

# Integrity assessments of a gravity dam with respect to pressurized crack propagation along the concrete foundation interface

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## Sommario

*L'International Committee for Large Dams (ICOLD), organizzazione internazionale promossa dalle maggiori aziende idroelettriche e da centri di ricerca universitari ed industriali, nell'ultimo "Workshop" tenutosi a Denver nel giugno 1999 ha trattato, accanto ad altri problemi tecnico scientifici di attualità nell'ingegneria delle dighe, l'analisi di una diga a gravità con particolare riferimento a fenomeni di frattura alimentati dalla pressione dell'acqua ("uplift") lungo l'interfaccia tra calcestruzzo e roccia di fondazione.*

*In questa comunicazione si assumono come dati geometrici e di comportamento dell'interfaccia quelli proposti dall'ICOLD per il "Benchmark exercise" [8] discusso nel citato incontro. Gli scopi sono stati l'implementazione, la sperimentazione numerica e il vaglio critico comparativo di un metodo semplificato per la simulazione di fenomeni fessurativi lungo interfacce e di varianti del metodo stesso. Precisamente, nella comunicazione si intende trattare i seguenti temi:*

*(A) Modello d'interfaccia coesivo anolonomo con attrito. Questo modello è formulato nell'ambito della elastoplasticità incrementale con una legge costitutiva che non soddisfa il postulato di Drucker sulla stabilità del materiale (cfr. [12]). In questa comunicazione, la discontinuità di spostamento tangenziale (accumulata) in corrispondenza dell'interfaccia è interpretata come variabile interna del modello d'interfaccia coesivo con attrito dove l'interazione tangenziale è definita come funzione lineare a tratti di questa variabile interna (con assunzioni analoghe a quelle adottate in tutt'altro contesto in [6]). Per quanto concerne gli aspetti computazionali, si utilizza un efficiente algoritmo per l'integrazione passo-passo del legame costitutivo elastoplastico.*

*(B) Modelli olonomi di interfaccia tipo "cohesive-crack" per il modo I di apertura della fessura: lineare, bilineare (con "break point"), esponenziale (cfr [4]).*

(C) *Messa in conto dell' "uplift" con l'assimilazione nel modello di interfaccia (cfr. [3]), in diverse situazioni di drenaggio.*

(D) *Analisi globale, in un contesto di elementi finiti nel programma commerciale ABAQUS [1], utilizzando la formulazione e l'implementazione dei modelli di interfaccia di cui sopra. Per superare la soglia di instabilità è utilizzato l'algoritmo di Riks [14] e l'incremento di carico risulta incognito.*

(E) *Impiego di metodi di programmazione matematica, recentemente applicati allo studio dei modelli di interfaccia tipo "cohesive-crack" che portano alla formulazione di un problema di complementarità non lineare [2], [11]. Nella presente comunicazione, questo approccio è adottato con riferimento al modello coesivo omonimo esponenziale per il Modo I di apertura della fessura. La pressione del fluido è funzione dell'apertura di fessura in direzione normale con legge di tipo esponenziale. Nelle analisi numeriche, il codice di calcolo ('PATH') sviluppato da Dirkse e Ferris [7] è utilizzato. I risultati ottenuti con i metodi diretti non evolutivi risultano in buono accordo con quelli ottenuti attraverso l'approccio tradizionale passo-passo (evolutivo).*

### **Nonholonomic cohesive interface model with friction**

In this communication the nonholonomic cohesive model with friction proposed in [8] is formulated in the framework of incremental elastoplasticity, disregarding the Drucker postulate of material stability (see e. g. [12]).

It is well known that in a frictional contact, the interaction between normal and tangent components leads to a reduction of the local resistance of the interface (see for instance [6]). The resistance "damage" can be easily related to the maximum relative "sliding" displacement between the two contacting surfaces, which assume the meaning of "internal variable".

In the present approach, the internal variable is identified as the cumulated tangential displacement jump between the interface surfaces. This definition has been incorporated in the proposed cohesive model, assuming that the tangent reaction is a piecewise-linear function of the internal variable.

In several works the elastoplasticity theory is used to describe the friction phenomenon (see e. g., [6], [12]). In this approach, the tangential displacement discontinuity  $w_t$  across the interface is assumed to be the sum of an elastic  $w_t^e$  and an irreversible (permanent or plastic) part  $w_t^p$ . Herein, a mixed-formulation is used for the contact problem, thus the contact pressures  $p_n$  and the displacements  $u_j$  are unknowns.

The interface law is governed by the following equation:

$$w_t = w_t^e + w_t^p \quad (1)$$

$$p_t = \frac{\partial \mathbf{p}}{\partial w_t^e}(w_t^e, s), \quad p_t = \frac{\partial \mathbf{p}}{\partial s}(w_t^e, s) \quad (2)$$

$$\dot{w}_t^p = \frac{\partial \hat{\Phi}}{\partial p_t}(p_t, q) \dot{\mathbf{I}}, \quad \dot{s} = -\frac{\partial \hat{\Phi}}{\partial q}(p_t, q) \dot{\mathbf{I}} \quad (3)$$

$$\dot{\mathbf{I}} \geq 0 \quad \Phi(p_n, p_t, q) \leq 0 \quad \Phi \dot{\mathbf{I}} = 0 \quad (4)$$

In Eq. (2) a potential  $\pi$  represents the free energy function:  $\pi = \pi^E + \pi^L$ , where  $\pi^E$  is the elastic strain energy, and  $\pi^L$  is the energy locked in the material by rearrangements at the microscale reflected by an internal variable  $s$ . A plastic potential  $\hat{\Phi}$  is adopted in Eqs. (3) to describe the evolution of the internal variables  $w_t$  and  $s$  introducing a non-decreasing plastic multiplier  $\lambda$ . A superimposed dot means derivative respect to any strictly monotonically increasing parameter identifying the chronological time. The function  $\Phi(p_n, p_t, q)$  characterizes the corresponding elastic domain, which is assumed to be convex. For  $\Phi(p_n, p_t, q) < 0$ , (4-c) yields  $\dot{\lambda} = 0$ , i.e. elastic behavior, while plastic flow is characterized by  $\dot{\lambda} > 0$ , which, in view of (4-c), imposes the satisfaction of the yield criterion with  $\Phi = 0$ . In the friction model the yield function  $\Phi$  is different from the plastic potential  $\hat{\Phi}$  (non-associated plasticity). The failure surface and the piecewise-linear cohesive model are shown in Fig. 1. Herein, the joint dilatancy is neglected, as in previous analyses on large dams carried out by Hohberg [9]. The values of the model parameters used in the numerical simulations are reported in Table 1.

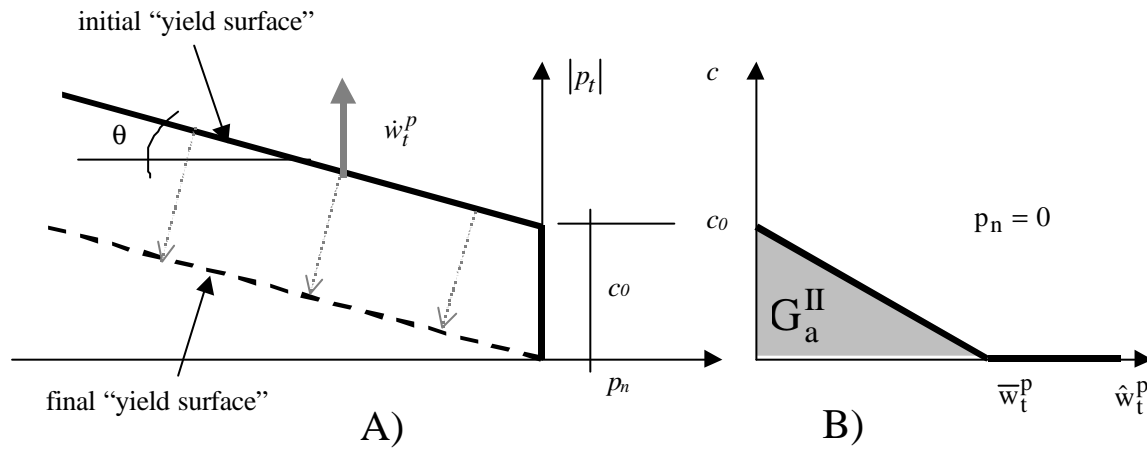


Figure 1

A) Failure surfaces; B) piecewise-linear cohesive model.  $\hat{w}_t^p$  cumulated tangential jump.

Table 1

Parameters used for the cohesive model with friction

Parameter	Value
Shear Stiffness K [N/m <sup>3</sup> ]	20 x 10 <sup>9</sup>
Peak cohesion $c_0$ [MPa]	0.3
Friction angle $\theta$ [deg.]	30
Fracture energy $GII_a$ [MPa]	600 – 6000

### Holonomic cohesive crack models with uplift

When the loads applied to a structure are monotonically increased in time by a common (amplification) factor, the hypothesis that the distribution of a non decreasing opening displacement

$w_n$  (i.e. no local unloading takes place) is often practically acceptable, although not necessarily fulfilled. Thus, disregarding unloading, the interface constitutive model can be expressed by a holonomic law, namely a nonlinear elastic (path-independent) relation between stress and opening displacement. At time  $t$ , the locus of potential or actual displacement jumps can be divided in three portions: (i) fully opened crack  $\Gamma_d^c$ , where no interaction exists ( $p = 0$ ), (ii) undamaged elastic material  $\Gamma_d^e$  not involved yet into crack opening, (iii) the process zone  $\Gamma_d^p$  where ( $p \neq 0$ ). As for the transmission of shear force  $p_t$  along the craze zone, the assumption that no bound on  $p_t$  and no discontinuity of tangential jump is introduced ( $w_t = 0$ ) [4]. The different Cohesive Crack Models (CCMs) considered for case (iii), are shown in Fig. 2.

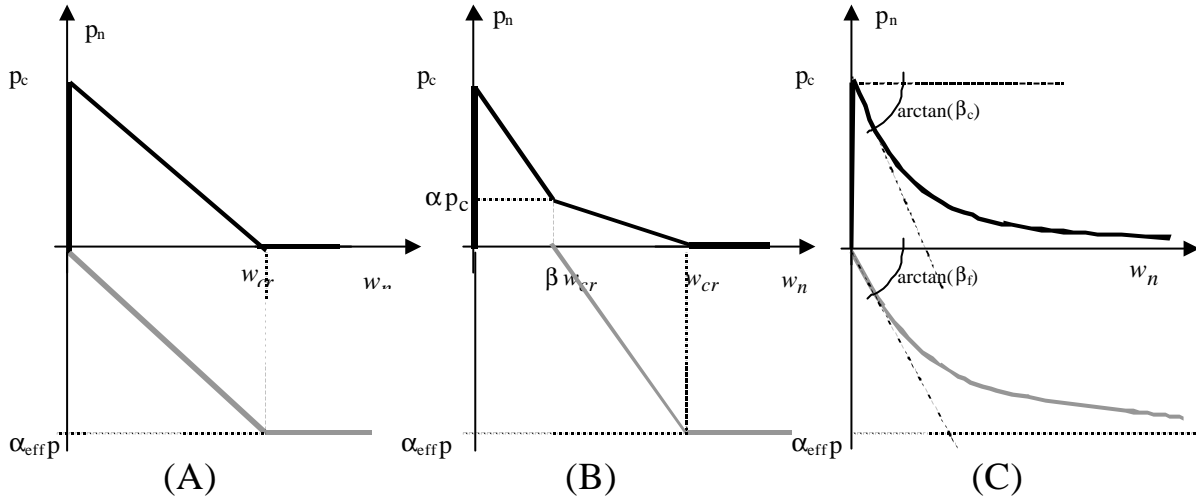


Figure 2

Mode I: Holonomic piecewise-linear cohesive crack models with uplift: (A) Linear (B) Bilinear (with “break point”); (C) Holonomic exponential cohesive crack model with uplift.

In Fig. 2,  $p$  is the water pressure,  $\alpha_{\text{eff}}$  is the drain efficiency coefficient and  $\alpha, \beta, \beta_c, \beta_f$  are model parameters. A linear variation of pressure with the opening displacement in the process zone is assumed for the linear and bilinear cohesive crack models (Fig. 2.A-B) in accordance with the experimental evidence [3], while an exponential variation is assumed for the non linear cohesive crack model in Fig. 3.C.

In order to compare the results obtained with the different cohesive crack models, the same fracture energy ( $G_f^I = 90 \text{ N/m}$ ) and the peak tension strength ( $p_c = 0.3 \text{ MPa}$ ) are considered in numerical analyses. Further, the following parameters are assumed for the piecewise-linear cohesive law with “break point”:  $\alpha = 0.25, \beta = 0.14$ .

## Methods and results: an outline

A commercial finite element code ABAQUS [1] has been used for the numerical simulations. The cohesive interface models presented above have been implemented into this code. Implementation details can be found in [13].

The geometry of the dam's cross-section is shown in Fig. 4. Both concrete and rock were assumed to behave elastically (rock:  $E_r = 41000$  MPa,  $\nu_r = 0.10$ , concrete:  $E_c = 24000$  MPa,  $\nu_c = 0.15$ ), the weight densities for the concrete is  $\gamma_c = 2400$  Kg/m<sup>3</sup>, the rock self weight is neglected. In the evolutive analysis, the water elevation is gradually increased up to the top of the dam. Then, an indirect displacement control algorithm ('arc length' method) [14] is used to determine the peak and post peak load carrying capacity.

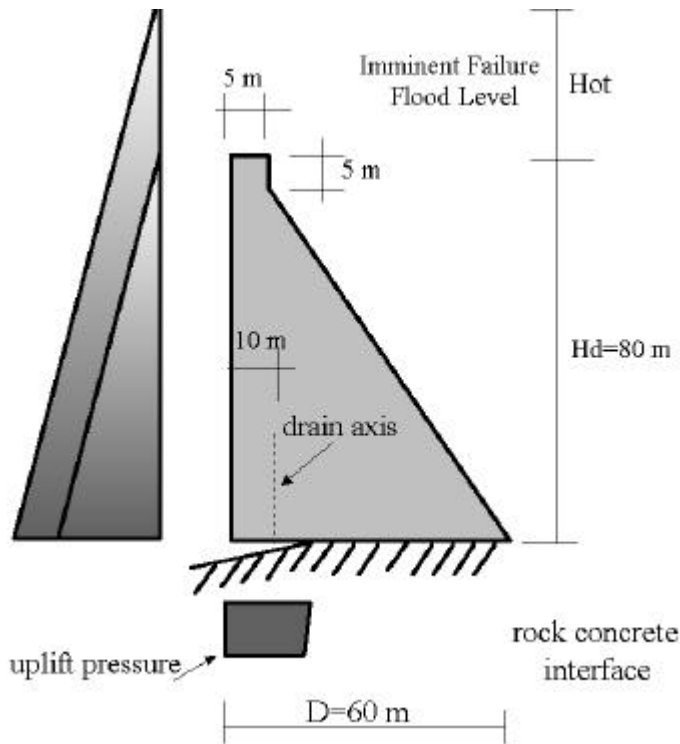
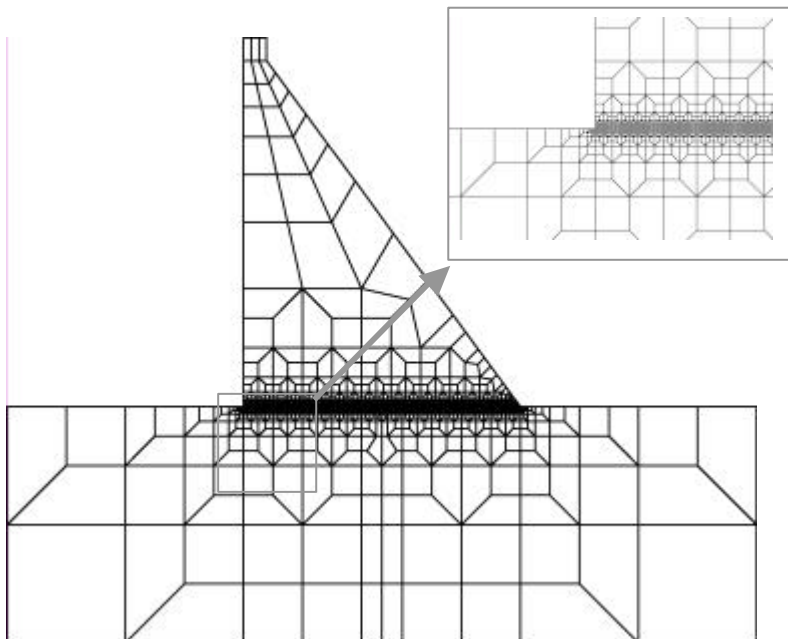


Figure 3  
Geometry and boundary representation for the dam



The finite element mesh used in the fracture analysis is shown in Fig. 4 a total of 3703 node and 4358 four node isoparametric elements are used in the discretization. It is important to note that the mesh size in the interface is about 1/20 of the characteristic cohesive length in order to obtain mesh-size insensitivity results. However, this mesh is very expensive because of the same size of the element is used along the interface, while the finer elements should be used only in the cohesive zone. An adaptive remeshing strategy should be employed in order to obtain numerical solutions with a controlled accuracy. A tool for evaluating the error of the

solution computed with a given mesh and a refinement algorithm to define a new spatial discretization should be introduced. An algorithm for self-adaptive procedure in Limit Analysis can be found in [13].

The results obtained by the nonholonomic cohesive model with friction are partly illustrated by Figs. 5-6

Figs. 5 and 6 show the nondimensional overtopping load ( $H_{ot}/H_d$ ) versus the nondimensional crack mouth

Figure 4  
Detail of mesh employed in the calculations showing the square element along the interface

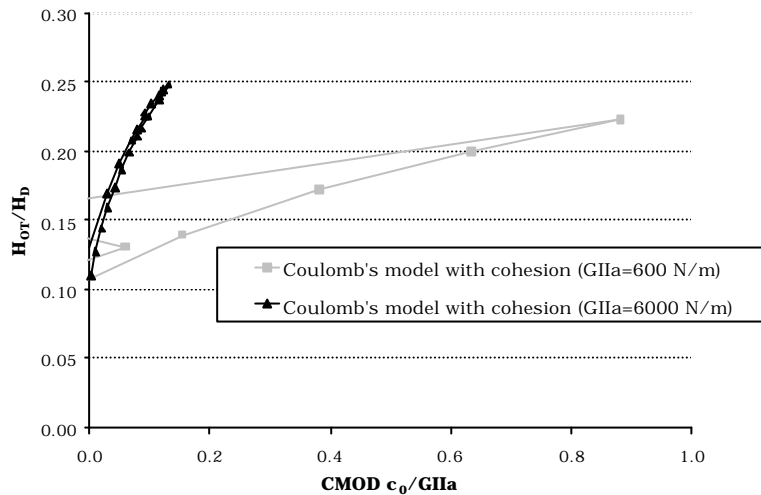
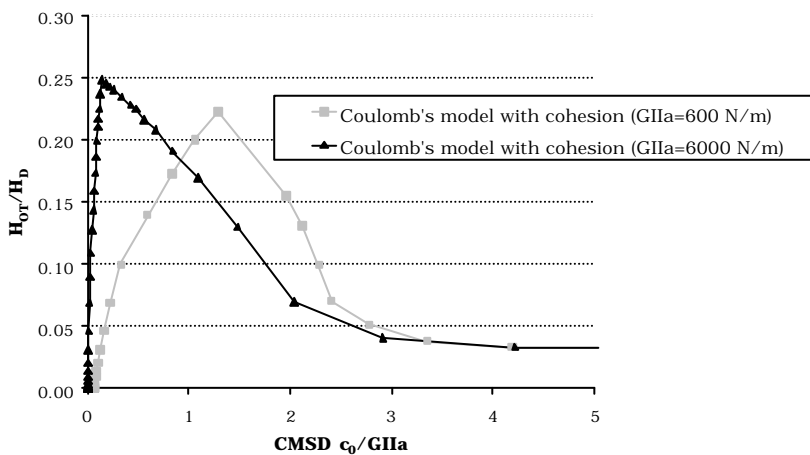


Figure 5  
Nondimensional overtopping load versus nondimensional crack mouth opening displacement for different values of the fracture energy.

and contact conditions changes, the numerical solution obtained by the traditional “*trial and error*” contact algorithm often show unstable behavior in the post-peak range. In the Fig. 6, the post peak branch of the curves decrease until the usual Coulomb friction conditions are obtained.



opening displacement (CMOD  $c_0/GIIa$ ) and versus nondimensional crack mouth sliding displacement, (CMSD  $c_0/GIIa$ ),

respectively, for two different values of the fracture energy ( $GIIa = 600 \text{ N/m}$ ,  $GIIa = 6000 \text{ N/m}$ ). In the Fig. 5, it is interesting to note that the CMOD increases until the maximum value of the overtopping load is reached, then it decreases. A penetration is permitted between *slave and master surfaces* in order to obtain the solution.

Thus, due to the coupling of the non-linearities from cohesive law with friction and

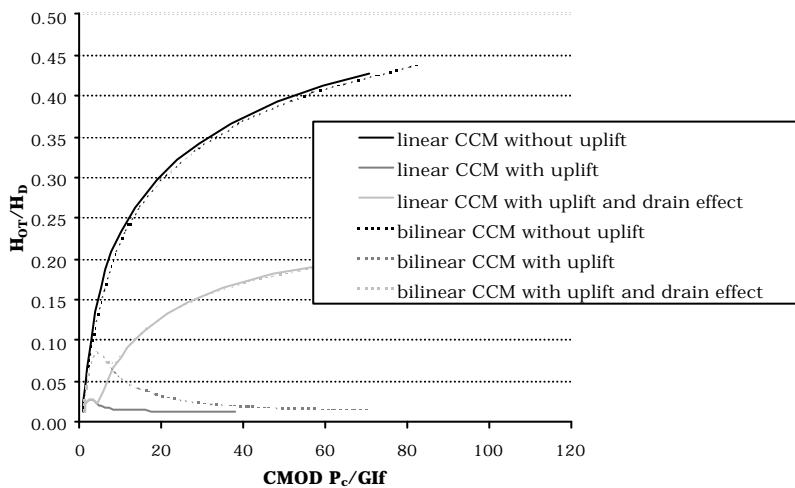
The results obtained by the holonomic cohesive crack models for mode I opening the fracture are reported in Fig. 7. These results show that the effect of the uplift in the process zone significantly reduce the load carrying capacity of the dam. In particular, if the piecewise linear cohesive model with ‘*break point*’ is considered and the

*Figure 6*  
*Nondimensional overtopping load versus nondimensional crack mouth sliding displacement for different values of the fracture energy.*

penetration of the fluid in the ‘process zone’ is assumed up to ‘break point’ the maximum

overtopping load is greater than one obtained by the linear cohesive model in which the fluid can penetrate entirely the process zone. Further, it is important to note the effect of the position of the drain axis. The reduction of the uplift due to the drain occur after that the maximum value of the overtopping load is reached. Thus, a correct position of the drain axis is important in order to guarantee the safety of the dam.

The behavior of the dam when the cohesive crack model for mode I opening of the fracture is assumed is strongly different from the case in which the nonholonomic cohesive crack model with friction is considered. Tests on the specimens of the dam-foundation interface [10] show that the frictional behavior is important, thus a nonholonomic cohesive model with friction should be used in order to evaluate the maximum load carrying capacity of the dam.



*Figure 7*  
*Nondimensional overtopping load versus nondimensional CMOD displacement for different values of the fracture energy.*

Finally, an innovative method recently proposed in [2], [5], [11] based on the formulation of the interface model as Nonlinear Complementarity Problem (NCP) is applied. Herein, this method is adopted with particular reference to the holonomic cohesive exponential model for the mode I opening of the fracture. The uplift pressure is taken into account in the constitutive model.

The formulation of the problem as an NCP and the use of mathematical

programming algorithm (e.g. ‘PATH’ solver) [7] has the following advantages: (a) can

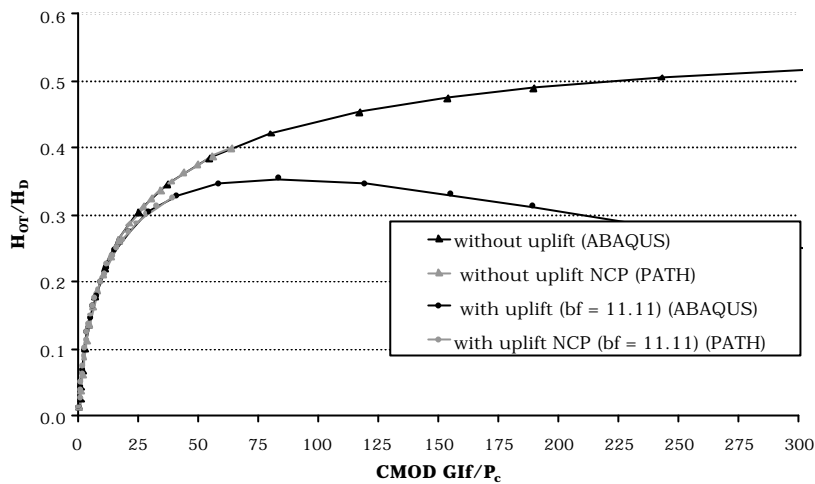


Figure 8  
Nondimensional overtopping load versus nondimensional crack mouth opening displacement for exponential Cohesive Crack Models (CCM). Mathematical programming ('PATH' solver) versus ABAQUS code.

allow to capture the whole set of the multiplicity solutions of the quasi-brittle fracture analysis [2], (b) the holonomic single-step analysis of the structural response (including cohesive cracks) to given external actions is lesser expensive than the traditional time-stepping (evolutionary) procedures [11].

The results are reported in Fig. 8, and they are in good agreement with time stepping-evolutionary analysis.

The author's computational experience indicate that there is no certainty of finding all the solutions. In fact, for a given load only the solution on the ascending branch of the response curve is obtained (see Fig. 8). Thus, further research work is needed in order to achieve the above results for general case in a more reliable and efficient manner.

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