Laboratoire Central
des Ponts et Chaussées

Thèse de doctorat de
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École Nationale
des Ponts et Chaussées

Modélisation de la stabilité des massifs rocheux avec prise en compte de l'endommagement des joints et des effets hydromécaniques

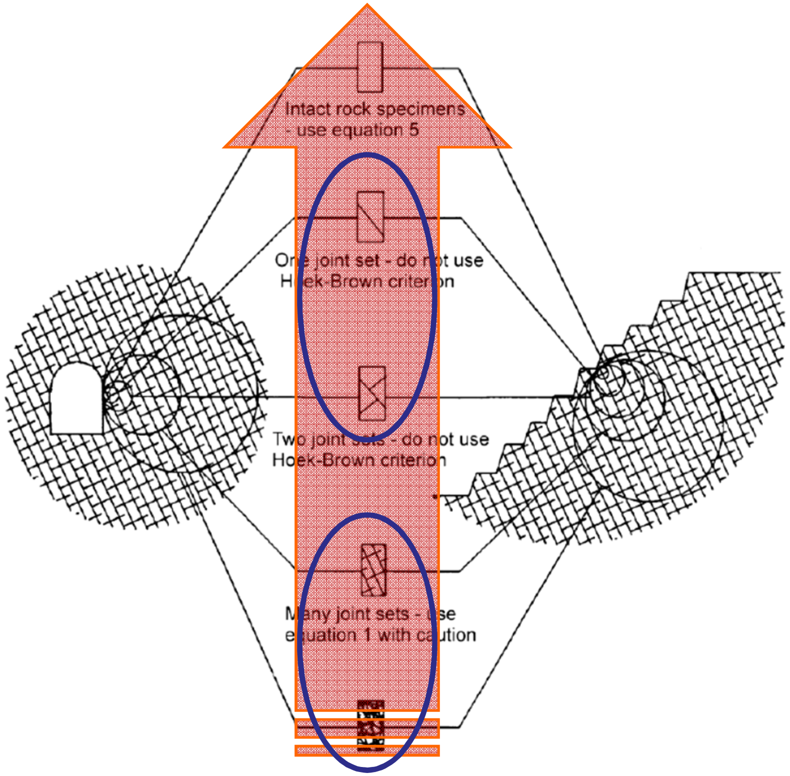
Pedram BEMANI YAZDI

Directeur de thèse: Ahmad POUYA

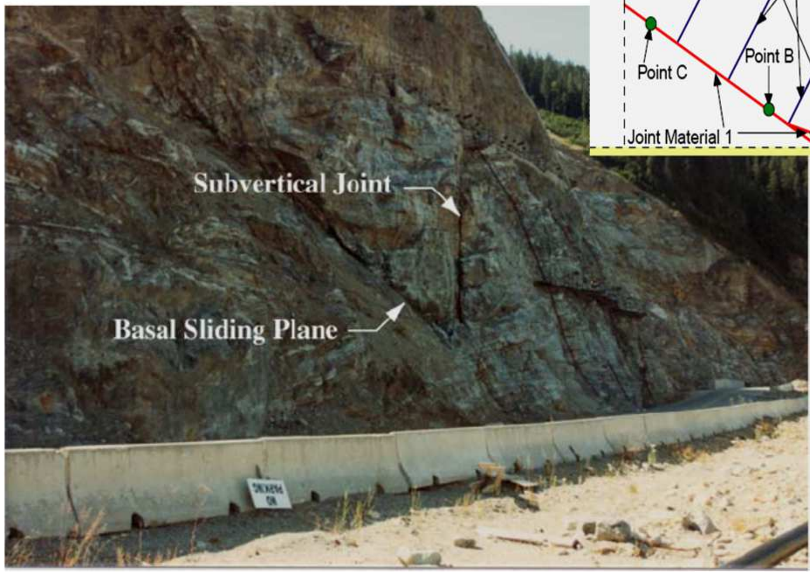
CFMR Paris - 3 décembre 2009

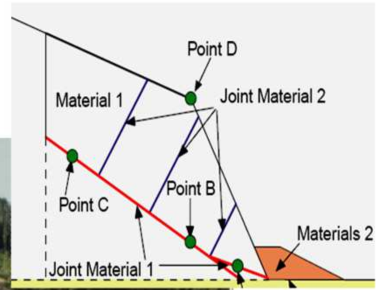
1. Les discontinuités dans les massifs rocheux

Modélisation explicite des discontinuités



Milieu continu équivalant (homogénéisation) ou Méthodes empiriques





E ,ν, φ, c $_{\text{équivalant}}$

2. Comportement mécanique des discontinuités

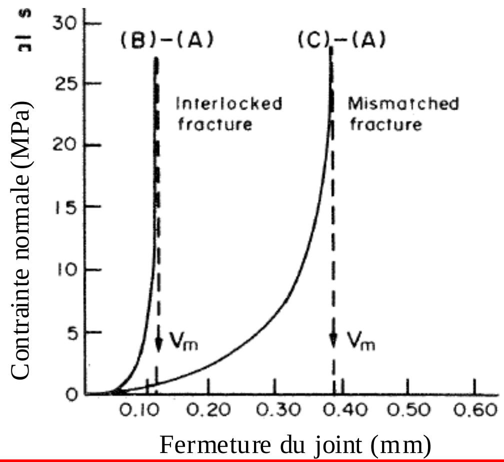
- **Chargement normal**

Goodman (1976) :

$$\frac{\sigma_n - \sigma_{n0}}{\sigma_{n0}} = C\left(\frac{u_n}{e - u_n}\right)^t$$

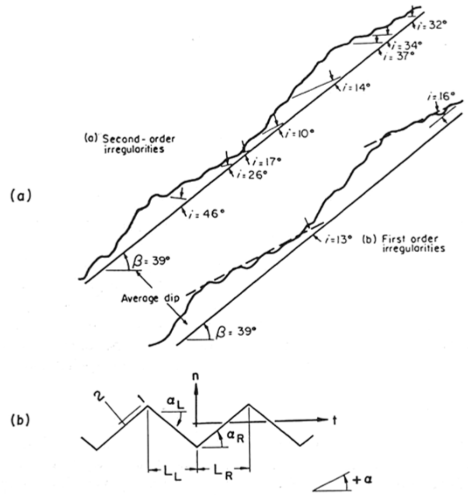
Bandis (1980) :

$$\sigma_n = \frac{u_n}{a - bu_n} = k_{n0}\left(\frac{u_n}{1 - u_n/e}\right)$$



- **Critères de la résistance au cisaillement**

Des aspérités



Critère de Mohr-Coulomb : $\tau_p = c + \sigma_n \tan\varphi$

Critère de Patton (1966) :

$$\begin{cases} \tau_p = \sigma_n \tan(\varphi_b + i) & (\sigma_n < \sigma_T) \\ \tau_p = \sigma_n \tan\varphi_r + C_a & (\sigma_n \geq \sigma_T) \end{cases}$$

Amadei et Saeb (1990) :

$$\tau_p = \sigma_n(1 - a_s)\tan(\varphi_b + i) + a_s\tau_{ca}$$

Critère de Barton (1971) :

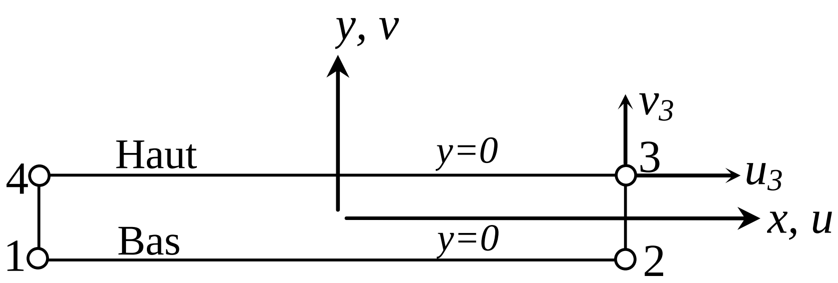
$$\tau_p = \sigma_n \tan\left[JRC \log_{10}\left(\frac{JCS}{\sigma_n}\right) + \varphi_b\right]$$

2. Comportement mécanique des discontinuités

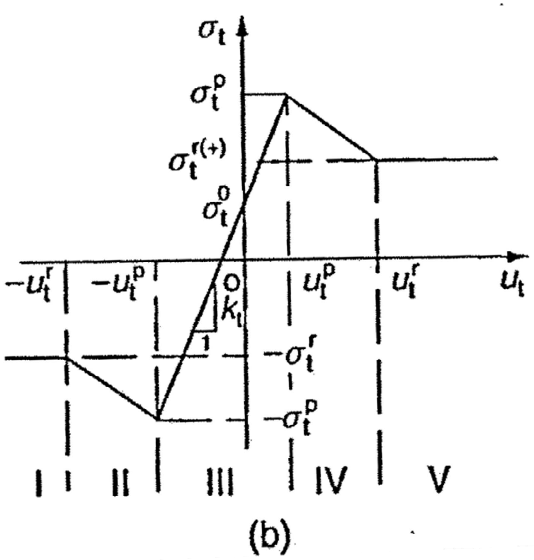
- **Modèles constitutifs pour les joints rocheux**

Eléments joints d'épaisseur nulle de Goodman (Goodman et al., 1968) :

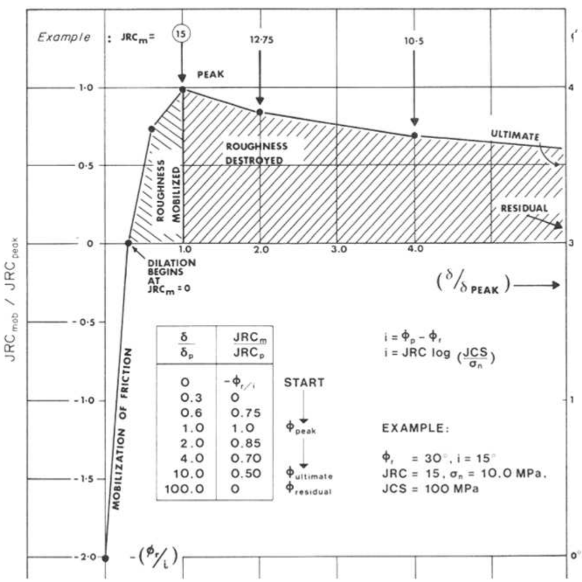
$$\begin{bmatrix} \tau \\ \sigma_n \end{bmatrix} = \begin{bmatrix} k_t & 0 \\ 0 & k_n \end{bmatrix} \begin{bmatrix} u_t \\ u_n \end{bmatrix}$$



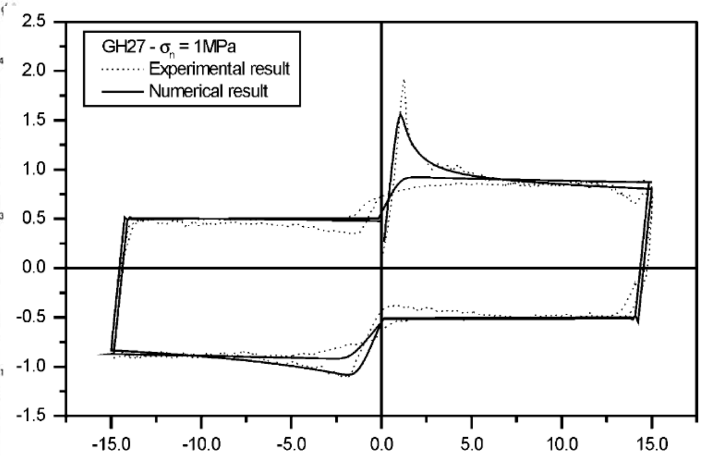
Goodman (1976) :



Barton-Bandis (1977-85) :



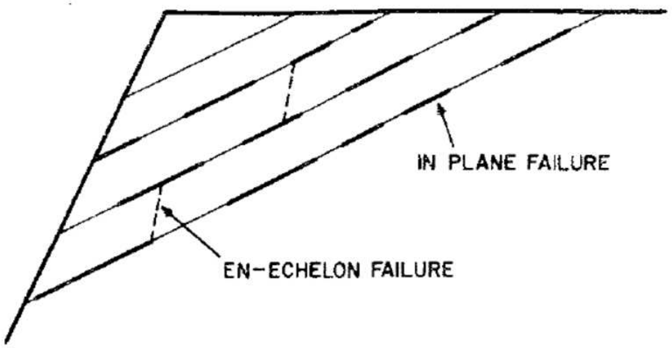
Plesha (1987), Lee et al. (2001) :



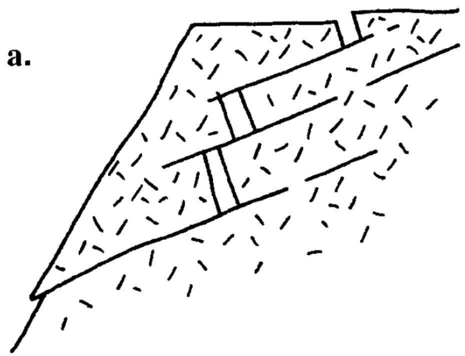
3. Un nouveau modèle endommagement-plastique pour discontinuités

- **Rupture fragile par fissuration/endommagement**

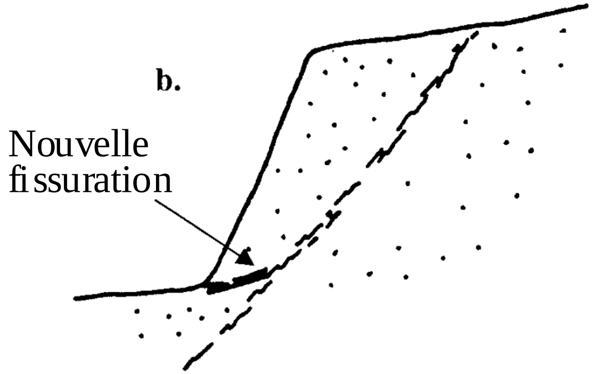
Rupture en plan et rupture en échelon à travers des **discontinuités non persistantes** dans un problème de stabilité des massifs rocheux (Einstein et al., 1983) :



Rupture par fissuration de la roche (Goodman et Kieffer, 2000) :

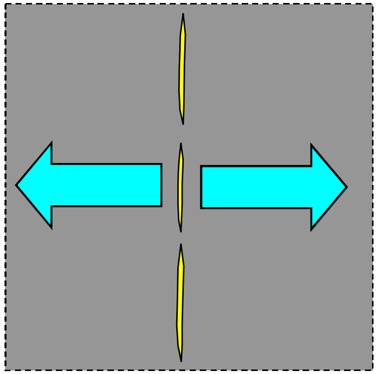


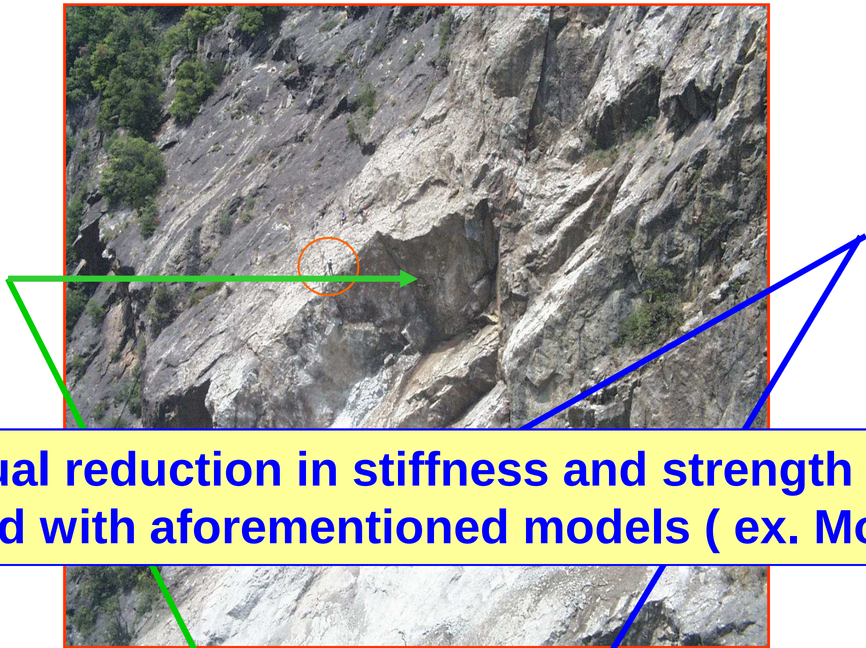
Fissuration **des ponts rocheux** sous traction

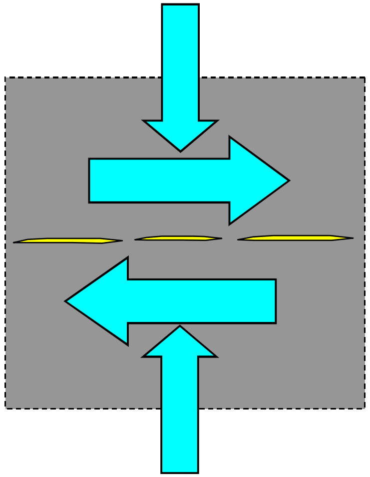


Rupture **des ponts rocheux** en cisaillement sous compression

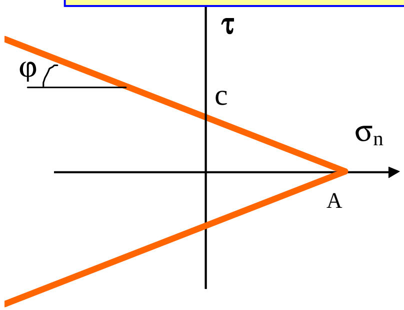
Damage in rock joints containing rock bridges or cemented contacts under different loading conditions

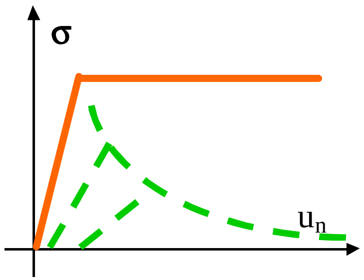


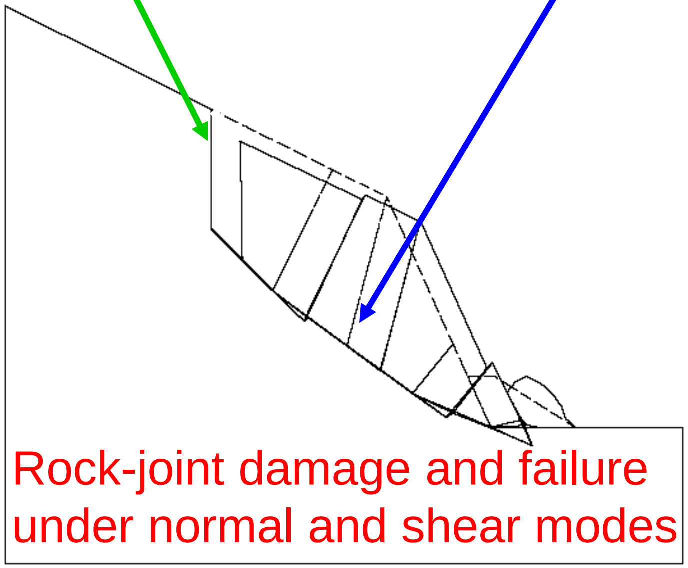


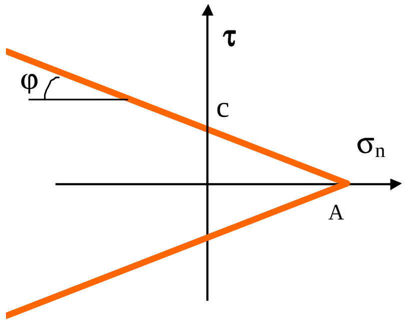


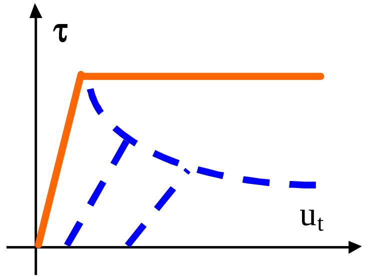
Damage, gradual reduction in stiffness and strength parameters not represented with aforementioned models (ex. Mohr-Coulomb)



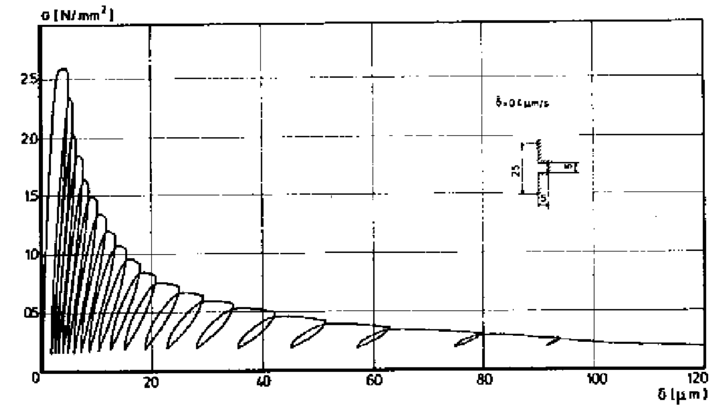




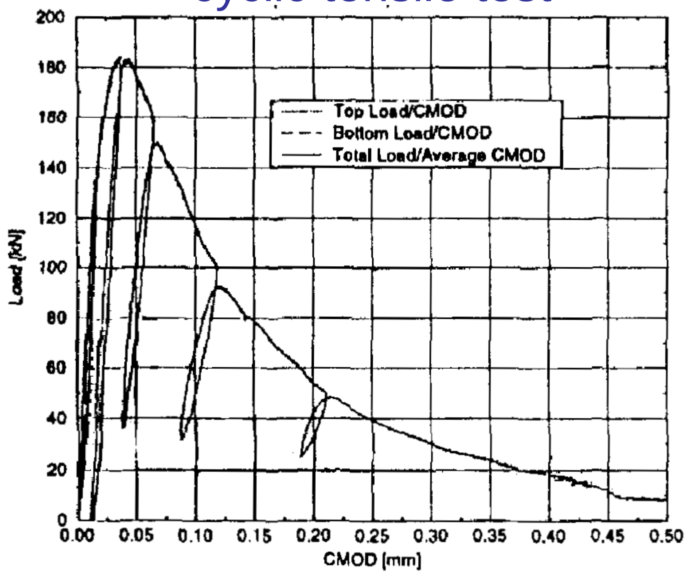




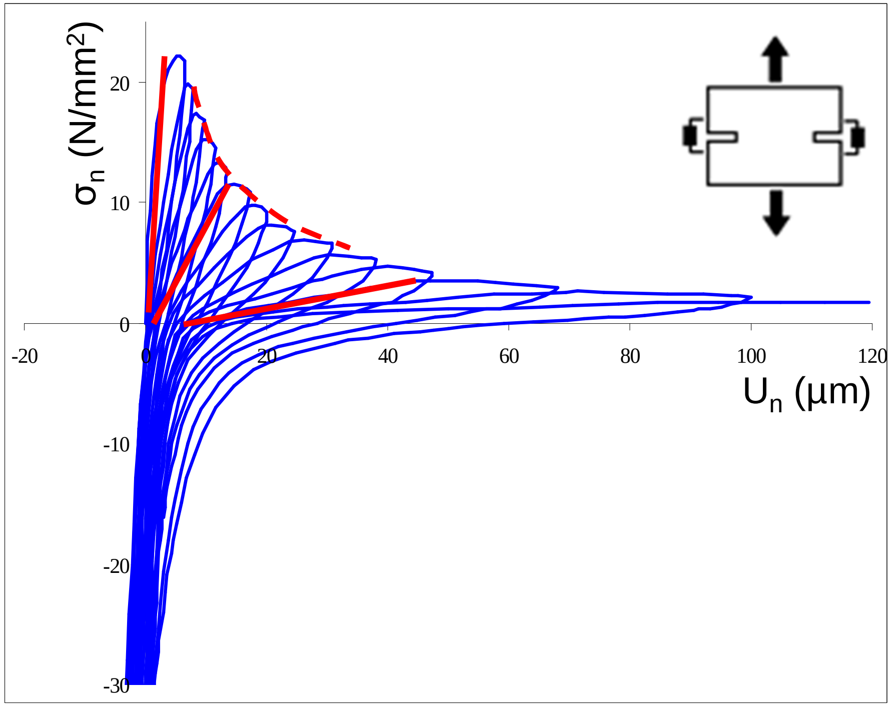
Damage under cyclic loading : experimental results



cyclic tensile test[1]



Large scale cyclic tensile test [2]



Stress - relative displacement curve under cyclic tensile-compression test[1]

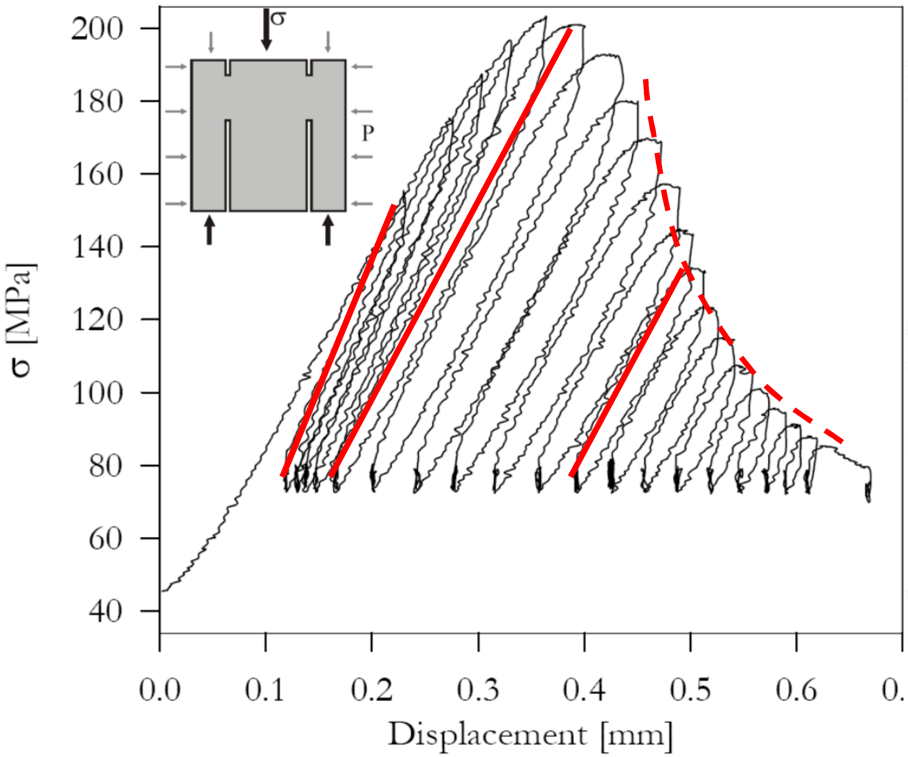
- Decrease of the tensile strength
- Decrease of the stiffness to zero
- Irreversible plastic displacement

[2] Slowik et al. (1996)

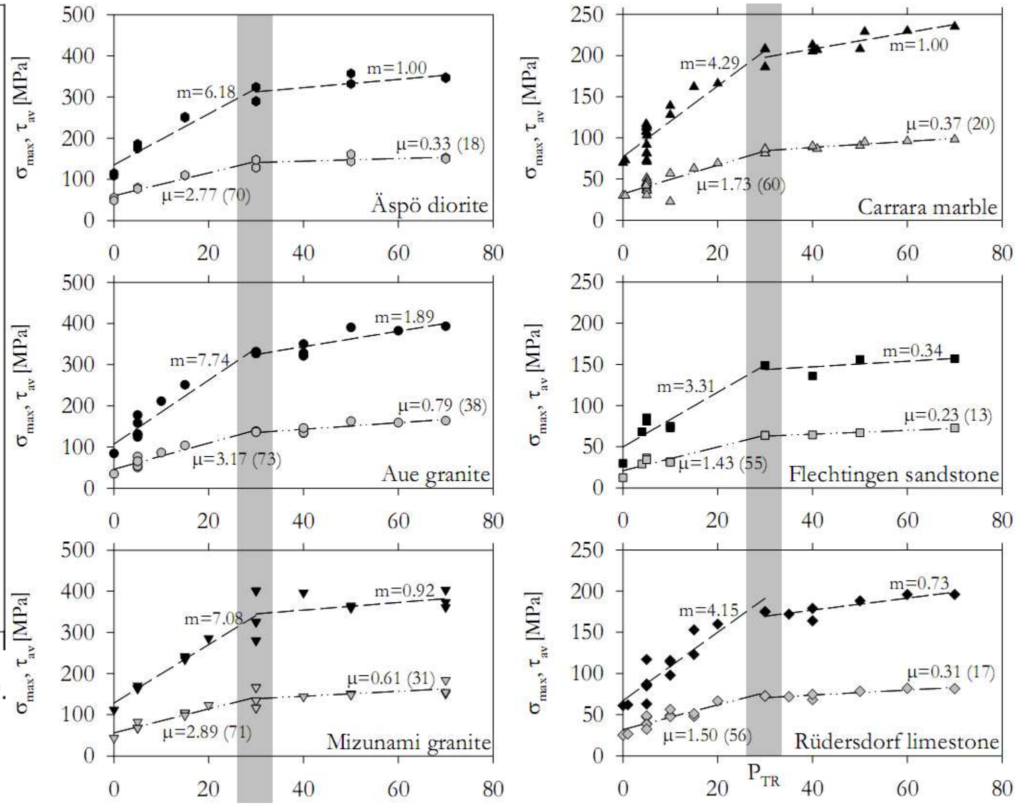
[1] Reinhardt, H.W. and Cornelissen, H.A.W. (1984)

3. Un nouveau modèle endommagement-plastique pour discontinuités

Backers (2005) :



Cyclic shear loading of Carrara marble sample at P= 40 MPa



Résistance au cisaillement en fonction de la contrainte de confinement – différents types de roche

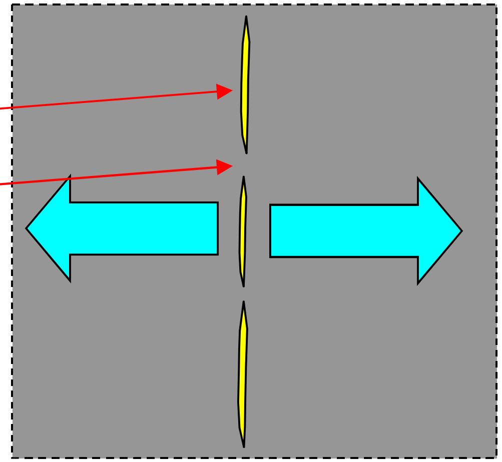
- Decrease of the cohesive strength & stiffness
- Residual stiffness
- Irreversible plastic displacement

Damage theory used to define joint damage process

Joint surface :

Fracture zones

Rock-bridges



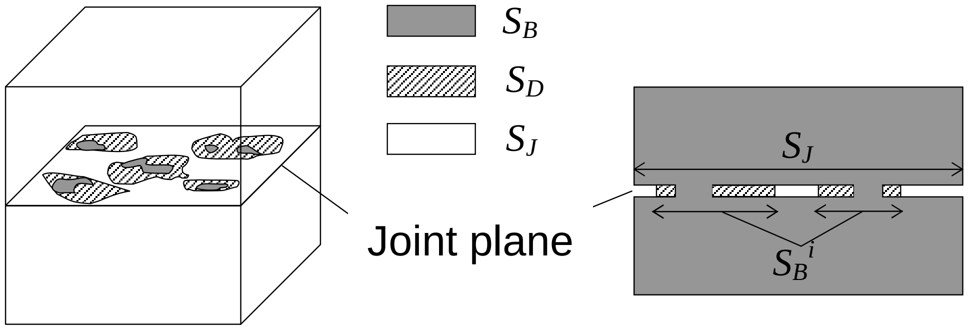
Damage process in the joint surface consists in gradual breakage of rock-bridges or gradual development of fractures into the rock bridges

Rock bridges → Fracture zones

Current damaged surface of rock bridges

Damage variable : $$D = \frac{S_D}{S_B{}^i}$$

Initial surface of rock bridges correspond to intact joint

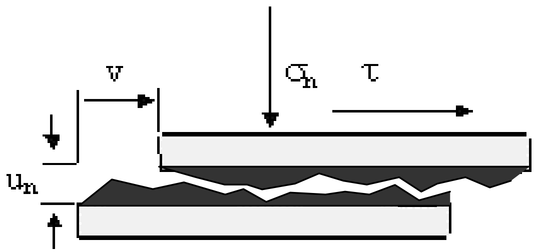


$$\begin{cases} D = 0 \text{ Intact} \\ D = 1 \text{ Damaged} \end{cases}$$

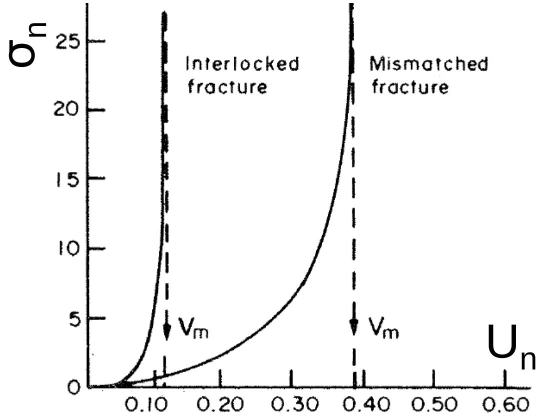
$$\begin{cases} \sigma_n = (1 - D) k_{nn} u_n \\ \tau = (1 - D) k_{tt} u_t \end{cases}$$

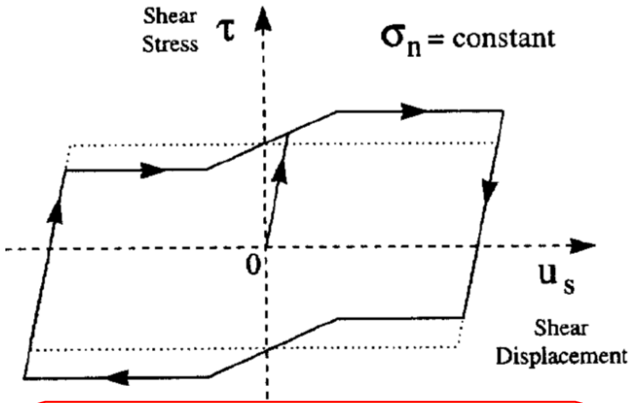
Totally damaged joint = Fracture

For a fracture,
we have:



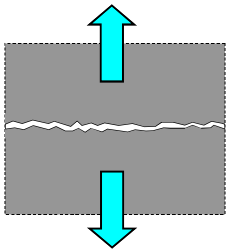
typical curves of a joint wall's normal and shear stress-relative displacement





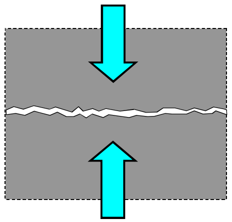
zero normal stiffness under **tensile stresses**

$$\sigma_n = (1-D)k_{nn}u_n$$



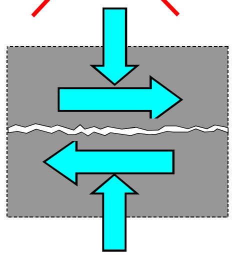
non zero normal stiffness under **compression**

$$\sigma_n = (1-D)k_{nn}u_n$$

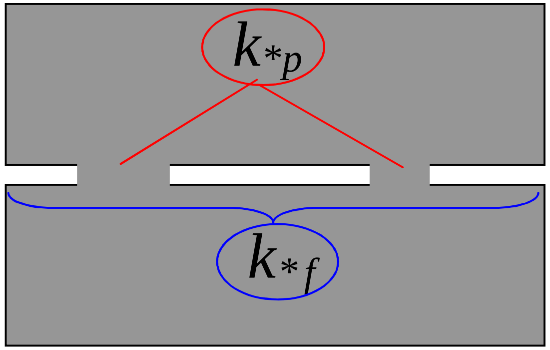


non zero tangent stiffness under **a normal stress**

$$\tau = (1-D)k_{tt}u_t$$



Normal Stiffness evolution with normal displacement



k_{np} , k_{tp} :
Normal and shear stiffness related to the rock bridges

k_{nf} , k_{tf} :
Normal and shear stiffness related to the joint walls

$$\sigma_n = (1-D)k_{np}u_n \qquad u_n \geq 0$$

$$\sigma_n = (1-D)\ k_{np}u_n - \frac{k_{nf}u_n^2}{e+u_n} \qquad u_n < 0$$

$$\tau = (1-D)k_{tp}u_t + k_{tf}u_t$$

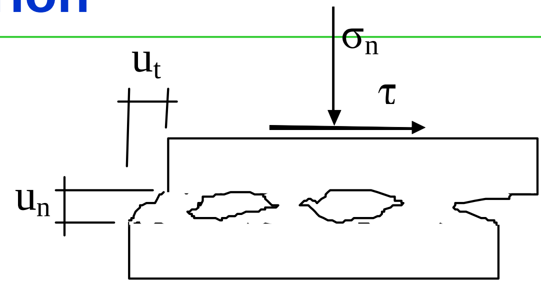
The terms related to rock bridges vanish after total damage (D=1)

The terms related to the joint walls are independent of damage

Damage-Plastic criterion

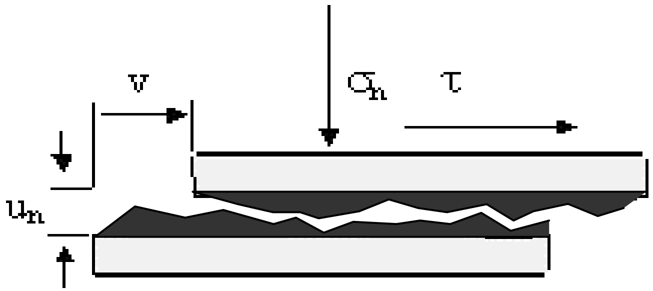
Non-damaged rock joint / Cemented interface (D =0) : Hyperbolic criterion

(Quadratic function of stress)



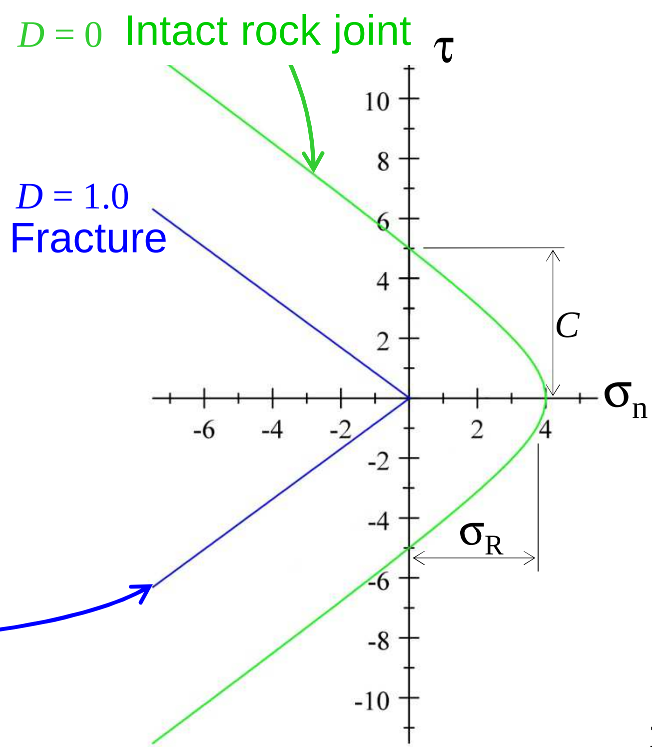
$$F(\tau,\sigma_n,D)=\tau^2-\sigma_n^2\tan^2\phi+2\sigma_0\sigma_n-C^2$$

$$s_0=\frac{C^2+s_R^2\tan^2 f}{2s_R}$$



Totally damaged joint (D = 1) :
Bilinear Mohr-Coulomb criterion

$$F(\tau,\sigma_n,D):\qquad \tau=\pm\sigma_n\tan\ \phi$$



Damage-Plastic criterion evolution

$$F(\tau,\sigma_n,D)=\tau^2-\sigma_n^2\tan^2\phi+2\sigma_0\sigma_n-C^2$$

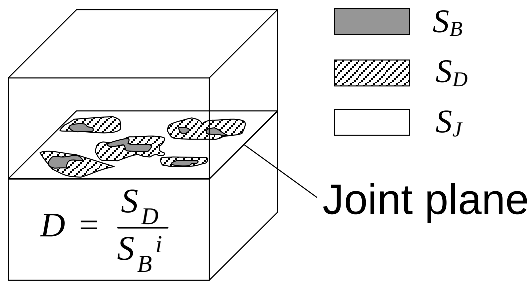
$$F(\tau,\sigma_n,D)=\tau^2-\sigma_n^2\tan^2\phi+2g(D)\sigma_0\sigma_n-g^2(D)C^2$$

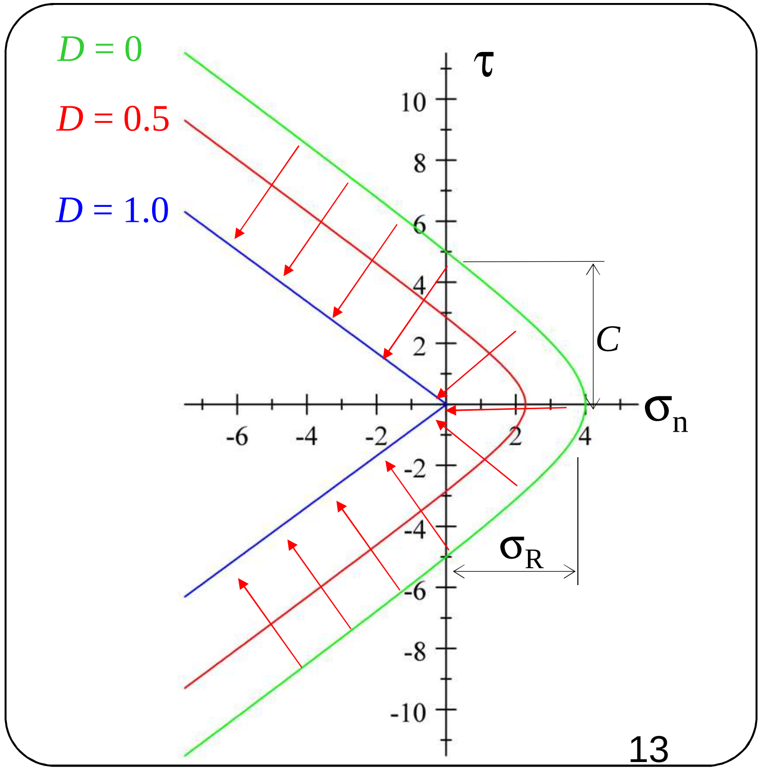
$$F(\tau,\sigma_n,D)=\tau\pm\sigma_n\tan\ \phi$$

" Damage Function " :

$$g(D)=(1-D)(1-\beta\ln(1-D))$$

$$\begin{cases} g(D)=1 & \text{for } D=0 \\ g(D)=0 & \text{for } D=1 \end{cases}$$





Damage and Plastic relative displacements

Each displacement increment is supposed to be composed of two parts: damage and plastic components

$$\begin{cases} du_n = du_n^e + du_n^p \\ du_t = du_t^e + du_t^p \end{cases}$$

Elastic-damage dD

$$\begin{cases} \tau = (1-D)\;\; k_{tp}u_t^e + k_{tf}u_t^e & \\ \sigma_n = (1-D)\;\; k_{np}u_n^e & u_n^e \geq 0 \\ \sigma_n = (1-D)\;\; k_{np}u_n^e - \dfrac{k_{nf}u_n^{e2}}{e+u_n^e} & u_n^e < 0 \end{cases}$$

$$e = e_0 + u_n^p$$

Plastic $d\lambda$

$$\begin{cases} du_t^p = d\lambda \dfrac{\partial G}{\partial \tau} \\ du_n^p = d\lambda \dfrac{\partial G}{\partial \sigma_n} \end{cases}$$

Plastic potential : $G(\tau, \sigma_n, D) = \tau^2 - \sigma_n^2 \tan^2 \psi + 2g(D)\sigma_s \sigma_n - g^2(D) C_s^2$

$$\sigma_s = \frac{C_s^2 + \sigma_R^2 \tan^2 \psi}{2\sigma_R}$$

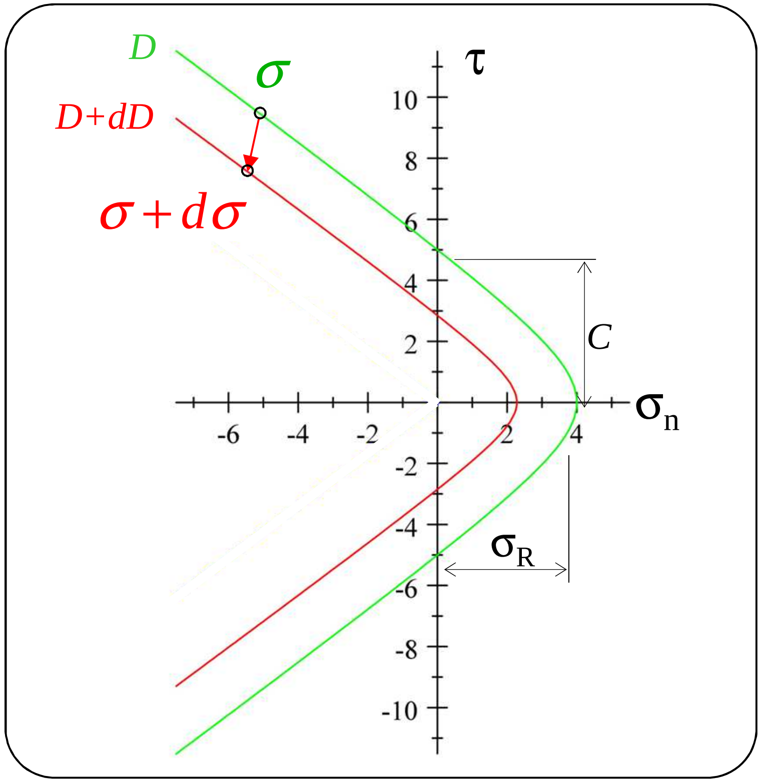
Damage Evolution and Plastic Displacement

Damage-plastic consistency condition :

$$F(\tau, \sigma_n, D) \quad \Rightarrow \quad dF = \frac{\partial F(\tau, \sigma_n, D)}{\partial \tau} d\tau + \frac{\partial F(\tau, \sigma_n, D)}{\partial \sigma_n} d\sigma_n + \frac{\partial F(\tau, \sigma_n, D)}{\partial D} dD = 0$$

Damage parameter increment as function of stress increments :

$$dD = \frac{\tau d\tau + \left(g(D)\,\sigma_0 - \sigma_n \tan^2\phi\right) d\sigma_n}{\left(\beta - \left(1 - \beta \ln(1-D)\right)\right)\left(g(D)\, C^2 - \sigma_0 \sigma_n\right)}$$



Two parts of displacement increments -damage and plastic components- are supposed to be related with

$$d\lambda = \frac{dD}{A(g(D))^m}$$

3. Un nouveau modèle endommagement-plastique pour discontinuités

- ### Choix des paramètres

Les paramètres de la résistance :

σ_R, C, φ

Les paramètres de la dilatance :

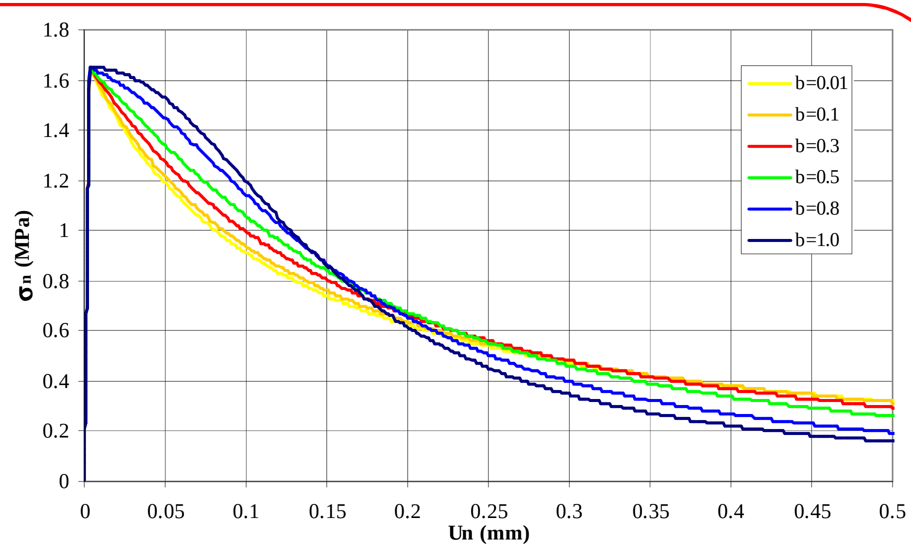
ψ, C_s

Les paramètres de raideurs :

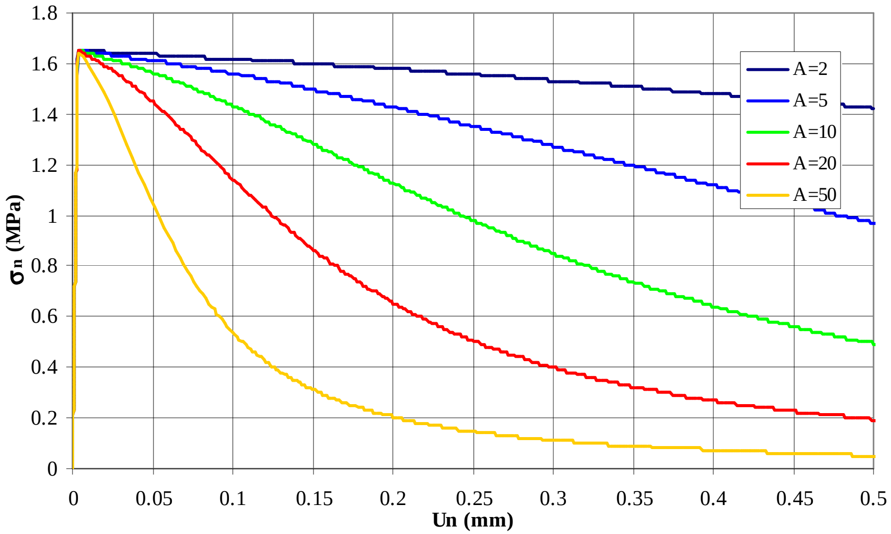
$k_{np}, k_{nf}, e_0, k_{tp}, k_{tf}$

Les paramètres de forme et couplage endo-plastique :

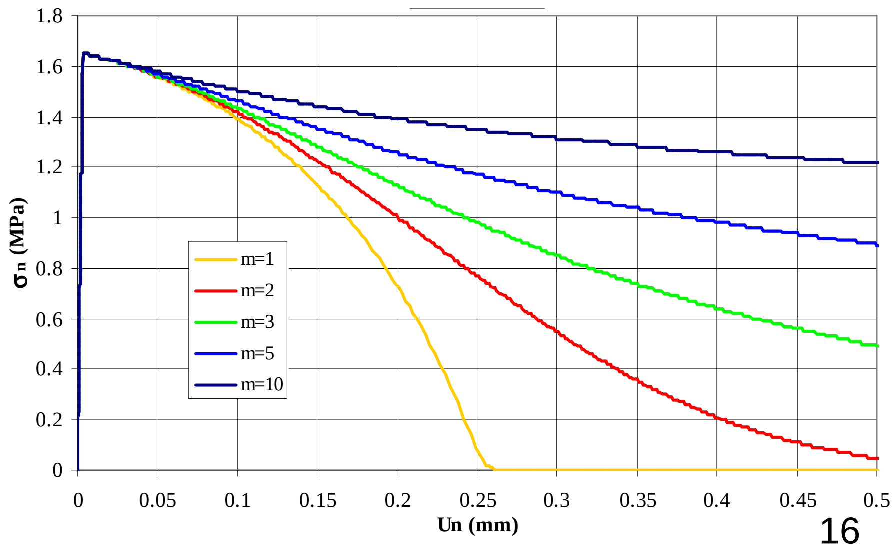
β, A, m



Effet du paramètre $\boldsymbol{\beta}$ avec A=20 MPa/mm et m=3

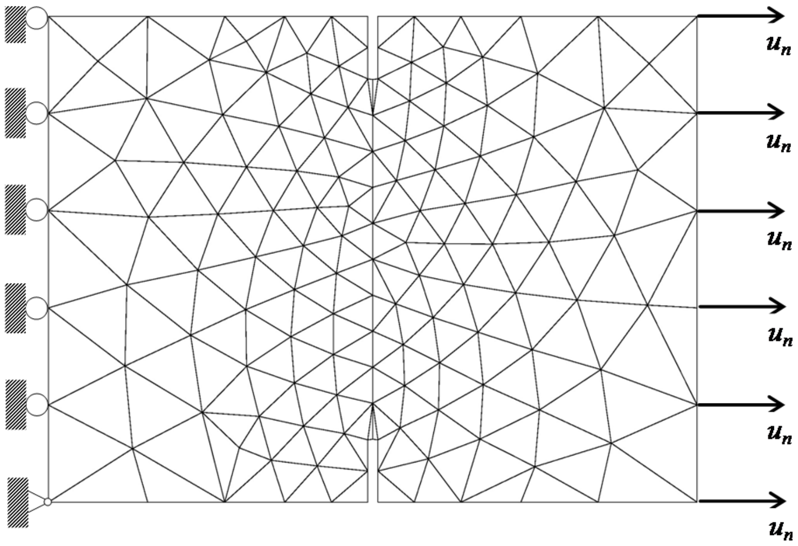


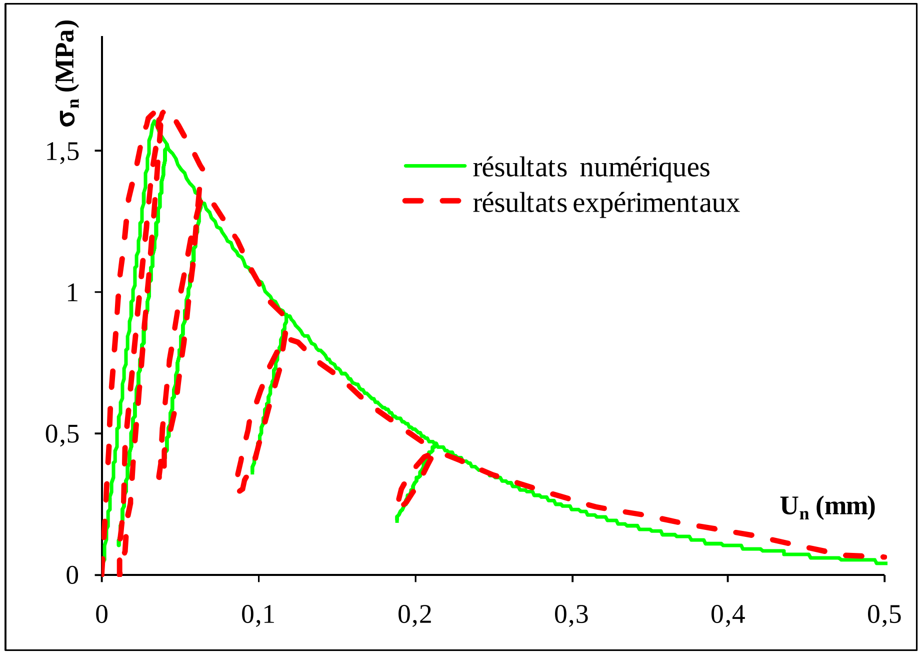
Effet du paramètre $\boldsymbol{A}$ avec avec β =0,8 et m=3



Effet du paramètre $\boldsymbol{m}$ avec β =0,8 et A =10 MPa/mm

Implementation in CESAR-LCPC FE Code and Comparison with Experimental Results

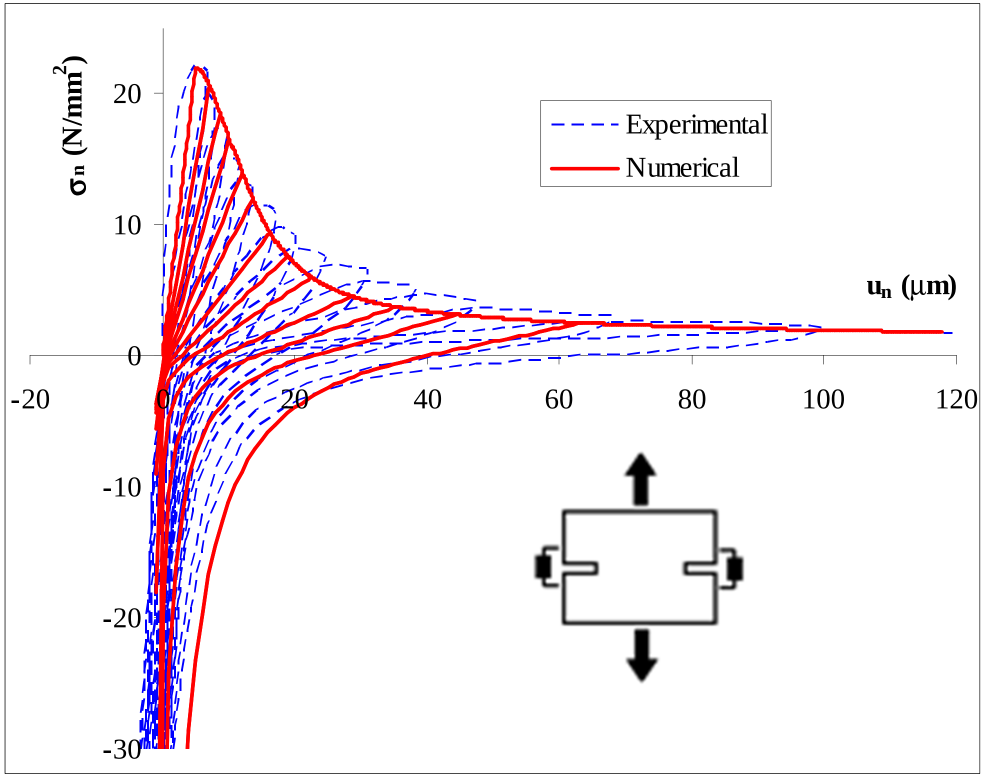




k_{np} (MPa/mm)	k_{nf} (MPa/mm)	e_0 (mm)	k_{tp} (MPa/mm)	k_{tf} (MPa/mm)	φ (°)	C (MPa)	σ_R (MPa)	ψ (°)	C_S (MPa)	β -	A (MPa/mm)	m -
50	10	0,05	4	16,8	45	2	1,65	10	2	0,2	20	2,1

Modélisation numérique contre les résultats expérimentaux de l'essai de traction directe à grande échelle de Slowik et al. (1996) sur le béton

Implementation in CESAR-LCPC FE Code and Comparison with Experimental Results

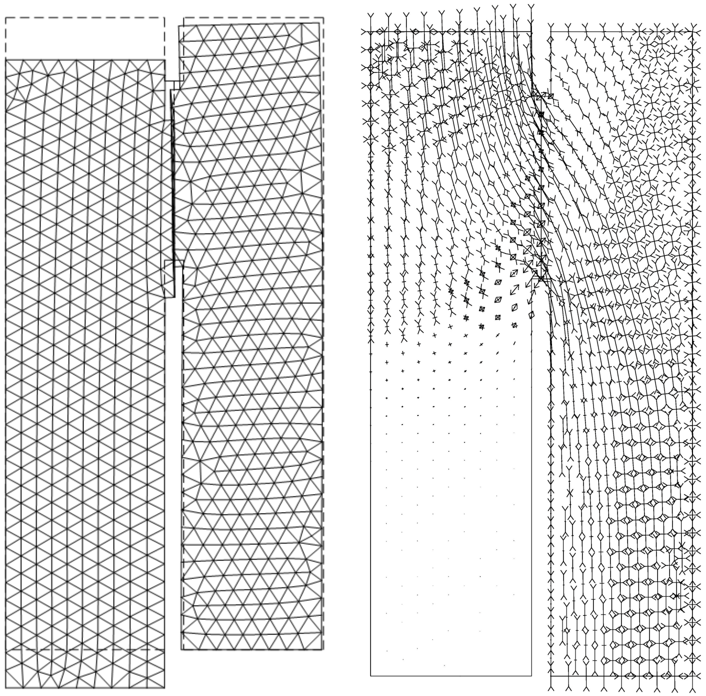


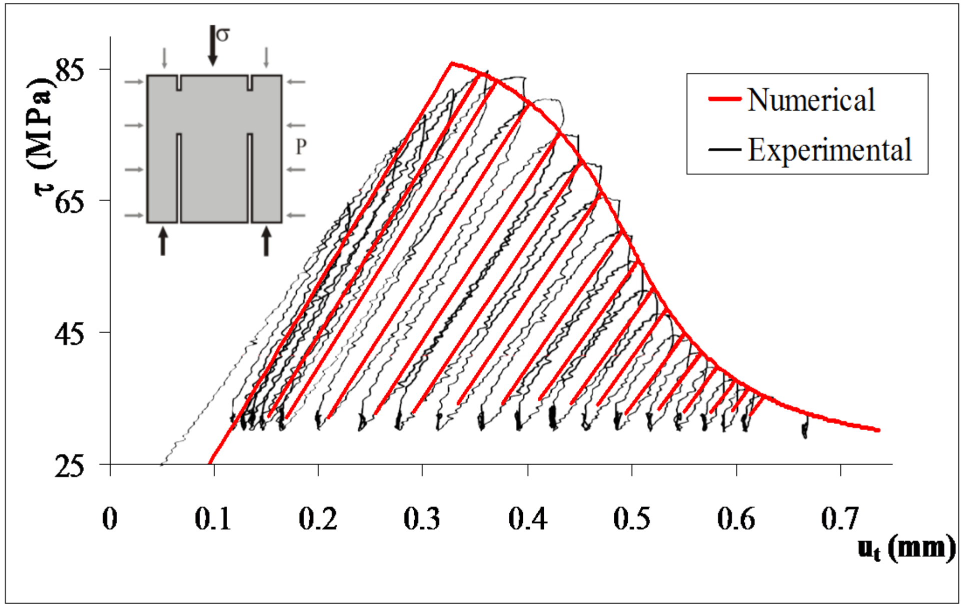
k_{np} (MPa/ mm)	k_{nf} (MPa/ mm)	e_0 (µm)	k_{tp} (MPa/ mm)	k_{tf} (MPa/ mm)	φ (°)	C (MPa)	σ_R (MPa)	ψ (°)	C_S (MPa)	β -	A (MPa/ mm)	m -
660	5	1,2	0	200	40	5,0	1,65	0	0,5	2,4	50	5

Reinhardt and Cornelissen's stress-relative displacement curve under cyclic tensile-compression test and the numerical results of damage-plastic model

Implementation in CESAR-LCPC FE Code and Comparison with Experimental Results

(a) (b)



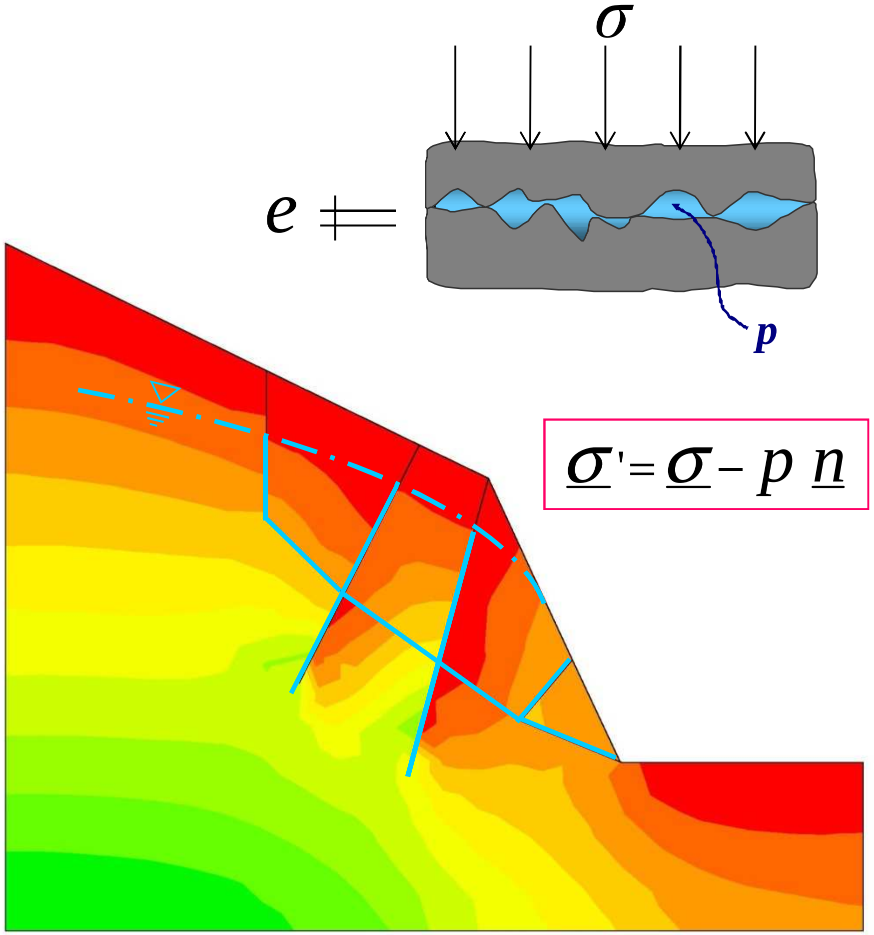


k_{np} (MPa/mm)	k_{nf} (MPa/mm)	e_0 (mm)	k_{tp} (MPa/mm)	k_{tf} (MPa/mm)	φ (°)	C (MPa)	σ_R (MPa)	ψ (°)	C_S (MPa)	β -	A (MPa/mm)	m -
640	23	0,15	52	210	50	37	3,5	12	12,8	0,5	1000	2.44

Cyclic shear test of Backers (2005) on Carrara marble sample compared to the numerical results of damage-plastic model

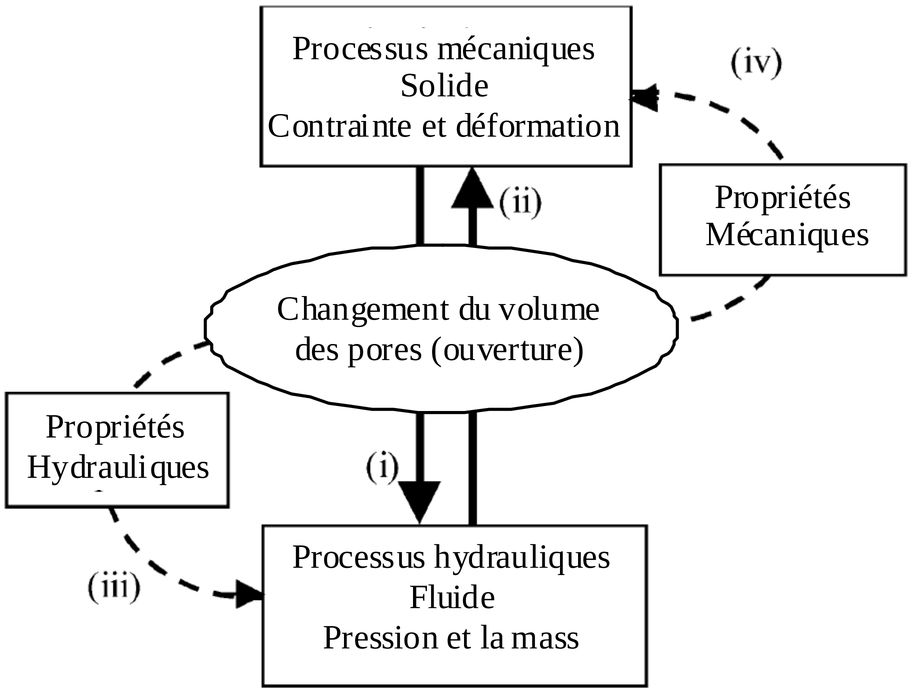
4. Couplage hydromécanique dans les massifs rocheux fracturés

La contrainte effective



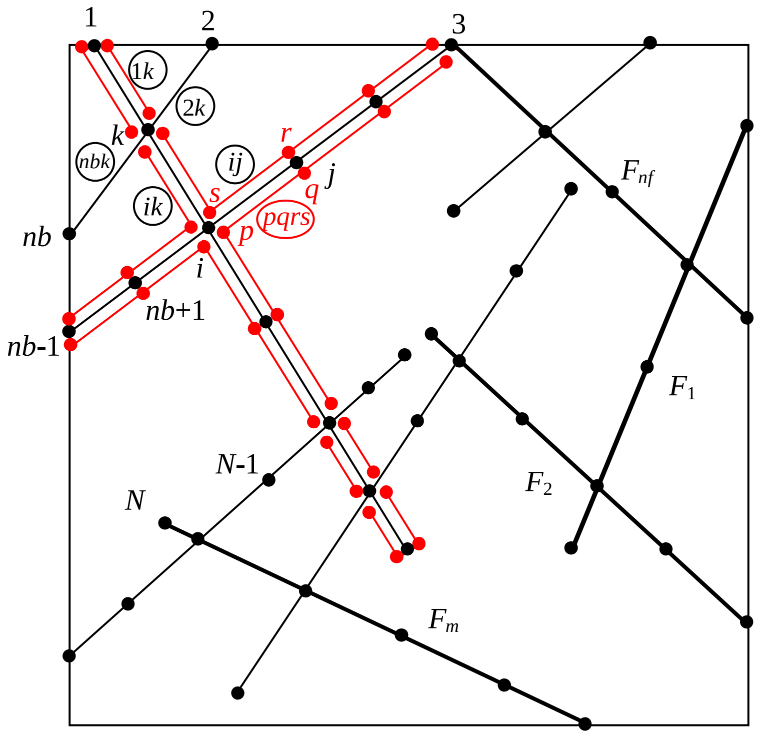
$$\underline{\sigma}' = \underline{\sigma} - p\,\underline{n}$$

Couplage hydromécanique directe et indirect



4. Couplage hydromécanique dans les massifs rocheux fracturés

- **Implémentation d'un module hydromécanique couplé dans CESAR-LCPC**

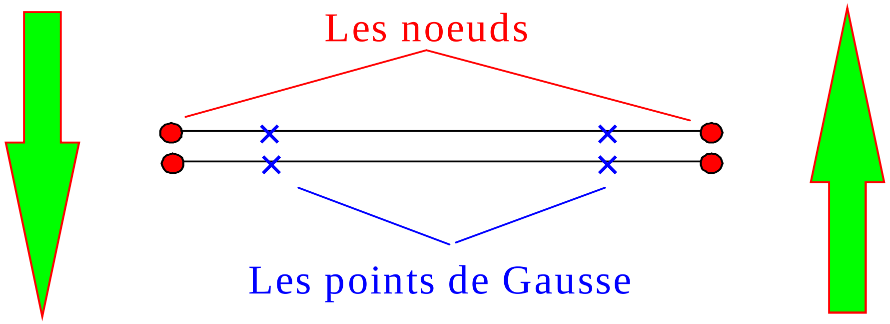


$$e_h = e_h^{\ i} + du_n \quad \text{avec} \quad e_h \geq e_{hr}$$

$$\begin{bmatrix} \tau \\ \sigma'_n \end{bmatrix} = \begin{bmatrix} k_t & 0 \\ 0 & k_n \end{bmatrix} \begin{bmatrix} u_t \\ u_n \end{bmatrix} - \alpha \begin{bmatrix} 0 \\ p \end{bmatrix}$$

Calhyd : $p_i\,(h_i)$

calcul des pressions dans les nœuds en fonction des condition hydrauliques aux limites et les ouvertures des joints (e_h)

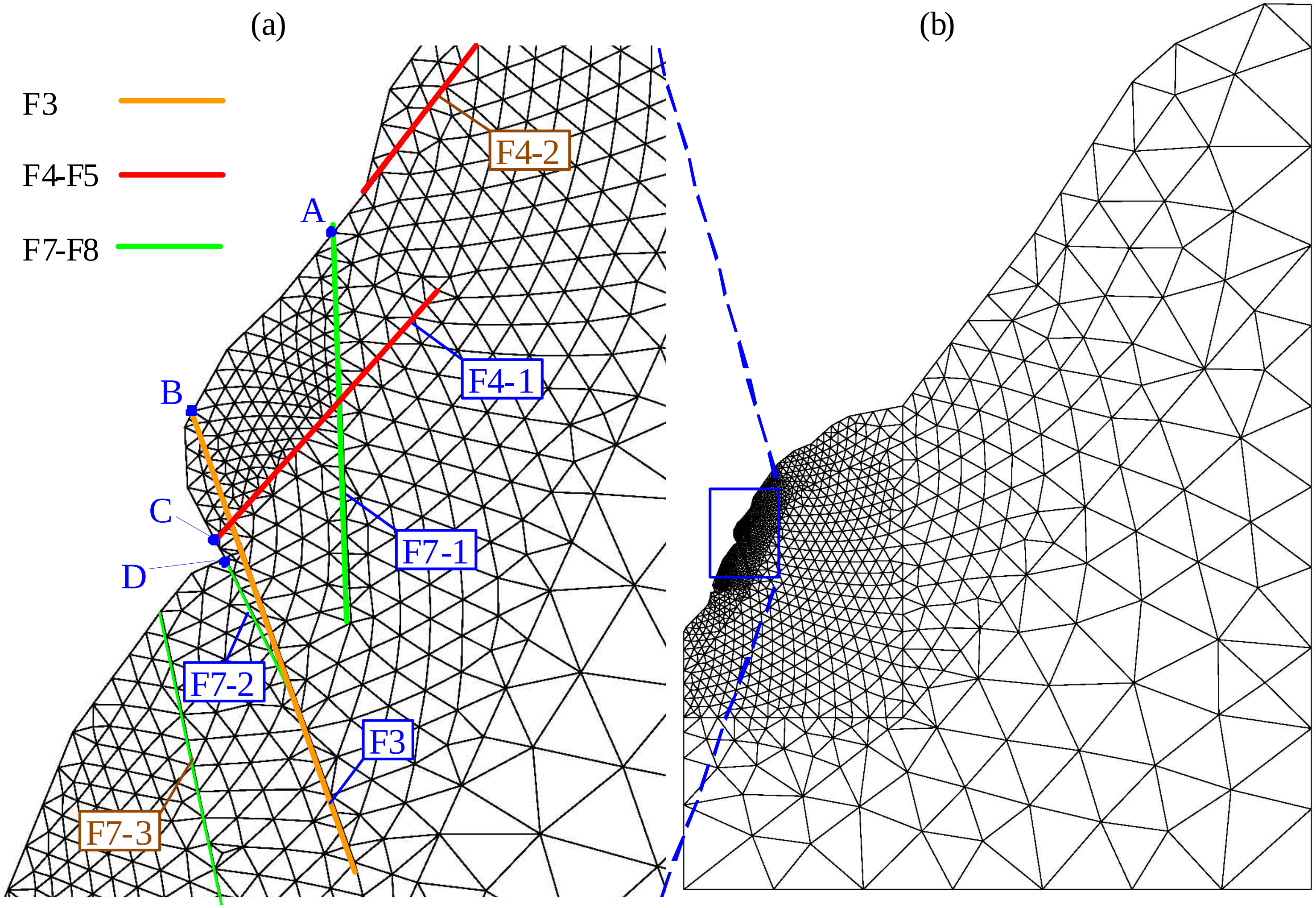


CESAR

calcul des ouvertures des joints en fonction des chargement mécaniques et les pressions dans les nœuds (p_i) : $e_m \rightarrow e_h$

5. Application à la modélisation de la stabilité des massifs rocheux

- **Modélisation de la stabilité des Rochers de Valabres (Projet ANR STABROCK coordonné par l'INERIS)**

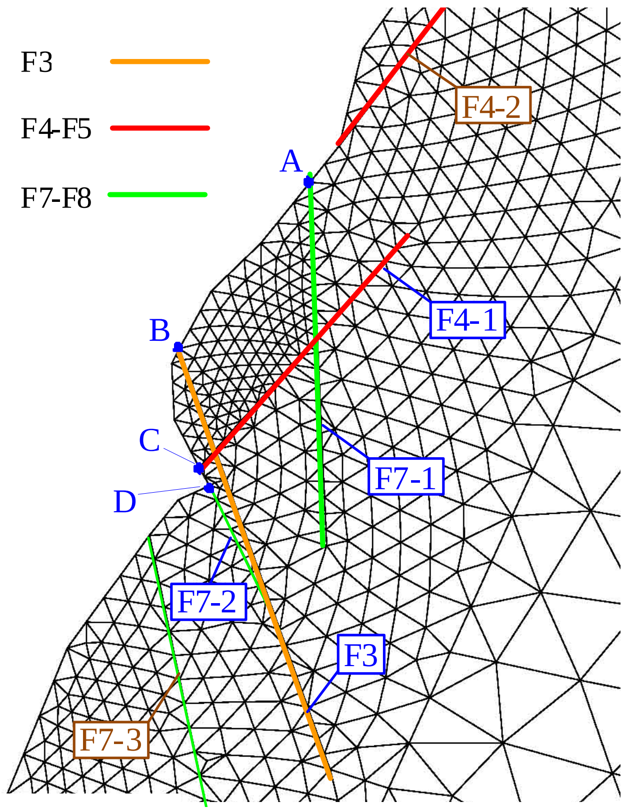


5. Application à la modélisation de la stabilité des massifs rocheux

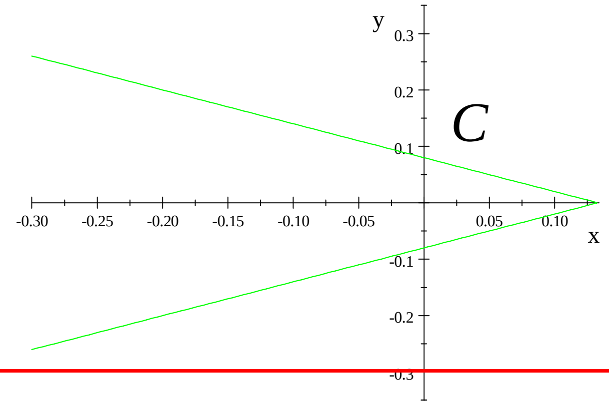
- **Modélisation de la stabilité des Rochers de Valabres (STABROCK)**

Modèle Mohr-Coulomb :

Familles de discontinuités	Paramètre	Valeur
Discontinuités subverticales (familles F3 et F7-F8)	k_n (MPa/mm)	1.0
	k_t (MPa/mm)	0.1
	C (MPa)	0.08
	ϕ_r (°)	31
	ψ_r (°)	5
Discontinuités de pendage vers la vallée (familles F4-F5)	k_n (MPa/mm)	0.8
	k_t (MPa/mm)	.08
	C (MPa)	0.04
	ϕ_r (°)	26
	ψ_r (°)	5



Modèle endo-plastique :

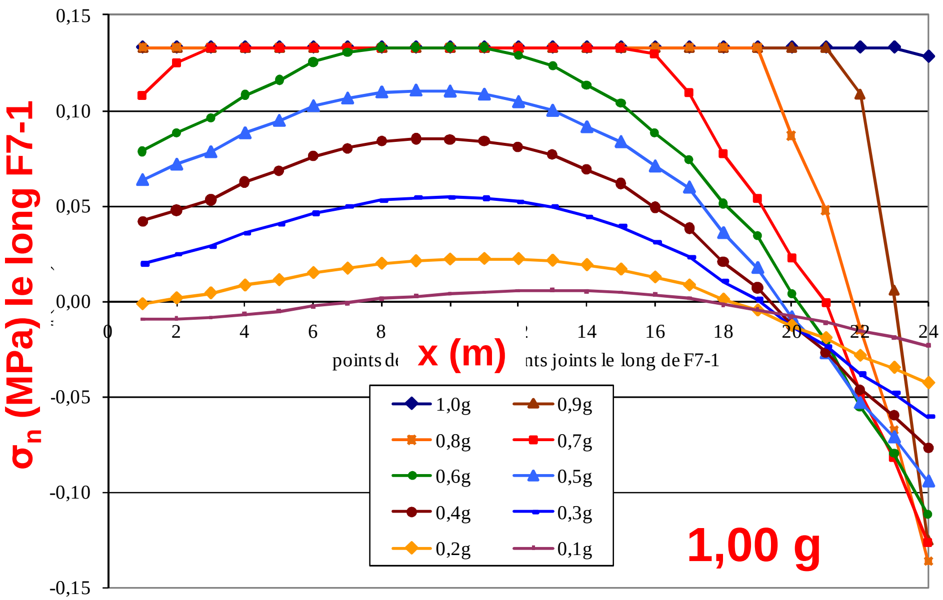


$$\sigma_R \approx \frac{C}{\tan\varphi}$$

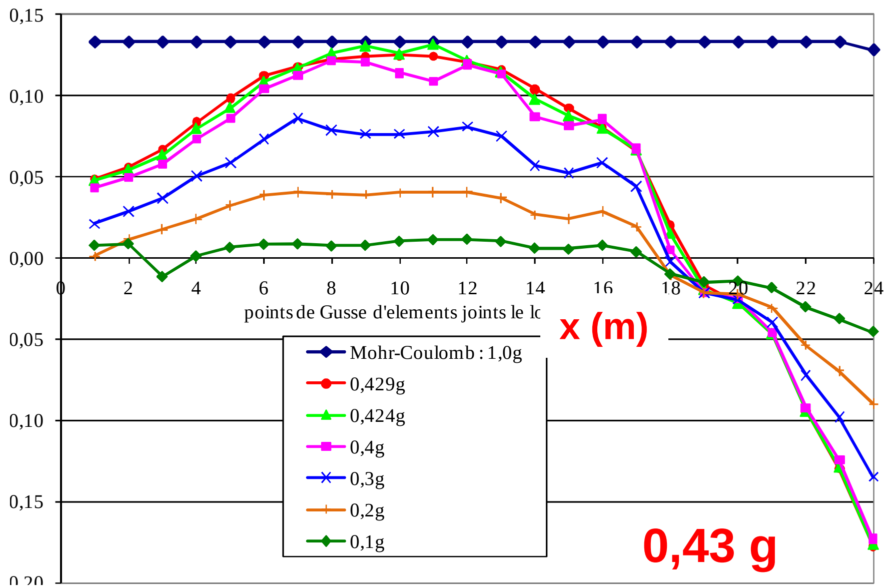
5. Application à la modélisation de la stabilité des massifs rocheux

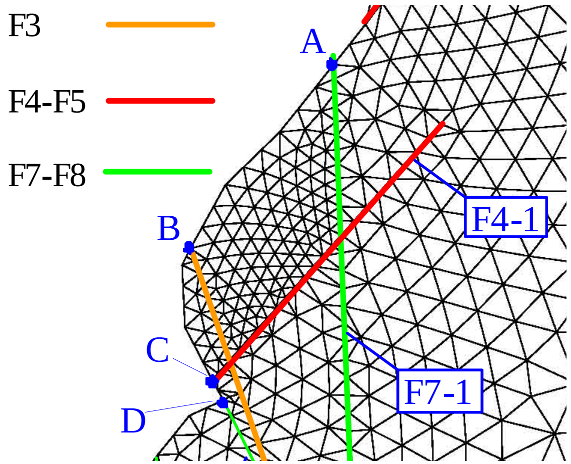
- **Modélisation de la stabilité des Rochers de Valabres (STABROCK)**

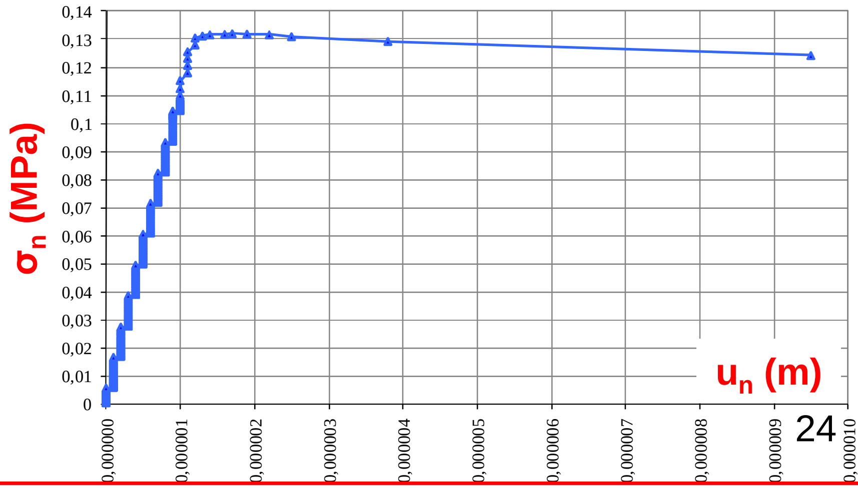
Modèle Mohr-Coulomb :



Modèle endo-plastique :



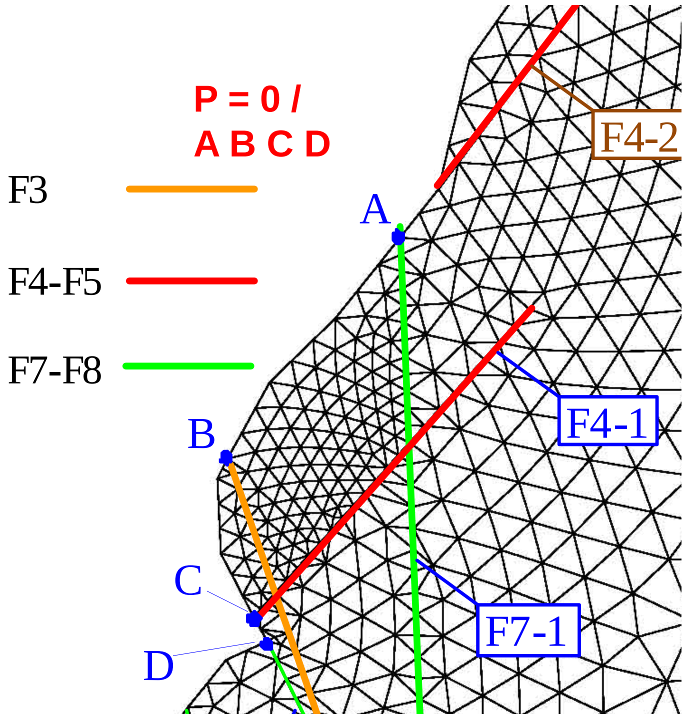




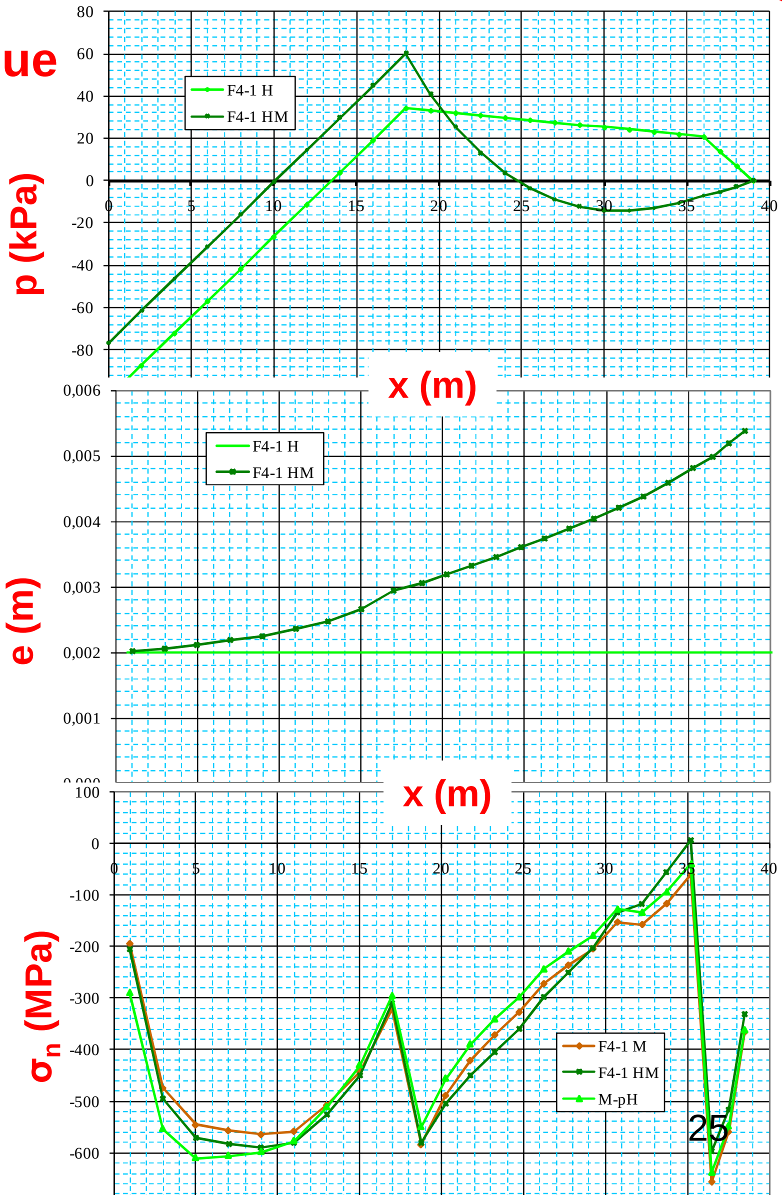
5. Application à la modélisation de la stabilité des massifs rocheux

- **Modélisation de la stabilité des Rochers de Valabres – effet de l'eau**

Prise en compte de couplage hydromécanique



Paramètre	Valeur
ρ (kg/m^3)	1000
g (m/s^2)	10
μ (Pa.s)	1
e_h^i (mm)	2
e_{hr} (mm)	0,2



6. conclusions

1. **Le modèle peut reproduire les aspects les plus importants du comportement des matériaux quasi-fragiles sous un chargement cyclique le long de la surface prédéfinie de fissuration en Modes I et II:**
    - **dégradation de la résistance et la raideur,**
    - **déplacement plastique,**
    - **résistance résiduelle au cisaillement**
    - **comportement non-linéaire sous chargement normale,**
2. **Un module de calcul hydromécanique a été développé sur la base des éléments finis constituant un réseau hydraulique**
3. **Application à la modélisation de la stabilité des Rochers de Valabres ont montré l'importance de prise en compte de phénomène de l'endommagement ainsi que le couplage hydromécanique lors de présence de l'eau**
4. **Le modèle endo-plastique est applicable à la modélisation du comportement des discontinuités non persistantes, des failles à grande échelle, de la fracturation hydraulique, au couplage hydromécanique dans les projets géothermiques, à la fissuration du béton, au comportement des ouvrages en maçonnerie etc.**