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**CAP TG3 Model III Needs: LCPC project on cracking  
in Pavement. RILEM TC-CAP annual meeting, Urbana  
Champaign (USA), October 10**

Armelle Chabot

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Armelle Chabot. CAP TG3 Model III Needs: LCPC project on cracking in Pavement. RILEM TC-CAP annual meeting, Urbana Champaign (USA), October 10. 2006. hal-00559922

**HAL Id: hal-00559922**

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Preprint submitted on 7 Mar 2020

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## CAP TG3 Model III Needs

# LCPC project on cracking in Pavement

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[www.lcpc.fr/msc](http://www.lcpc.fr/msc)

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## With the help of

JM Balay<sup>1</sup>, D. Bodin<sup>1</sup>, E. Chailleux<sup>1</sup>, P. Tamagny<sup>1</sup>,  
L. Wendling<sup>2</sup>,  
PhD<sup>1</sup>: Tran, Florence, Pérez, Pouteau, Lavigne, Chkir

 ATILH  
ASSOCIATION TECHNIQUE DE  
L'INDUSTRIE DES LIANTS HYDRAULIQUES



A. Ehlacher, C. Petit, G. Pijaudier-Cabot

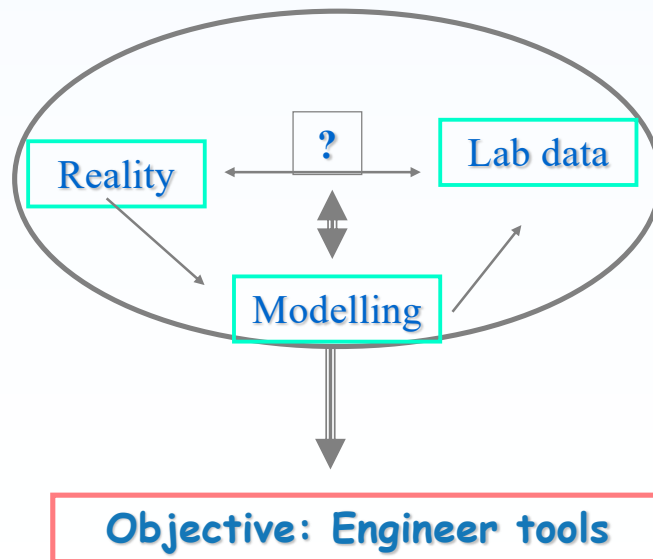


<sup>1</sup>Division for Pavement Structures and Materials

<sup>2</sup>Regional Laboratory of Autun

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# MOTIVATION



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# Reality...

## What kind of crack is expected?



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## RN4 in-situ testing for CRCP

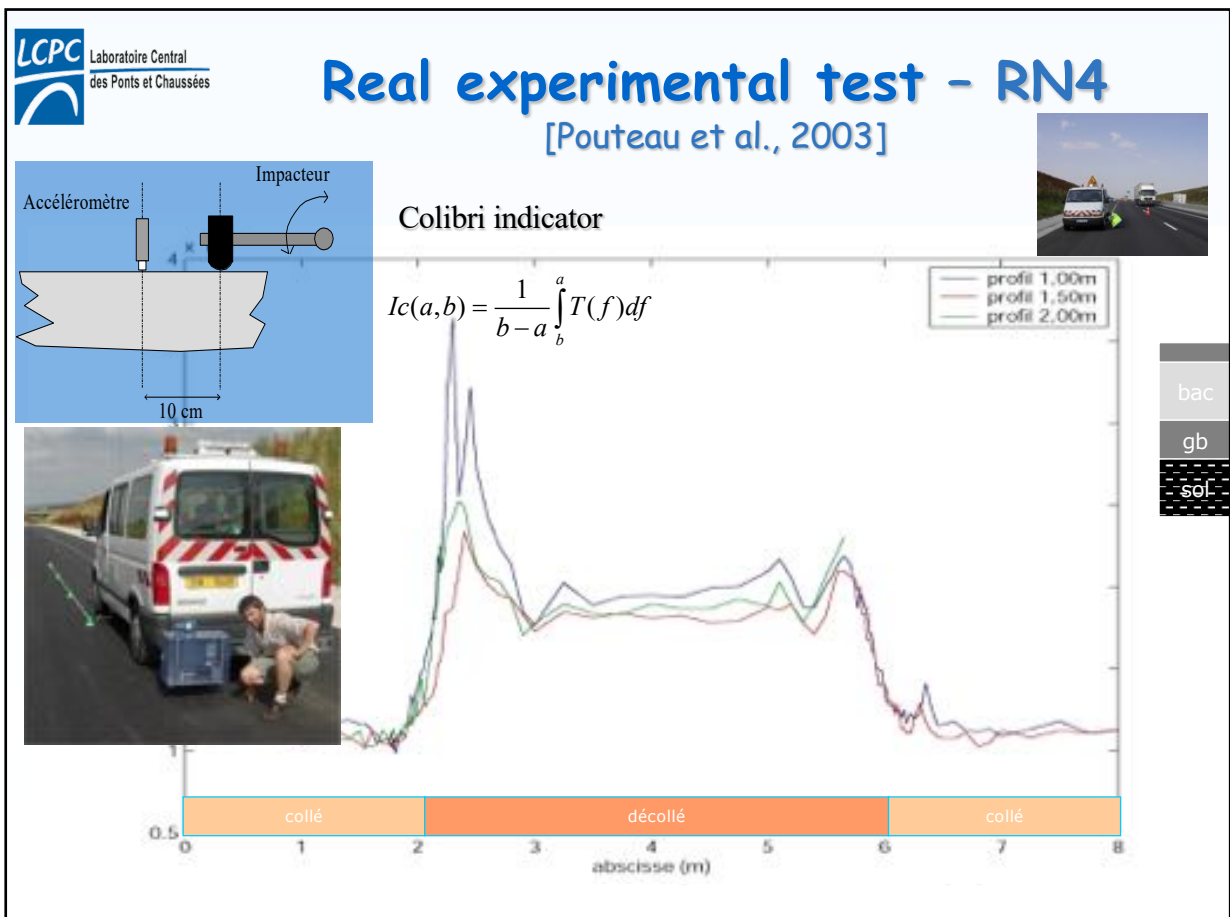


### Historique:

- Construction de la planche : 19 septembre 2001
- Première auscultation : fin octobre 2001
- Deuxième auscultation (avec BBTM) : juillet 2002
- Mise en circulation : 4 septembre 2002

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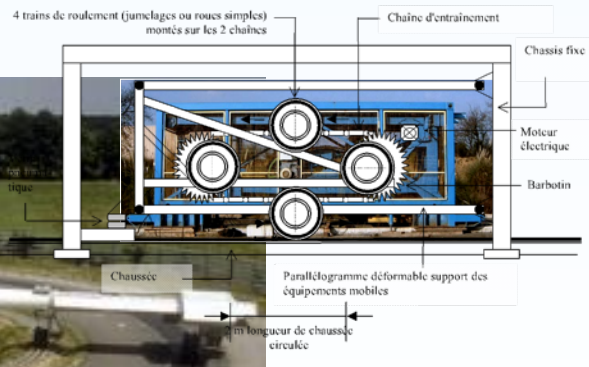
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# APT of LCPC-Nantes



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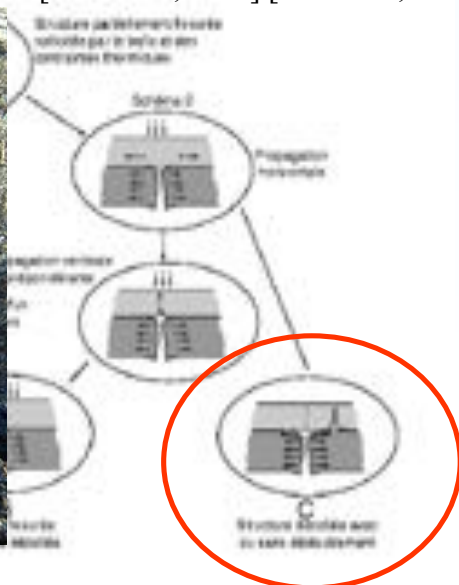
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# Bottom-up cracking?...

The ways it goes... (crack deviation angle?...)

[Marchand, 1984] [Goacolou, 1989]



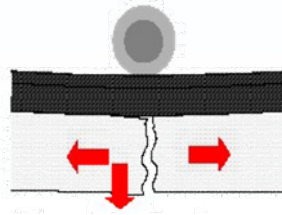
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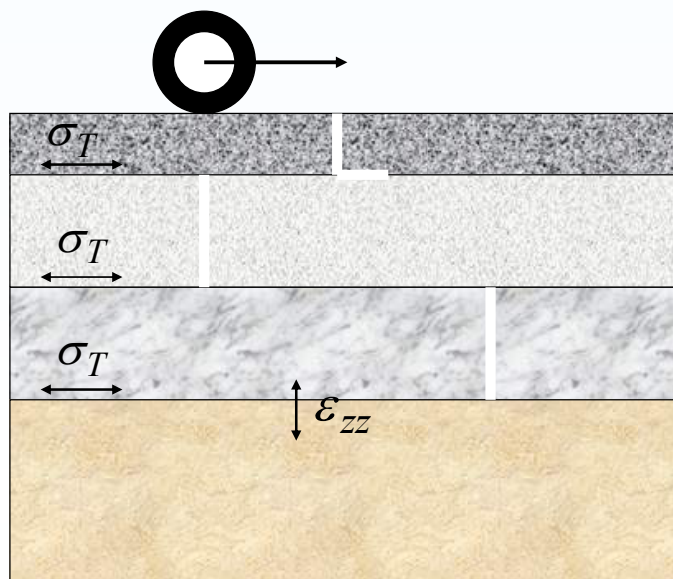
# Pavement modelling needs!



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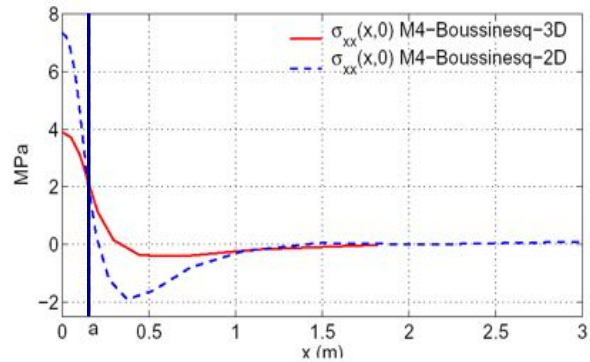
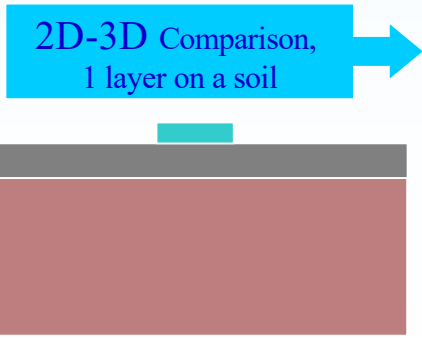
## Q1. Which Model? -> Tool for engineers:

- Evaluation of cracked pavements
- Design solution for rehabilitation



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## First response: Comparison between 2D and 3D modelling



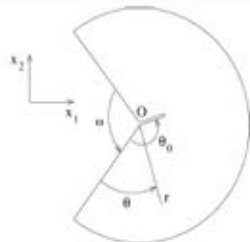
### 2D-3D ?

- differences of value
- differences of shape

→ needs 3D information

## Second question: Criteria ?

Homogeneous material



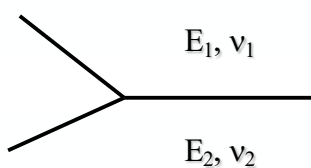
$$\bar{\sigma} = \frac{K_I}{\sqrt{r}} f_I(\theta) + \frac{K_{II}}{\sqrt{r}} f_{II}(\theta) + \dots \quad \left\{ \begin{array}{l} G(\bar{\sigma}, \bar{u}) = - \frac{\partial E_p(\bar{\sigma}, \bar{u}, a)}{\partial a} \\ G \leq G_{cr} \end{array} \right.$$

Nous ne pouvons pas afficher  $G_{cr}$ .

$$\underline{U}(x_1, x_2) = \underline{U}(O) + kr^\lambda \underline{u}(\theta) + \dots$$

The critical value  $k_c$  depends on the opening  $\omega$  of the notch, it must be experimentally determined. The factors  $k$  and  $k_c$  are strongly dependent of the singularity and in particular of the exponent  $\lambda$ . Units for

For bi- material, it is worst,  $\lambda$  can be a complexe field

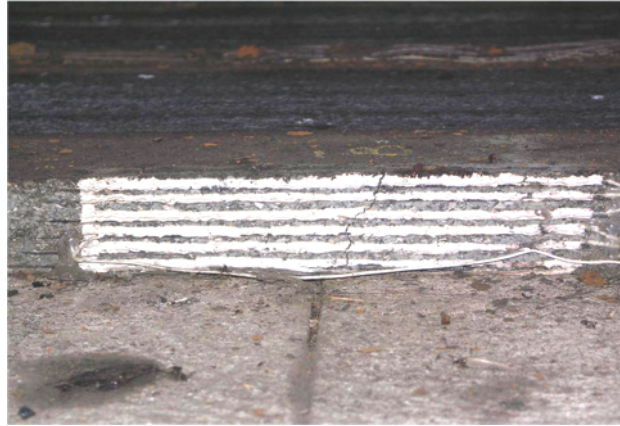
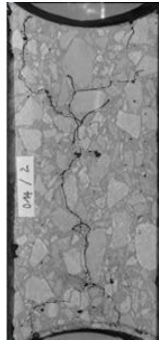
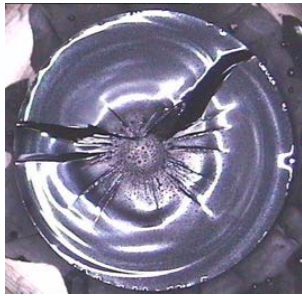


- ◆ Point stress?
- ◆ Average stress?
- ◆ Energy release rate -> fatigue...: Paris law?



# Lab data

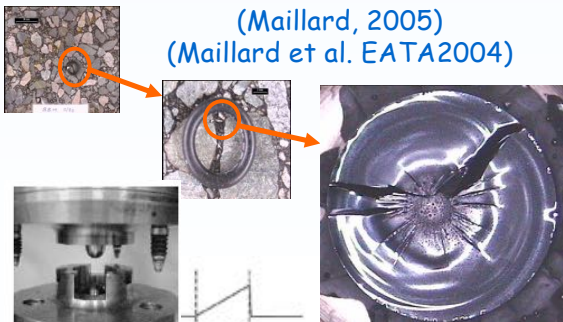
3 scales: bitumen, asphalt materials, structural -> interface data between materials



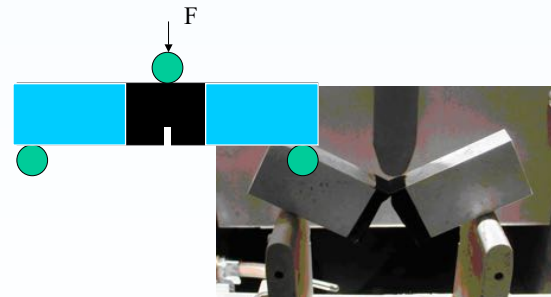
BB 0-14

# Investigations in different scales

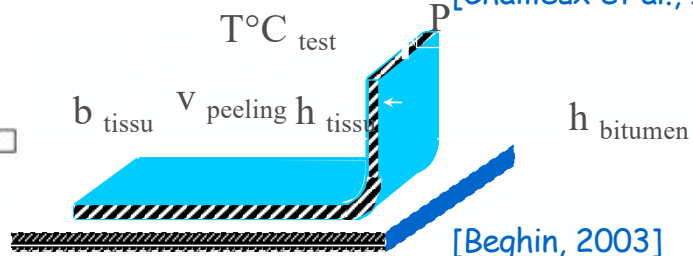
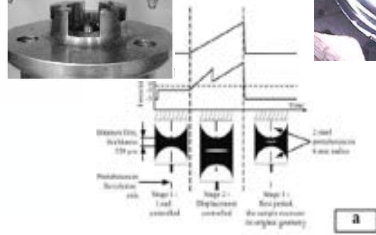
Bitumen E. Chailleux, De L. Roche, F. Hammoum,  
PhD: Maillard, Beghin, Nguyen, ....



(Maillard, 2005)  
(Maillard et al. EATA2004)



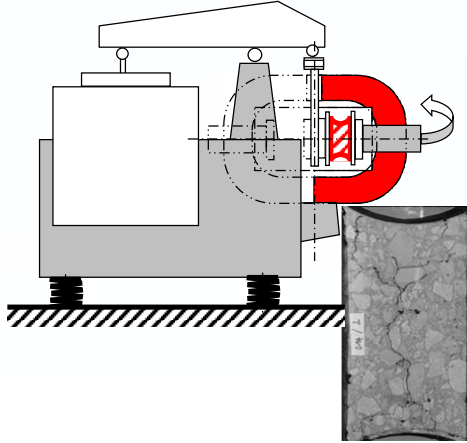
[Chailleux et al., ICAP2006]



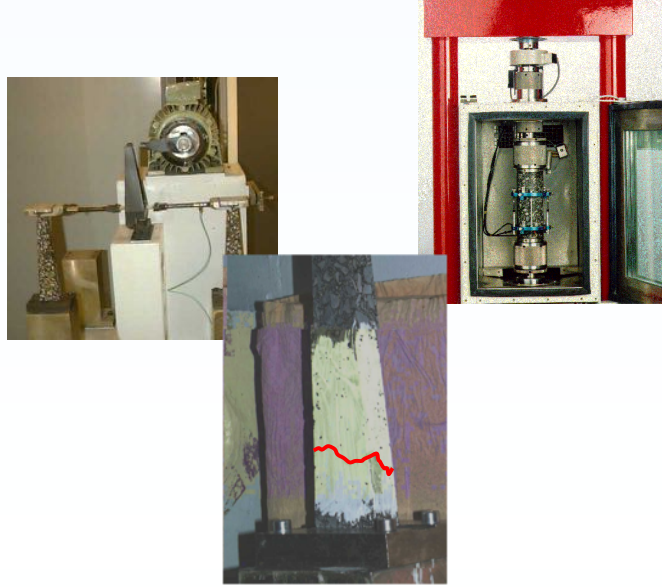
[Beghin, 2003]

## Investigations in different scales Asphalt material

(Bodin, 2002]



BB 0-14



(Bodin et al., ASCE/ JEM 2004)

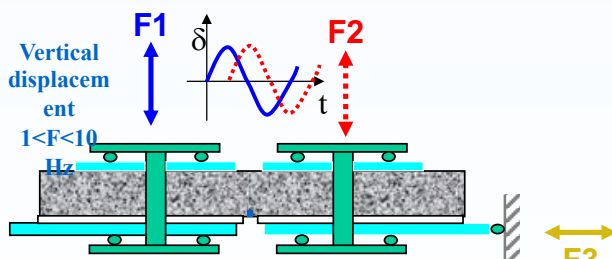
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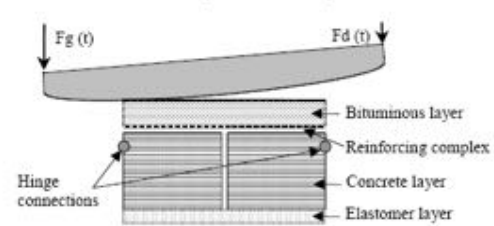
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## Investigations in different scales Asphalt material/Bi-material experiments



(Pérez et al., ICEFAII 2006)



(Florence et al., CP2004)

Mefisto device

ERA d'Autun L. Wendling



RILEM T



(Pouteau, 2004)

(Pouteau et al.,  
materiaux2002)

Champaign

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# Choice

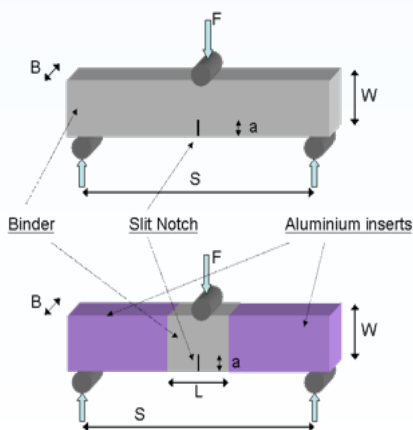
from bitumen to structure tests



LCPC OR-Fondephy 2006-2009  
in relation  
to TG1 and TG2 of TC-CAP...

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## I. For Bitumen -> 3pt bending test (TC-ATB)

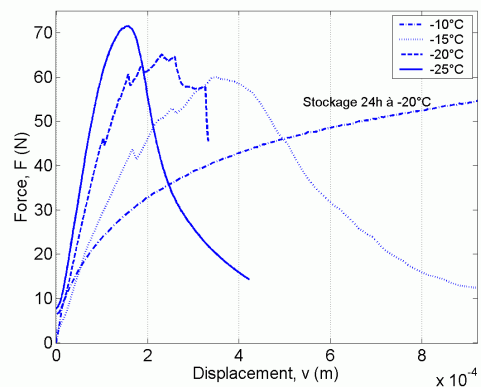


Standard three points bending test

Three points bending test using a non homogeneous sample



[Chailleux et al., ICAP2006]

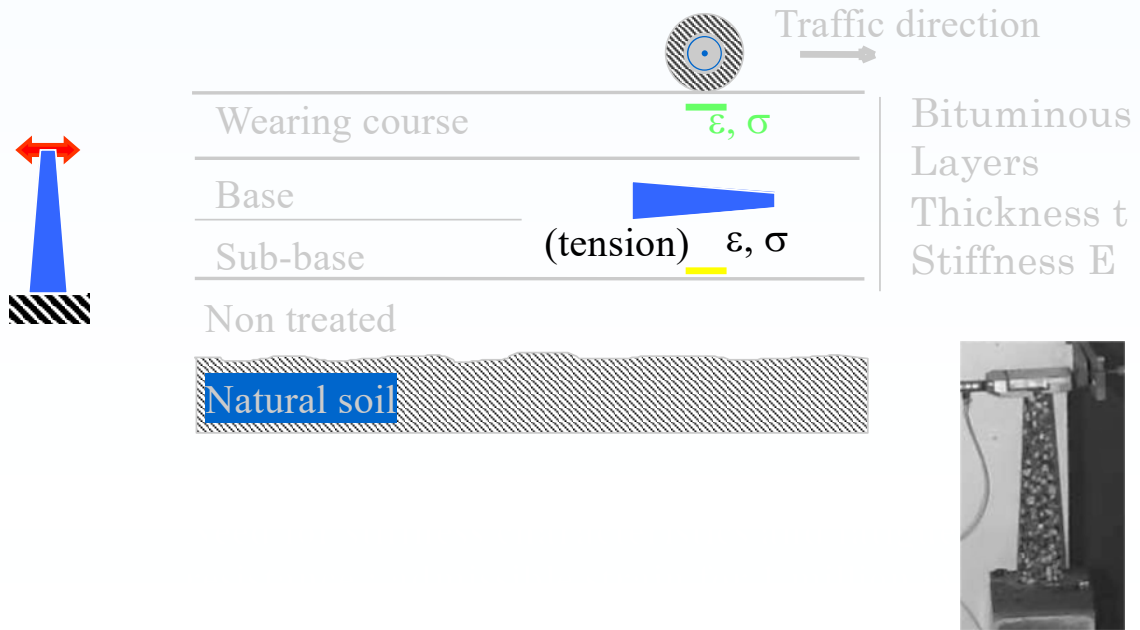


Needs: 20l of bitumen

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## II. Determination of bituminous mixes mechanical characteristics for pavement structural design



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## Fatigue damage modelling

(Bodin, 2002)(Bodin et al., ASCE/JEM 2004)

### Scalar damage model

$$\sigma_{ij} = (1 - D)C_{ijkl}\varepsilon_{kl}$$

$$\dot{D} = f(D) \tilde{\varepsilon}^\beta \langle \dot{\tilde{\varepsilon}} \rangle$$

$$\tilde{\varepsilon} = \sqrt{\sum_{i=1, \dots, 3} \frac{\langle \sigma_i \rangle}{E(1 - D)}}$$

### Nonlocal integration of the equivalent strain

$$\bar{\varepsilon} = \frac{1}{V_r(x)} \int_{\Omega} \Psi(x - s) \tilde{\varepsilon}(s) ds \quad \text{avec} \quad V_r(x) = \int_{\Omega} \Psi(x - s) ds$$

$$\Psi(x - s) = \exp - \frac{4 \|x - s\|^2}{l_c^2}$$

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# Application: fatigue cracking experiments

I	C1	6,5 t	8 BB <sub>1</sub>	8 BB <sub>2</sub>	8 BB <sub>3</sub>	8 BTM 12 GB	USAP SHELL	06/07/90 au 15/07/91	Fatig 1
			40 GRH	40 GRH	40 GRH	40GRH			
Nb passages			2 731 000	2 731 000	2 731 000	2 731 000			

II	C2	6,5 t	8 BB <sub>1</sub>	8 BB <sub>1</sub>	10 GB	8 BB <sub>3</sub>	USAP SHELL	10/10/91 au 31/12/91	Fatig 2
			42 GRH	42 GRH	40 GRH	46 GRH			
Nb passages			1.390 000	1.390.000	1.390.000	1.390.000			

Material damage modelling (Bodin et al., Eurobitume2004)

III	B2	6,5 t	8 BB <sub>1</sub>	8 BB <sub>2</sub>	8 BB <sub>3</sub>	10 BB <sub>3</sub>	USAP ELF	24/11/93 au 18/04/94	Fatig 3
			40 GRH 6% d'eau Selon manœuvre TFE	40 GRH	40 GRH	40 GRH			
Nb passages			3 160 000	3 160 000	3 160 000	3 160 000			

(Achimastos, 1998), Courage project (Hornych and Salaska, 1999)

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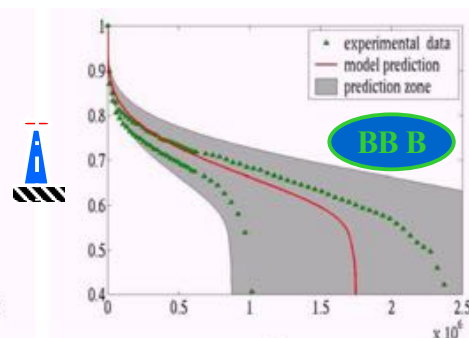
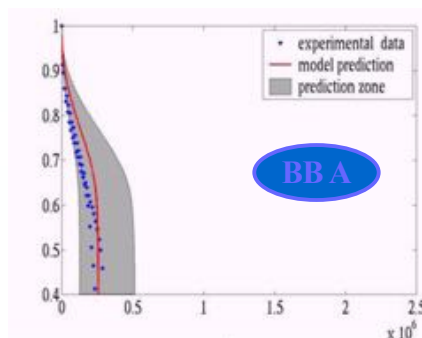
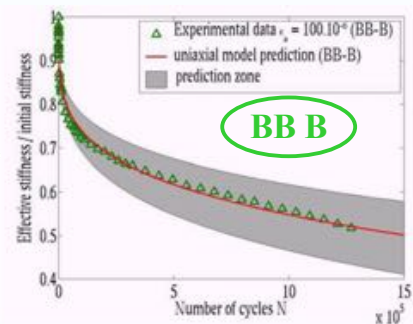
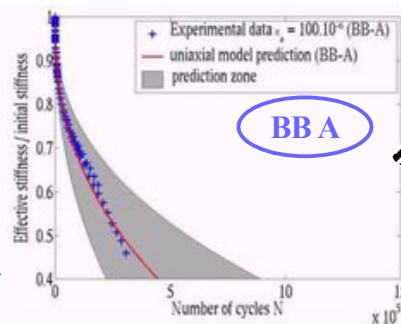
# Application: fatigue cracking experiments

(Bodin et al., Eurobitume2004)

→ Prise en compte des effets thermiques

→ Étude de l'influence du bitume (nature, teneur)

→ Étude des effets d'échelle (longueur caractéristique  $l_c$ )

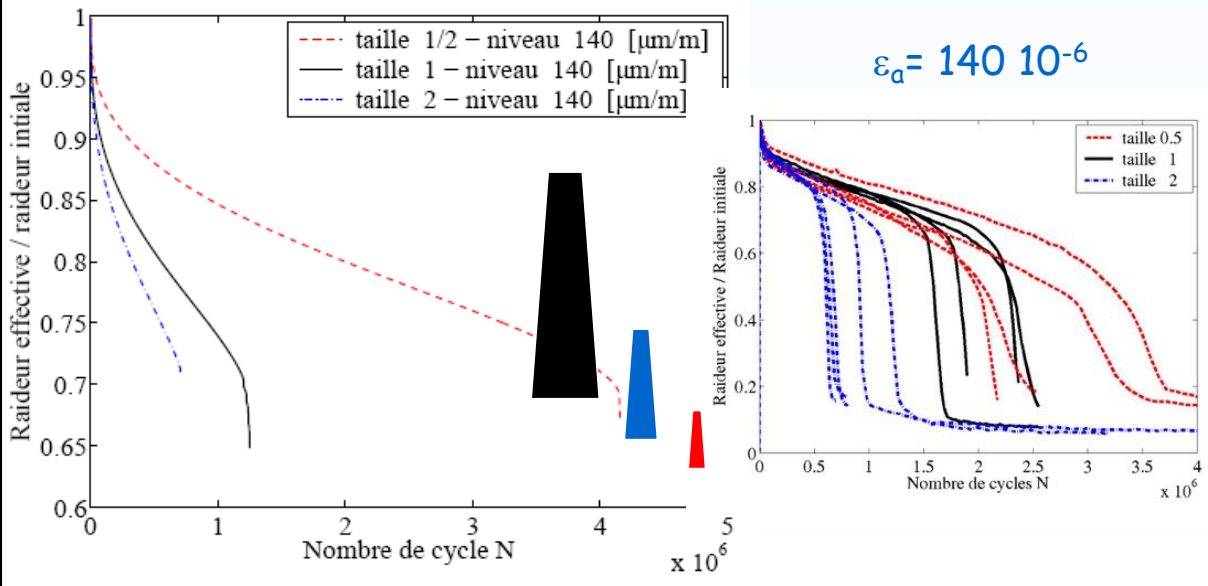


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# What about size effects?

(Bodin et al., RMPD2006)



**Needs: 7 slabs of asphalt material**  
**(400X600X120mm<sup>3</sup>)**

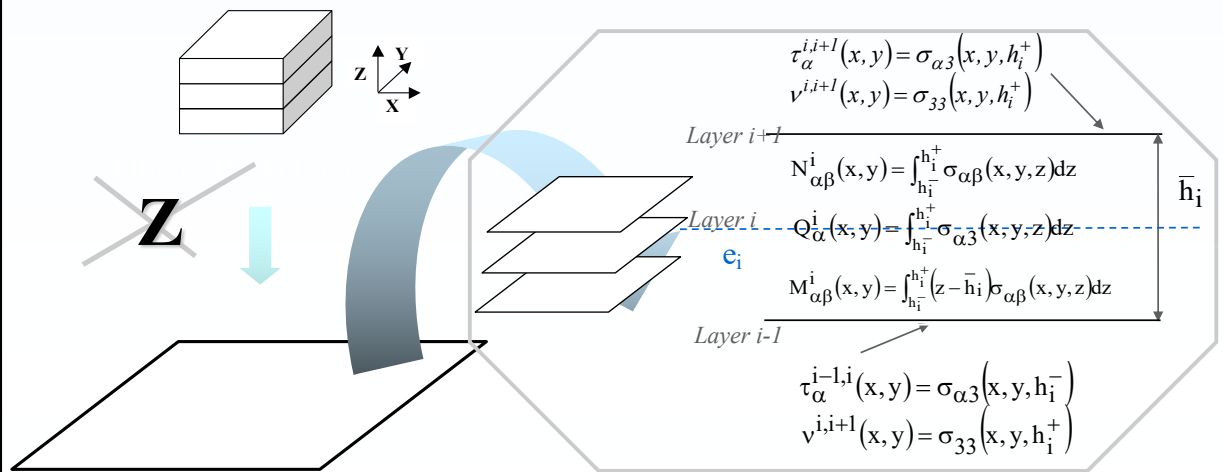
## III. Multi-particle Model of Multi-layer Materials (M4)

(Chabot, 1997) (Chabot & Ehrlacher, 1998)

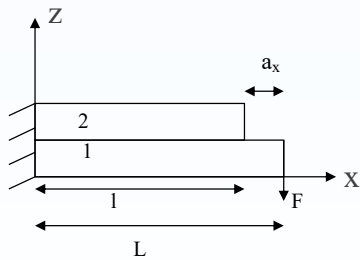
Simplified modelling for interface stress fields in multi-layered structure

### M4 building method

- Polynomial approximation per layer  $i$  in  $z$  for  $s_{ij}$
- Hellinger-Reissner formulation (Reissner, 1950)



## M4\_5n (5n champs cinématiques) -> Exemple hypothèses déformations planes [Pouteau et al., 2002]



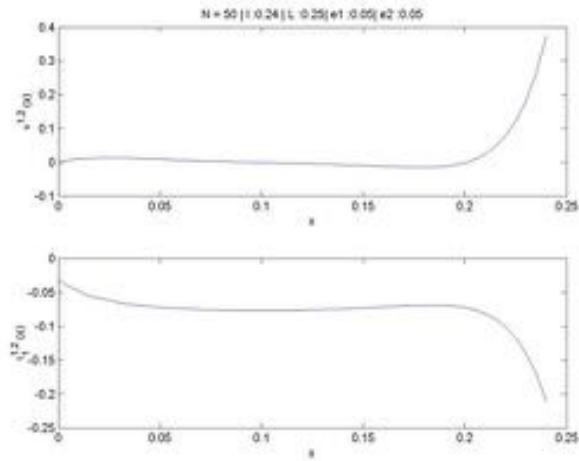
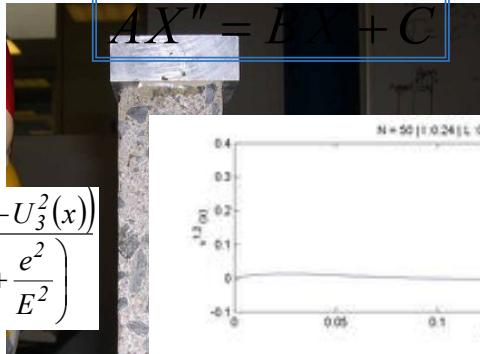
$$AX'' = BX + C$$

avec

$$\bar{X} = \begin{Bmatrix} Q_1^l(x) \\ U_1^l(x) \\ \Phi_1^l(x) \\ \Phi_1^2(x) \end{Bmatrix}$$

$$v^{1,2}(x) = -Q_{1,1}^l(x) = -\frac{35}{13} \frac{(U_3^2(x) - U_3^1(x))}{\left(\frac{e^1}{E^1} + \frac{e^2}{E^2}\right)}$$

$$\tau^{1,2}(x) = \frac{15G_1G_2}{2(e^1G^2 + e^2G^1)} \begin{pmatrix} \left(-\frac{e^1}{2}\Phi_1^l(x) - \frac{e^2}{2}\Phi_1^2(x)\right) \\ \left(-1 - \frac{E^1e^1}{E^2e^2} \frac{1-\nu_2^2}{1-\nu_1^2}\right)U_1^l(x) \\ \left(\frac{1}{10G_1} - \frac{1}{10G_2}\right)Q_1^l(x) - \frac{1}{10G_2}F \end{pmatrix}$$



## Second response: Classical criteria

- ◆ Monotonic case (for initiation exemple) [caron et al., 2005]:

- Quadratic delamination criterion (QDC) can be used:

$$\frac{\tau_1^{i,i+1^2}}{\tau_1^{c^2}} + \frac{\tau_2^{i,i+1^2}}{\tau_2^{c^2}} + \frac{\nu^{i,i+1^2}}{\nu^{c^2}} \leq 1$$

- Energy release rate  $\frac{G}{G_c} \leq 1$

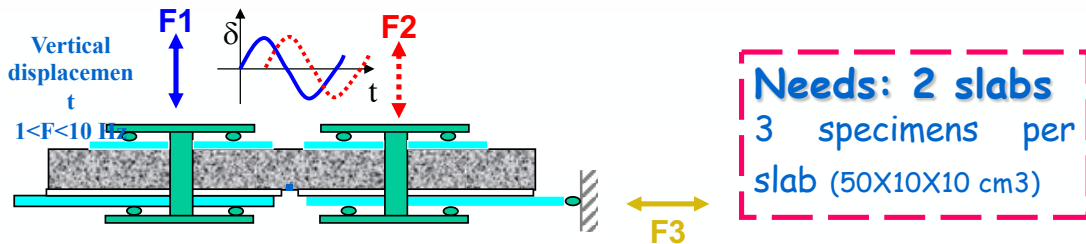
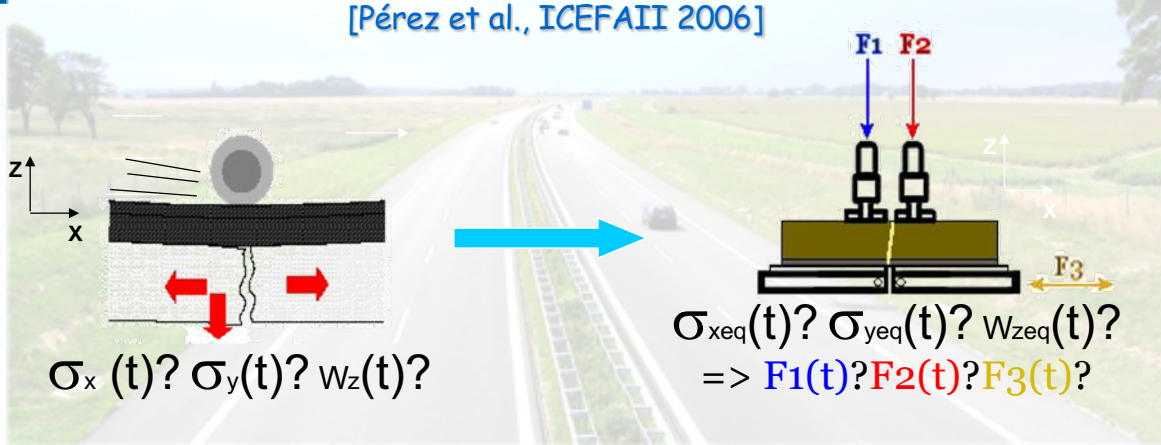
- ◆ Fatigue case (for propagation) (Pouteau, 2004):

- Energy release rate -> Paris law:

$$da/dN = C(\Delta G)^m$$

# Objective : set a laboratory test for evaluation of solution against reflective cracking

[Pérez et al., ICEFAII 2006]



Mefisto device ERA d'Autun L. Wendling

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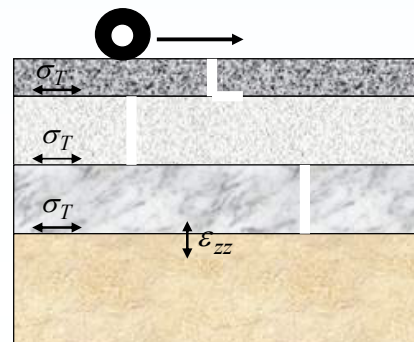
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# Cracking in Pavement

## Application -> Asphalt and/or concrete pavements



- ✓ Mechanical study of bond or no bond between layers
- ✓ Reflective cracking study



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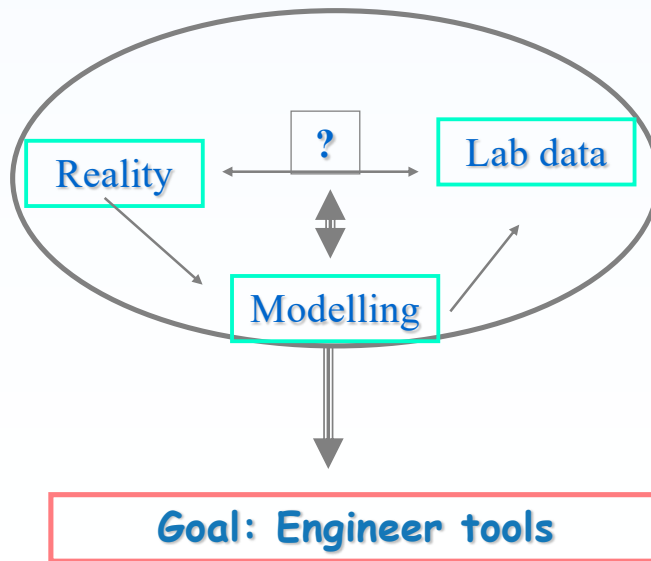
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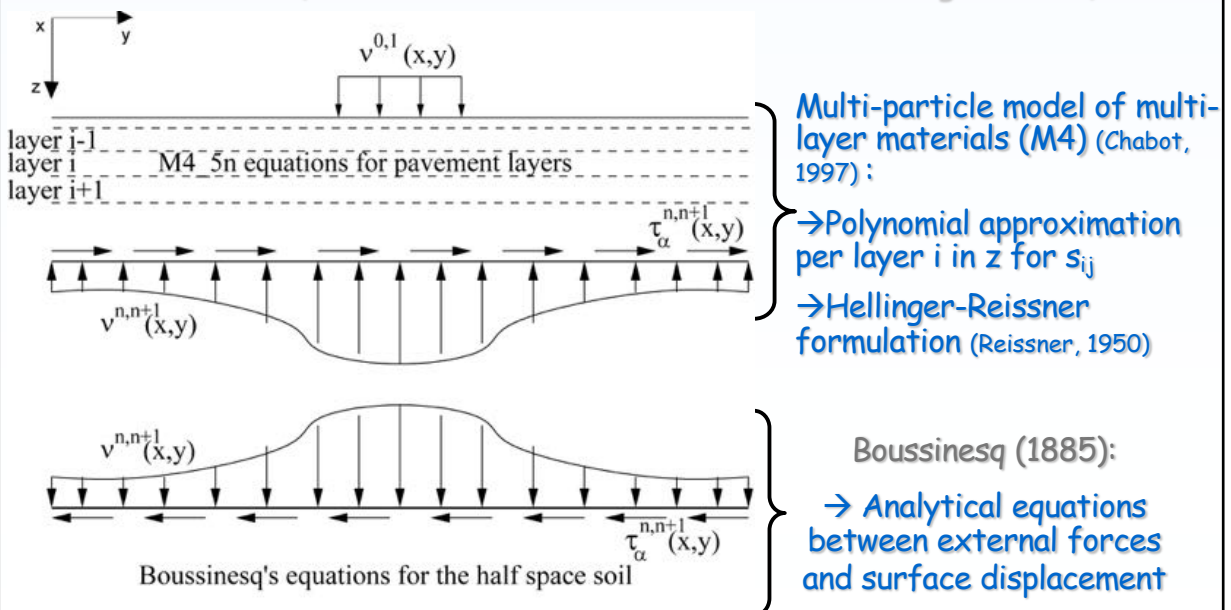
# MOTIVATION



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## M4-Boussinesq model (Tran, 2004) (chabot et al., BLPC2005)

(see Hoorn TC-CAP TG2 and TG3 meeting in 2005)

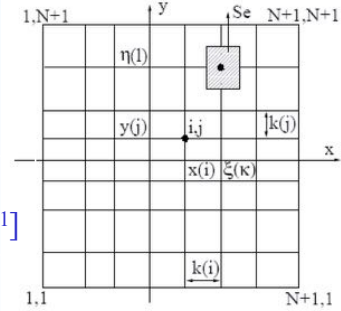


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# Numerical solving [Tran, 2004]



5 displacements per layer + 3 interface stresses

$$X = T[U_{\alpha}^1 \Phi_{\alpha}^1 U_3^1 \dots U_{\alpha}^n \Phi_{\alpha}^n U_3^n] \quad Y^{n,n+1} = T[\tau_{\alpha}^{n,n+1} v^{n,n+1}]$$

$$AAX'_{11} + BBX'_{22} + CCX'_{12} + DDX'_{11} + EEX'_{12} + FFX = GGY^{n,n+1} + HHY'_{12} + IIFY^{n,n+1} + JJ$$

$$M.X = \int_S f(x, y, \xi, \eta) Y^{n,n+1}(\xi, \eta) d\xi d\eta$$

Newmark  
Difference finite  
method

$$\frac{X_{(i,j)'1} + X_{(i+1,j)'1}}{2} = \frac{X_{(i+1,j)} - X_{(i,j)}}{k_{i+1}}$$

$$\frac{X_{(i,j)'2} + X_{(i,j+1)'2}}{2} = \frac{X_{(i,j+1)} - X_{(i,j)}}{k_{j+1}}$$

Half Analytic method

Linear system - use of Matlab software

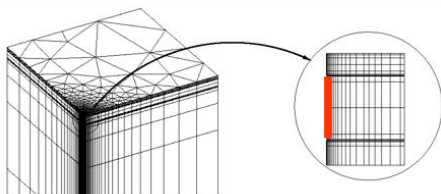
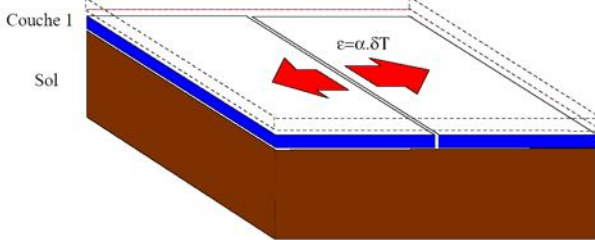
$$\mathbb{X} = [K_1 - K_2 K_5^{-1} K_4]^{-1} K_3$$

$$Y^{n,n+1} = K_5^{-1} K_4 \mathbb{X}$$



# M4-Boussinesq model validation

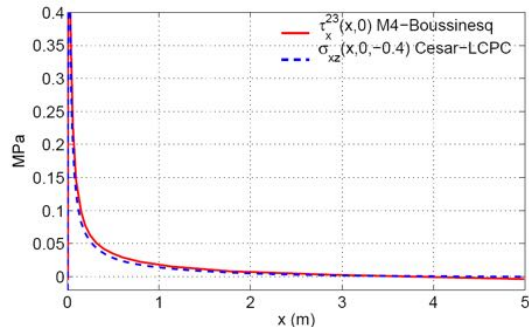
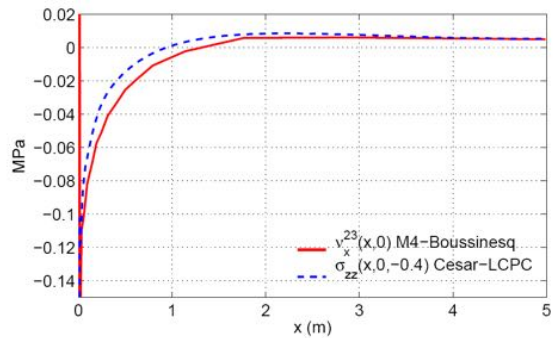
$e_1 = 0.1m \quad E_1 = 9300 MPa \quad \nu_1 = 0.35$   
 $e_2 = 0.3m \quad E_2 = 23000 MPa \quad \nu_2 = 0.25$   
 $\alpha = 12 \cdot 10^{-6} \quad \delta T = 10^\circ C$   
 $E_s = 50 MPa \quad \nu_s = 0.35$



EF 3D (César-LCPC) -> 2h CPU

(skrinkage)

(Tran, 2004)

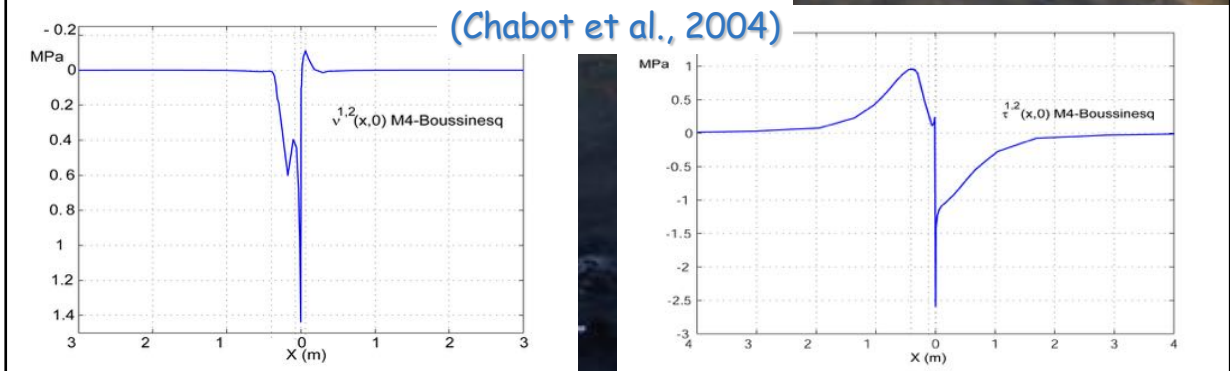
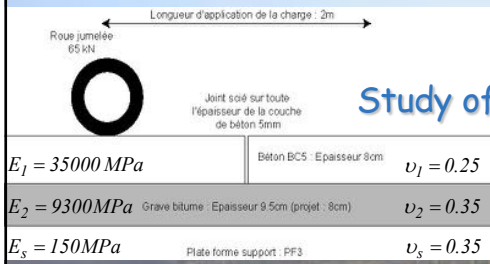


M4-B -> 15' CPU

# M4-Boussinesq model application

Alternative concrete pavement  
(Pouteau et al., 2004)

Study of bond between Concrete and Asphalt layers  
initial 3D stress state



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**LCPC** Laboratoire Central des Ponts et Chaussées

## Advantage -> iterative problem

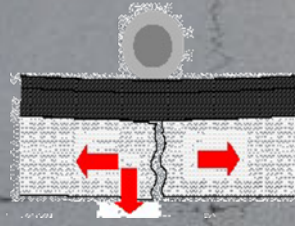
Pavement Problem	EF model	M4-Boussinesq model
3D problem	3D	2D fields (x,y) unknowns (Matlab+2 layers cracked on a soil) -> 10 times faster than 3D EF
2D « equivalent » Problem ?	2D	1D fields (x) unknowns (Matlab +2 layers cracked on a soil) -> 100 times faster

(Pouteau et al., 2004)

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# Modelling Prospect for simulate crack propagations

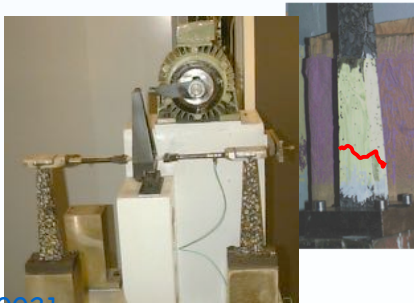


- # M4-5nB -> C++ Programming (Perez, PhD 2003-2006, Lavigne, PhD 2005-2008)
- # Introduce damage and delamination cracks
- # Simulate cracks propagation
- # water effects
- # what about visco-elastic behavior?.....

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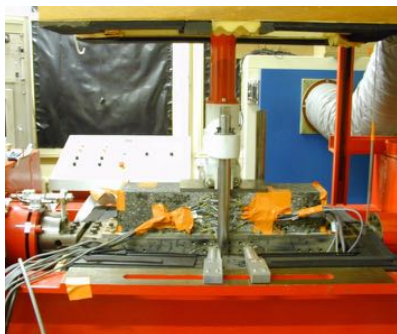


## Thanks

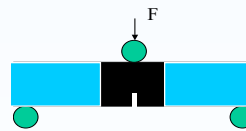


[Bodin, 2002]

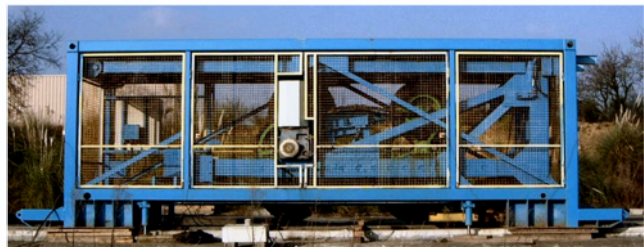
[Bodin et al., ASCE 2004]



[Tamagny et al., CP2004]



[Chailleux et al., ICAP2006]



[Pérez et al., ICEFAII 2006]

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