acceleration peak takes place. Cracking proceeds on the downstream face of the dam, mainly from t=7.9 to t=8.8 s. At this stage, a broad crack has developed running across the whole section. At its downstream opening, the crack is wide open (>40 mm) and doesn't close any more due to aggregate interlock. At t=15.2 s another phase of cracking occurs: A second broad crack runs from the upstream face through the dam body. Still, the dam body doesn't collapse completely, normal forces and friction prevent the dam's "head" from toppling.

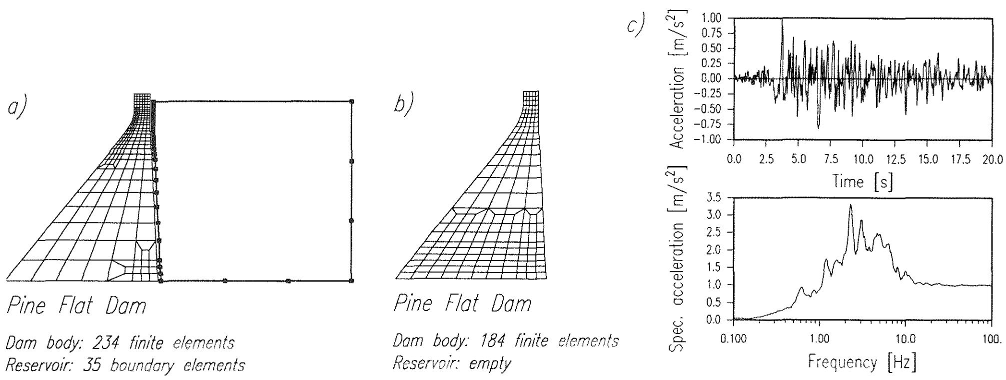

Fig. 5. Pine Flat dam: a) mesh "tensile strength" b) mesh "fracture energy" c) time history and response spectrum of "Taft" earthquake input

Table 1. Concrete properties

		Series "tensile strength"			Series "fracture energy"					Series "mesh sensitivity"
Tensile strength f_{ct}	MPa	2.5	2.0	1.5	2.5					2.6
E-Modulus E	GPa	22.0			22.4					20.7
Poisson number ν		0.2			0.2					0.2
Fracture energy G_f	J/m^2	350	280	210	3.5	175	350	1750	3500	161
Crack opening w_{max}	mm	0.3			$3 \cdot 10^{-3}$	0.15	0.3	1.5	3.0	0.57
Crack opening w_S	mm	0.1			$1 \cdot 10^{-3}$	0.05	0.1	0.5	1.0	0.08
Tensile stress σ_S	MPa	1.0	0.8	0.6	1.0					0.2
Crack velocity v_{max}	m/s	500			500					500
Aggregate interlock		y/n	yes		yes					no

The second case with a lower tensile strength of f_{ct}=2.0 MPa begins quite similar. But at t=7.7 s, a long crack near the dam's heel forms and runs deeply into the dam body. Another crack in the upper part propagates through the whole section at t=8.5 s. But the final crack pattern shows a much less damaged upper part of the dam compared to the case of higher tensile strength. This may be surprising, but it is a direct consequence of the long crack near the dam's heel: It reduces the structure's stiffness and fundamental frequency (f_0=2.5 Hz) drastically so that - in this case, see response spectrum in Fig. 5c - loading drops significantly, too.

In the last case with f_{ct}=1.5 MPa, a heel crack is predicted already in the static analysis. Excited by the earthquake this dam with low tensile strength exhibits excessive cracking on its downstream face starting at t=4 s. At t=4.2 s a couple of cracks form on the upstream face. The cracks from the downstream face propagate rapidly and penetrate the dam section at t=5.9 s. Many more cracks form and the dam becomes severely damaged.

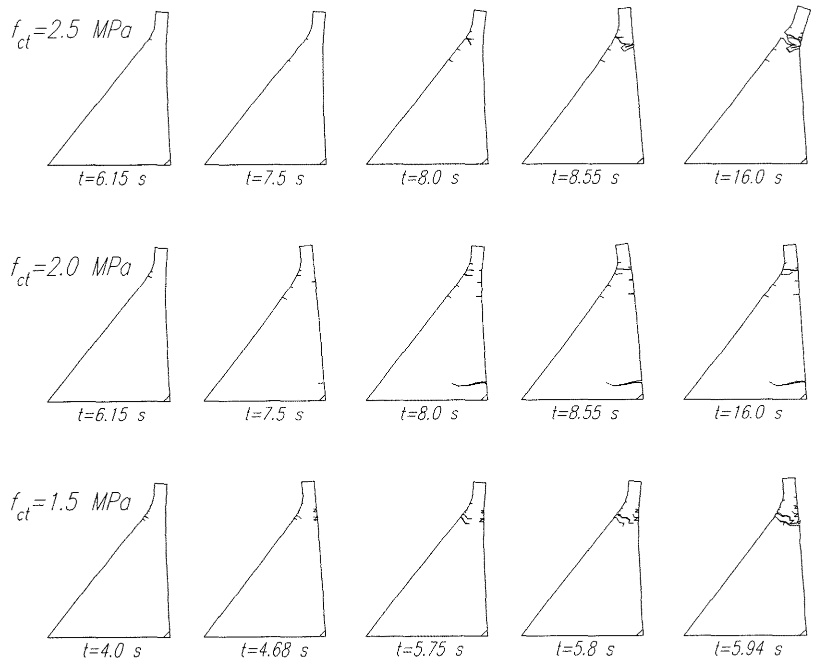

Fig. 6. Evolution of crack pattern for different tensile strength

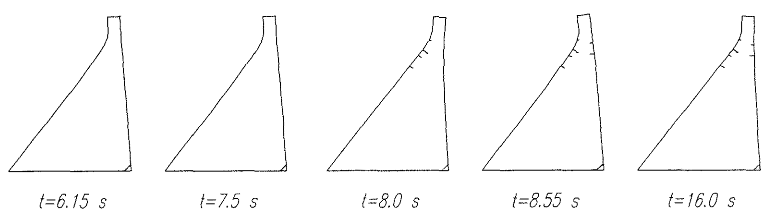

Fig. 7. Evolution of crack pattern without aggregate interlock

4.2 Influence of aggregate interlock

The cases in section 4.1 were all calculated with aggregate interlock, i.e. the crack surfaces were assumed rough. As a comparison, a case with f_{ct}=2.5 MPa has been calculated without aggregate interlock, i.e. with smooth crack surfaces. The results given in Fig. 7 illustrate how cracking is significantly reduced: It seems that the transfer of shear stresses due to aggregate interlock as shown in Fig. 6 leads to a stress field around the cracks that favours further cracking. Similar results have been shown by Feltrin (1992).

4.3 Influence of fracture energy

To demonstrate the influence of the fracture energy G_f, five different cases of Pine Flat dam meshed as shown in Fig. 5b) with empty reservoir and concrete as defined in Table 1, column 3 are examined. Excited by the "Taft"

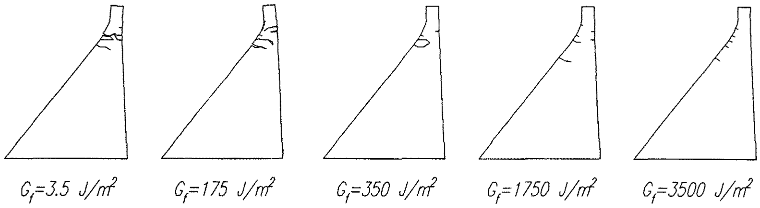

Fig. 8. Crack pattern: 5 cases of different fracture energy

acceleration record scaled to 30% of g, the results shown in Fig. 8 back the following conclusion: In the range from no fracture energy up to realistic values (175 and 350 J/m^2, e.g. Brühwiler (1988)) there is no significant influence on the general crack pattern. The third case with G_f=350 J/m^2 in Fig. 8 seems to exhibit much less cracking. In fact, the two longer cracks, united in the middle of the dam, were prevented from propagating further due to the crack initiation criterion (cf. section 3.1). But many other calculations, e.g. those by Feltrin (1992) have shown that the aforementioned statement is correct. Only an unrealistic high fracture energy (1750 and 3500 J/m^2) influences cracking clearly: Many short cracks, narrowly spaced, develop, their strain-softening lasts much longer and they hardly penetrate deep into the dam body, so that the total damage of the dam is clearly reduced. Further studies have shown that this influence can be found for lower fracture energies, if the tensile strength is reduced as well. Still, the necessary fracture energy remains much higher than realistic values.

4.4 Influence of the FE-mesh

In order to examine the mesh-sensitivity of our model, we calculated four cases of a 103.6 m high model dam with dimensions twice those suggested by Bourdarot et al. (1994) and material properties listed in Table 1, column 4. The meshes and the earthquake input - an artificially generated time history with a response spectrum compatible to the swiss design spectrum

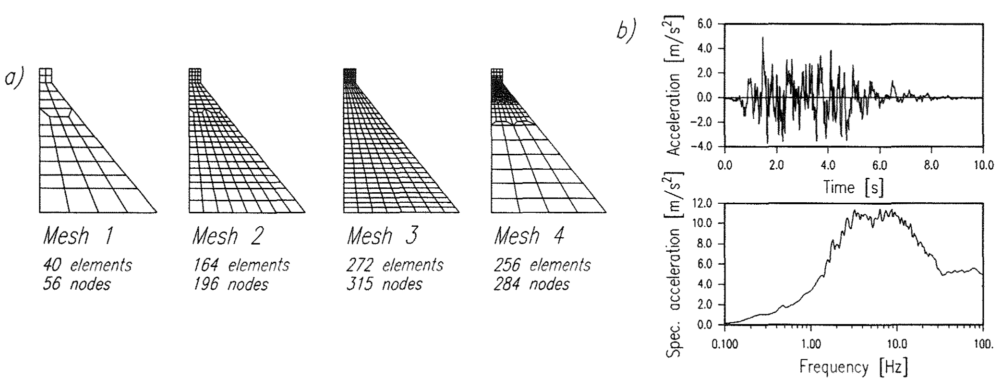

Fig. 9. a) Meshes and b) earthquake input for study of mesh-sensitivity

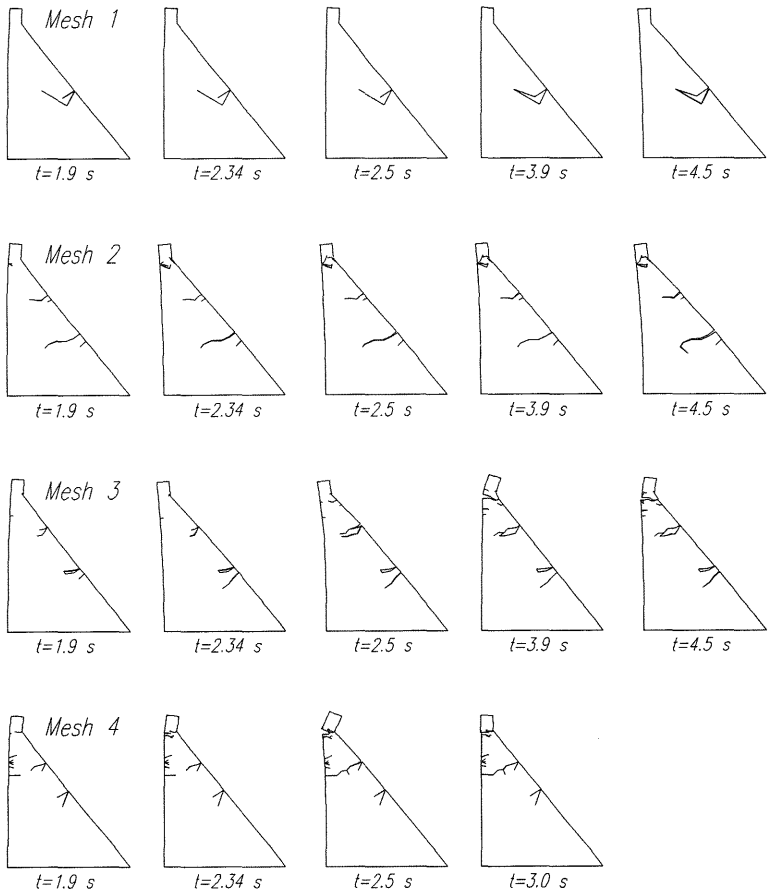

Fig. 10. Crack pattern for different meshes a) with iteration b) no iteration

scaled to 50% of g - are shown in Fig. 9. The evolution of the crack pattern is displayed in Fig. 10:

Mesh 1 - which must certainly be considered too crude - gives very poor results: it doesn't capture the cracks at two-thirds of the dam's height and doesn't predict any damage in the "head" of the dam, i.e. the damage is excessively underestimated.

Meshes 2 and 3 predict the same general crack pattern. Two zones of cracking develop starting from the downstream face of the dam, and heavy damage in the dam's "head" with cracks running through the whole section are predicted. The cracks are of course not identical, a certain influence of the chosen mesh cannot be denied, but the overall response of the dam and the final damage is quite similar.

Mesh 4 which is very fine in the "head" part of the dam with 16 elements across the section runs into some problems. Starting fairly well, with similar cracks on the downstream face as meshes 2 and 3, cracking starts earlier in the "head" portion. It is very soon ripped off the rest of the dam, a lot of small cracks form very quickly and make the whole calculation unstable.

This can be explained as follows: The abrupt changes in the stress field in case of the creation of a new crack result in very high-frequency stress waves. The peak stresses of these waves are of the same magnitude as the tensile strength that had been built up causing the new crack. As a consequence, tensile stresses in neighbouring elements will exceed the tensile strength during very short intervals. Then, our crack initiation criterion which doesn't consider stress-rates, will create many new cracks. The finer a mesh is, the more prone it is to this effect: There are many elements near a new crack and their integration points are much closer to the crack and its tip. As soon as there are already some cracks near each other, the stress waves stemming from the creation of a new crack element will propagate on very complicated paths which aggravates cracking even more.

5 FURTHER DEVELOPMENT

Using DUCS for different parametric studies some prominent advantages of the discrete crack approach and of the relevant fracture mechanics model cold be experienced. On the other hand weaknesses which help us to formulate new ideas for further development were identified as well. There are two main problems concerning the model of cracking:

- The "element-based" crack initiation criterion needs to be improved: The criterion checks the integration points, but the cracks do not really start at these points. An improved criterion should check crack tips and nodes along the surface of the structure. Even worse, the current criterion will sometimes prevent existing cracks from propagating, when the decisive stress is rotated and no crack perpendicular to it can be built in the element under consideration. This should be overcome by the new "node-based" criterion.
- The cracking due to very high-frequency stress waves as described in section 4.4 should be treated differently. Short time exceedance of the tensile strength near cracks which have just been created shouldn't lead to new crack elements.

In STRATUM2D,the successor of DUCS, an improved fracture mechanics model will be implemented. In its present state, the new program allows the consideration of the foundation flexibility and includes new boundary conditions for the reservoir and the foundation, see Feltrin (1995).

6 CONCLUSIONS

Using the non-linear fracture mechanics model of DUCS we find a distinct influence of the tensile strength. In general, damage increases drastically with lower tensile strength, unless a broad crack near the dam's base leads to a quasi-base-isolated structure.

The influence of aggregate interlock seems to be of great importance, too. It increases cracking significantly due to stress transfer across cracked portions of the dam.

Fracture energy is found to have less influence on a dam's behaviour. Only unrealistic values of the fracture energy could lead to a significant reduction of damage.

A short comparison of four different meshes shows coarse meshes to be inappropriate because their resolution of the stress field is insufficient and indicates, that very fine meshes might exhibit problems too, as the crack initiation criterion doesn't work very well with high-frequency stress-waves.

Ideas for further improvement of the fracture mechanics model are shortly stated; a successor called STRATUM2D is under development.

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