Simplified strategies based on damage mechanics for RC under dynamic loadings

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Question to solve:
For large size concrete structures such as building the use of FE techniques implies often to choose simplified modelling including multifiber beam or lattice descriptions

Is simplified modelling able to describe the response to low, medium and high velocity?

Content

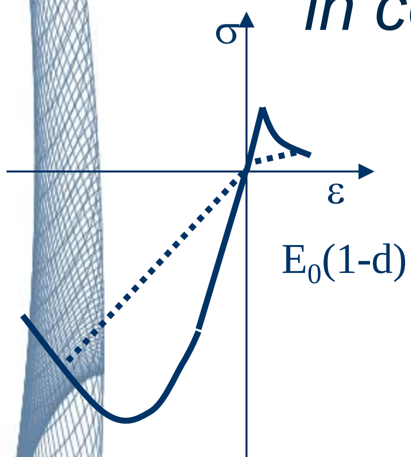
- Concrete model
- MF beam and localization pbs
- Applications:
  - *seismic response*
  - *strain rate effects (spalling test)*
  - *impact on a RC beam*
- Conclusions

Basis of the model (μ damage model)

From the coupling Elasticity – isotropic Damage,

$$\boldsymbol{\sigma} = \boldsymbol{\Lambda}_0 (1\text{-}d) : \boldsymbol{\varepsilon} = (1\text{-}d)\,[\,\lambda_0\, trace(\boldsymbol{\varepsilon})\,\mathbf{1} + 2\mu_0\, \boldsymbol{\varepsilon}\,]$$

The objective is to describe the main non linear effects in concrete (cracking and damage, unilaterality,….)



- **Main assumptions for the 3D version :**

  In order to stay as simple as possible:
  - only one damage variable d is used, which is the « activated» part of damage or « effective damage » (nil when cracks are closed)
  - no permanent strain

- **However for a 1D version** *(useful for simplified modelling)*

  Enhancements have been introduce such as :
  - hysteretic dissipation during cyclic loading
  - permanent strains
  - strain rate effects,…..

Mazars J., Hamon F., Grange S., 2015, A new 3D damage model for concrete under monotonic, cyclic and dynamic loading, Materials and Structures, 48, 3779–3793.

μ model : principles

- **To distinguish « cracking » and « crushing », 2 equivalent strains are defined :**

$$\varepsilon_t = \frac{I_\varepsilon}{2(1-2\upsilon)} + \frac{\sqrt{J_\varepsilon}}{2(1+\upsilon)} \quad \text{and} \quad \varepsilon_c = \frac{I_\varepsilon}{5(1-2\upsilon)} + \frac{6\sqrt{J_\varepsilon}}{5(1+\upsilon)} \quad \begin{cases} I_\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \\ J_\varepsilon = \frac{1}{2}\left[(\varepsilon_1-\varepsilon_2)^2 + (\varepsilon_2-\varepsilon_3)^2 + (\varepsilon_3-\varepsilon_1)^2\right] \end{cases}$$

- **From this, 2 thermodynamical variables are defined :**

$$Y_t = \max(\varepsilon_{0t}, \max(\varepsilon_t)) \quad \text{and} \quad Y_c = \max(\varepsilon_{0c}, \max(\varepsilon_c))$$

- **2 loading surfaces are associated to this variables**

$$f_t = \varepsilon_t - Y_t \le 0 \quad \text{and} \quad f_c = \varepsilon_c - Y_c \le 0$$

- **Evolution of the « effective damage »**

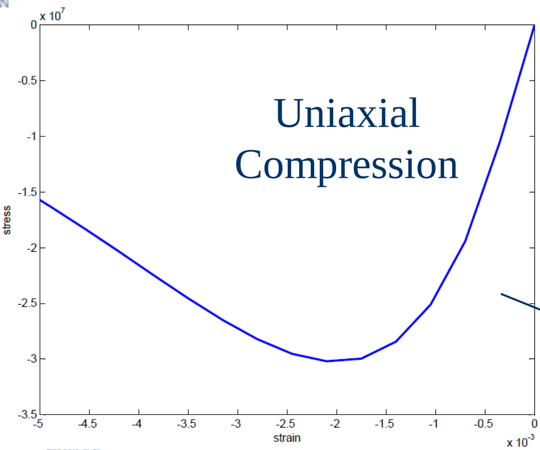
d=fct.(Y_0, *Y*, *A*, *B*), with $Y = rY_t + (1-r)\,Y_c$ and $Y_0 = r\,\varepsilon_{t0} + (1-r)\,\varepsilon_{c0}$

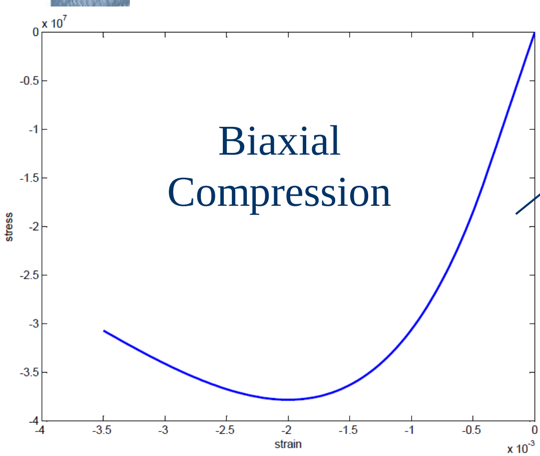
r is the triaxiality factor $r = \dfrac{\sum_i \langle \tilde{\sigma}_i \rangle_+}{\sum_i |\tilde{\sigma}_i|}$ (Lee,Fenves 98) $\tilde{\boldsymbol{\sigma}} = \Lambda_0 : \boldsymbol{\varepsilon}$ (effective stress)

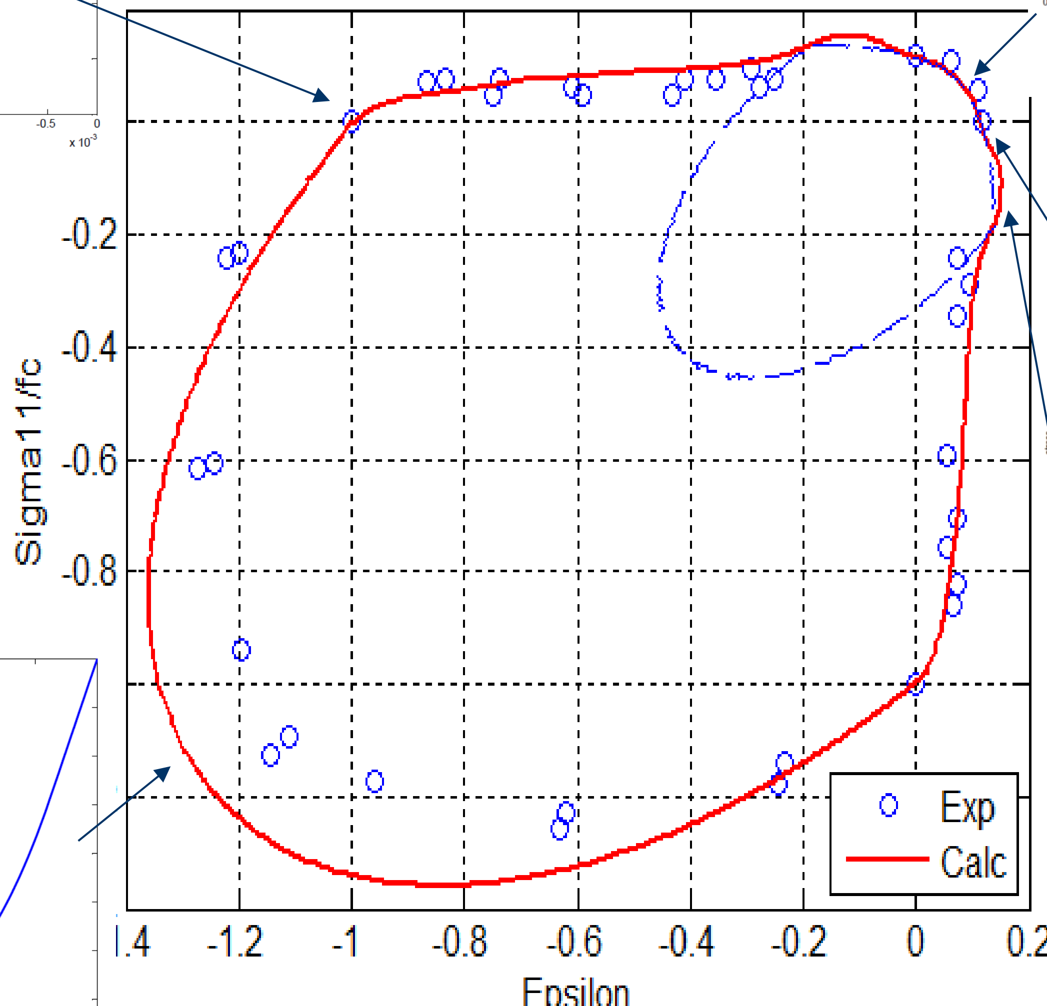
A= f (At, Ac, r) B=f (Bt, Bc, r) : *At, Bt, Ac, Bc material parameters (from tests on sample)*

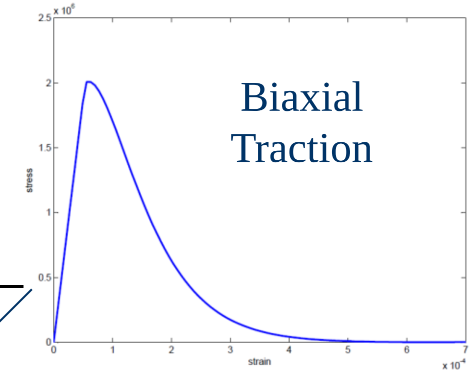
Mazars J., Hamon F., Grange S., 2015, A new 3D damage model for concrete under monotonic, cyclic and dynamic loading, Materials and Structures, 48, 3779–3793.

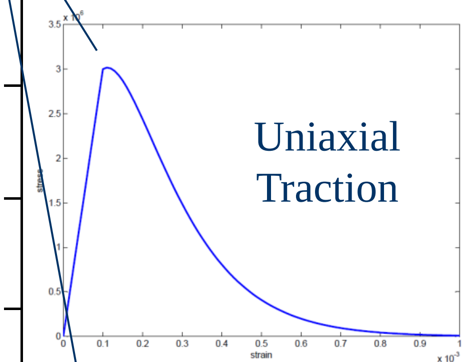
Failure surface : section $\sigma_3=0$

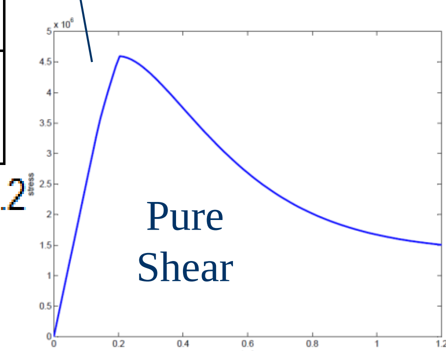












O Experiment (Kupfer et al 1973)

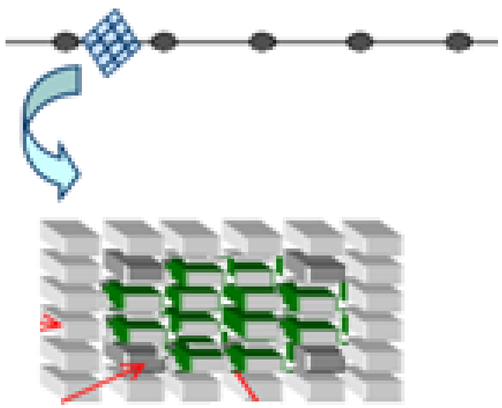
Simplified modelling :
Multifiber Timoshenko beam description

Principle :

- in each beam element the section is composed of // fibres (concrete – steel)

- the behaviour of each fiber is 1D
  (but the global behaviour is 3D)

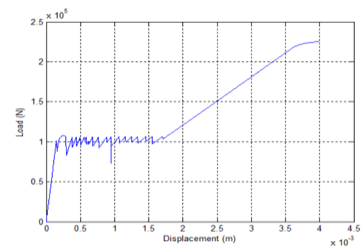
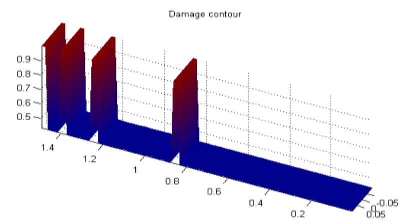
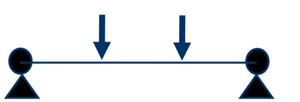
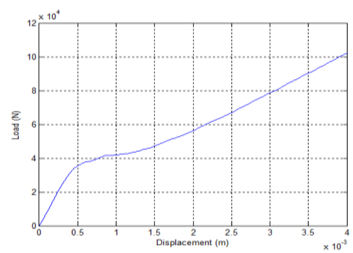
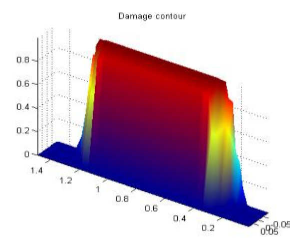
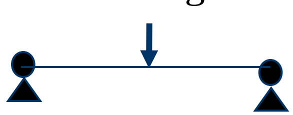
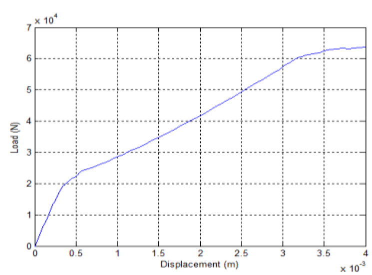
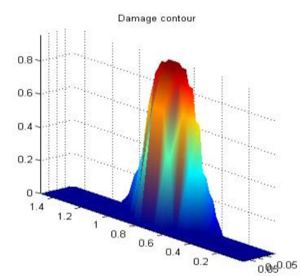
- kinematics constraint at the connection between 2 elements :
  - plane section remains plane



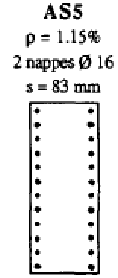
Multifiber description and localization

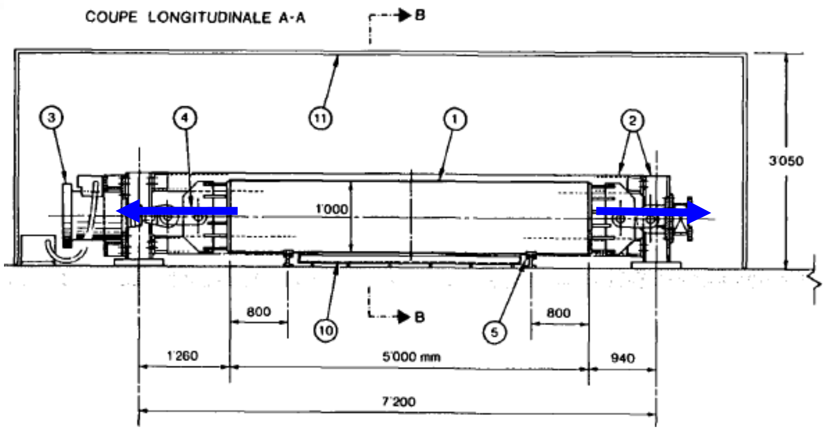
On the same RC beam (1.5m long section 5x5 fiber) : 3 different types of loading are considered

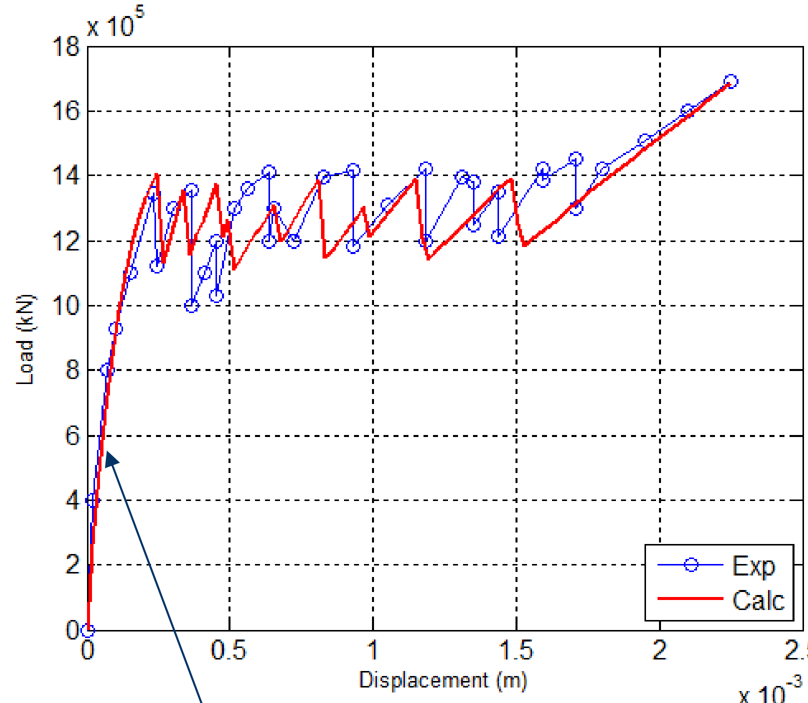
Conclusion : Localization appears only on specific cases (RC tie, plain concrete beam,…)
In these cases, solutions to solve mesh dependency are the same as 2D-3D FE

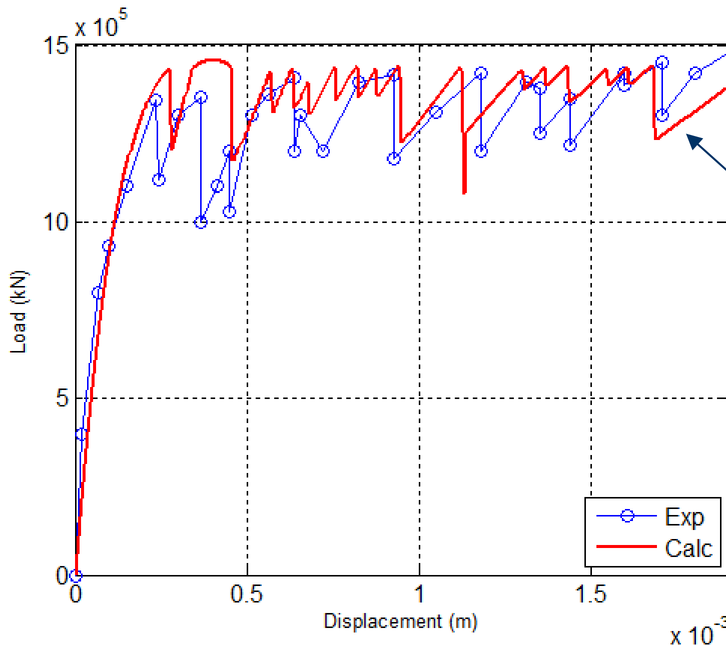
Type of loading	Global behaviour	Damage contour (at a given loading)	Type of response
Tensile loading (tie) 			Strain is localized
Four point bending 			Strain is distributed
Three point bending 			Strain is distributed

RC beam under tensile loading : tie
(Mivelaz – EPFL 1996)









Calcul. FE 2D

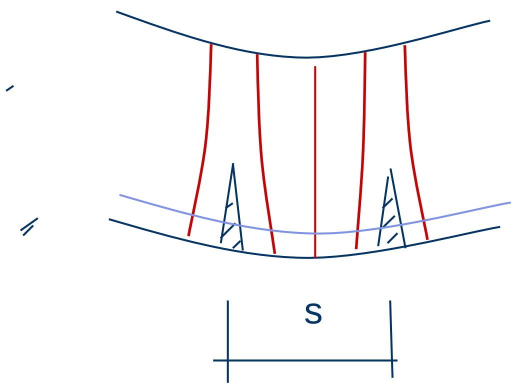
Calcul. MF

For both calculations:

- Same model (μ model)
- Same size of elements
- Same materials parameters

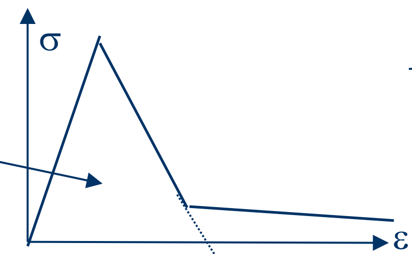
RC beam under bending

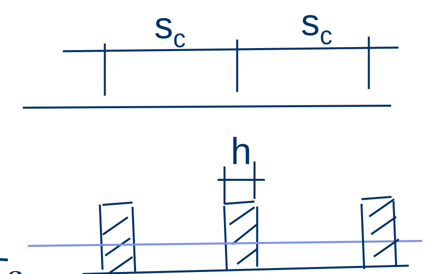
1. In a 2D-FE beam: localization generates section warping



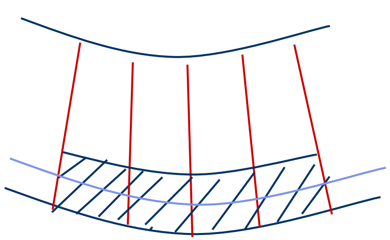
In the framework of the crack-band theory, cracking is localized in a band of elements (**size h**) the behaviour of which is calibrated from the Hillerborg method :

$G_f/h=\int\sigma.d\varepsilon$



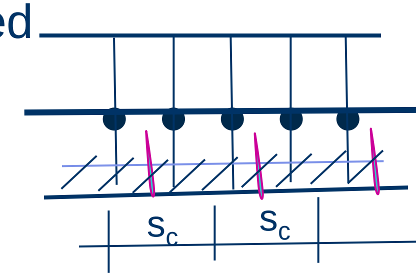


2. In a MF beam: sections remain plane which thwart localization



Then the damage-cracking processes for one crack is distributed on both side of the crack over a volume defined by the distance s_c (**s_c is the crack spacing**)

→ $G_f/s_c=\int\sigma.d\varepsilon$



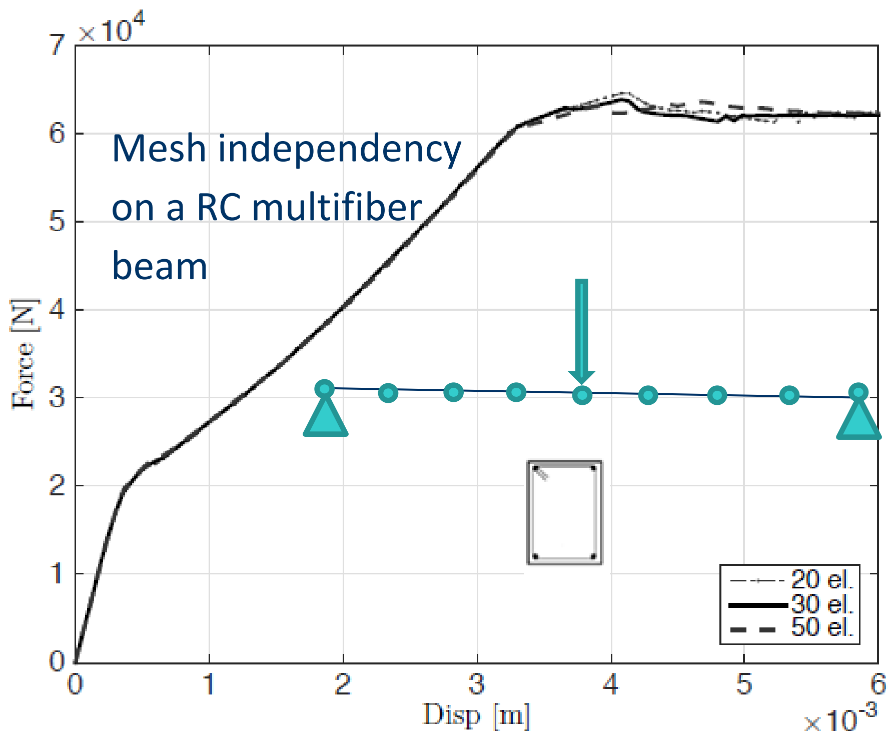
*Bazant Z.P., Oh B.H., 1983, Crack band theory for fracture of concrete, Materials and structures, Vol. 16 n°3, pp. 155-177.
Bazant Z.P., 2002 Concrete fracture models: testing and practice, Engineering Fracture Mechanics, 69, 165-205.

RC beam under bending…. again

***Conclusion** : there is no localization problem,*

***But** : material parameters for MF beam description are different from the ones used for FE-2D calculations*

***Finding** : this way leads to a mesh independency*



1D concrete behaviour : introduction of hysteretic loops and permanent strain

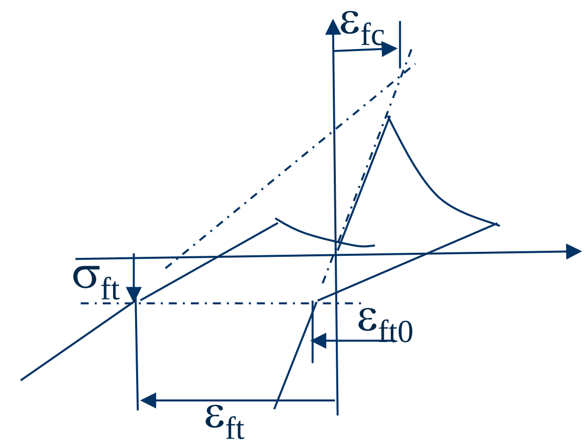
- *Permanent strain* *(Pontiroli 1995)*

  $(\sigma - \sigma_{ft}) = E\,(1-d_i)\,(\varepsilon - \varepsilon_{ft})$ $\qquad d_i = d_t$ or d_c

  $\varepsilon_{ft} = \varepsilon_{ft0}/(1-d_c).(\varepsilon_{ft} - \varepsilon_{fc}) - \varepsilon_{fc}.d_c/(1-d_c)$

  $\sigma_{ft} = E\,(1-d_c)\,(\varepsilon_{ft} - \varepsilon_{fc}) + E.\ \varepsilon_{fc}$

  ε_{ft0} *et* ε_{fc} *are 2 materials parameters*



- *Hysteretic loop*

  $\sigma_t = \sigma + \sigma_d$, $\sigma = E(1-d)\varepsilon$,

  $\sigma_d = (\beta_1 + \beta_2 d_i).E.(1-d_i)\varepsilon.f(\varepsilon).\text{sign}$

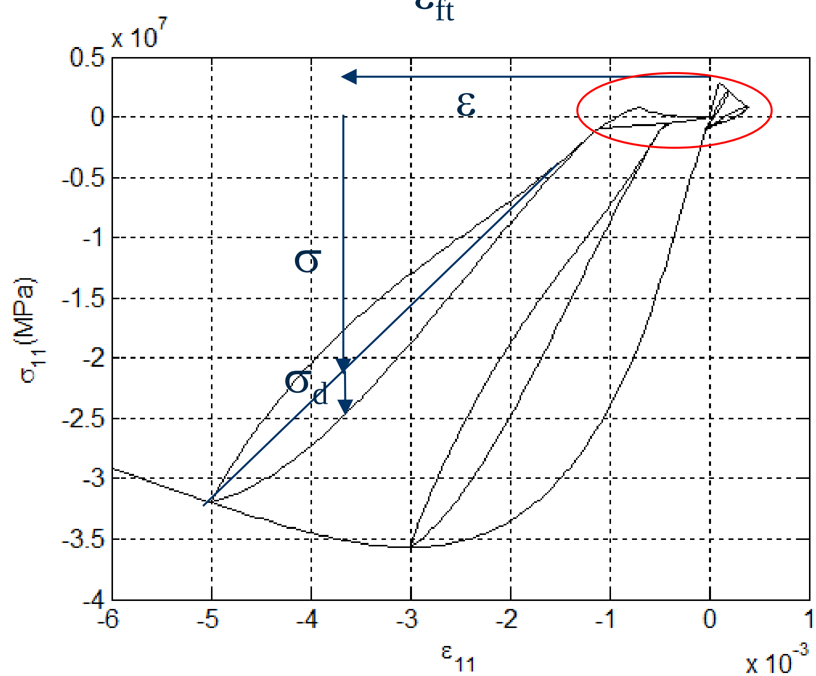
  β_1 and β_2 are 2 parameters

  $f(\varepsilon)$ gives the form

  and the size of the loop

  sign is – for unloading

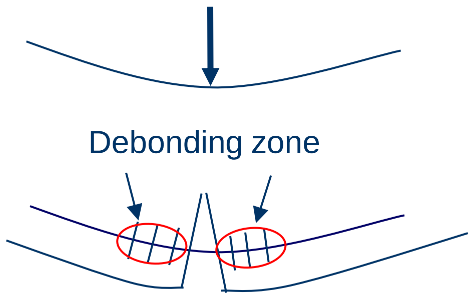
  and + for reloading



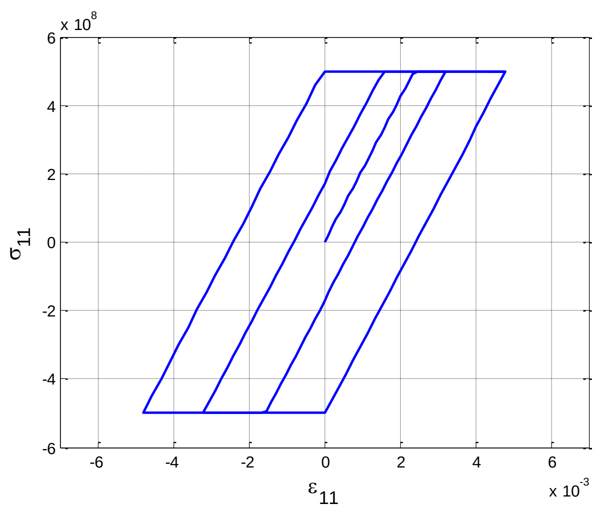
What about cylic loading response for large deformation?

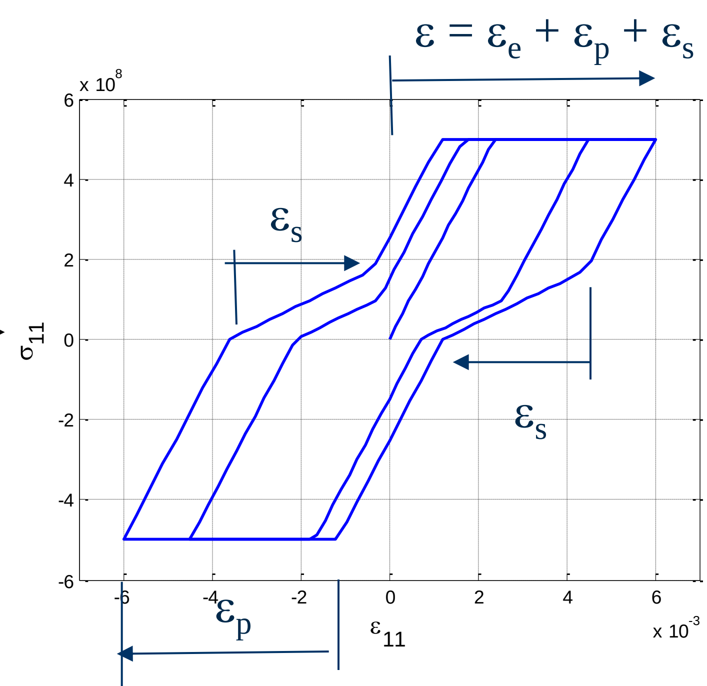
<u>In the real life</u> : when crack opens and Rebar yield, a debonding zone appears in the vicinity of the crack

→ relative slide between steel and concrete :

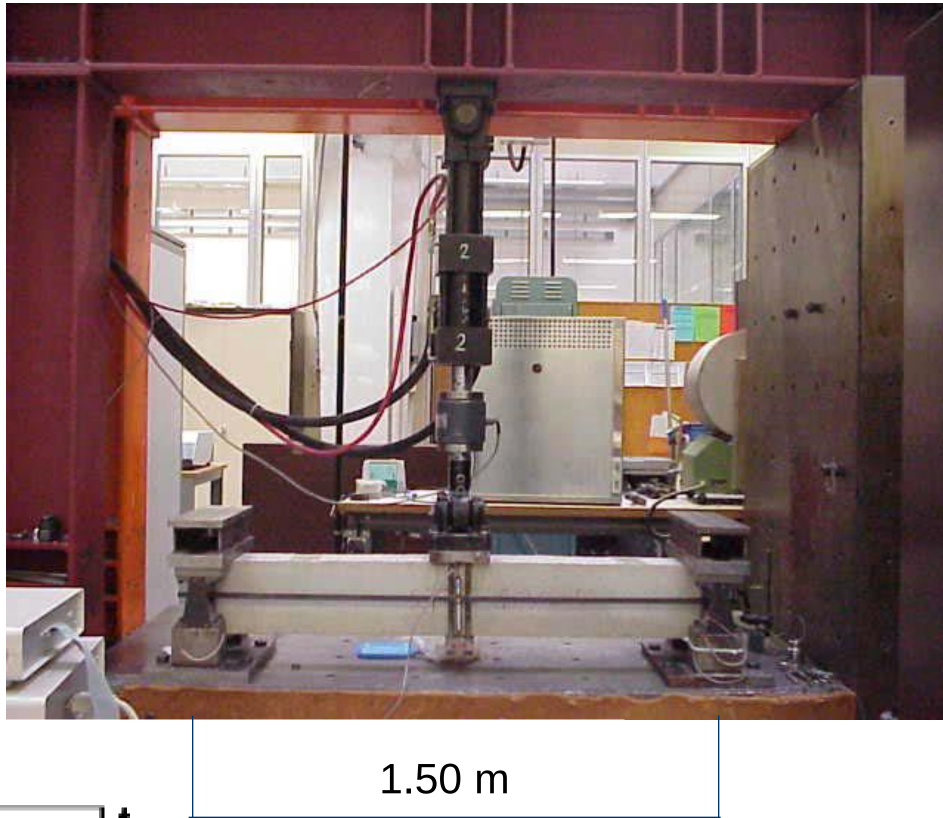


<u>Proposition</u> : *introduce this sliding in the behaviour of the steel ($\varepsilon_s = \kappa\varepsilon_p$)*

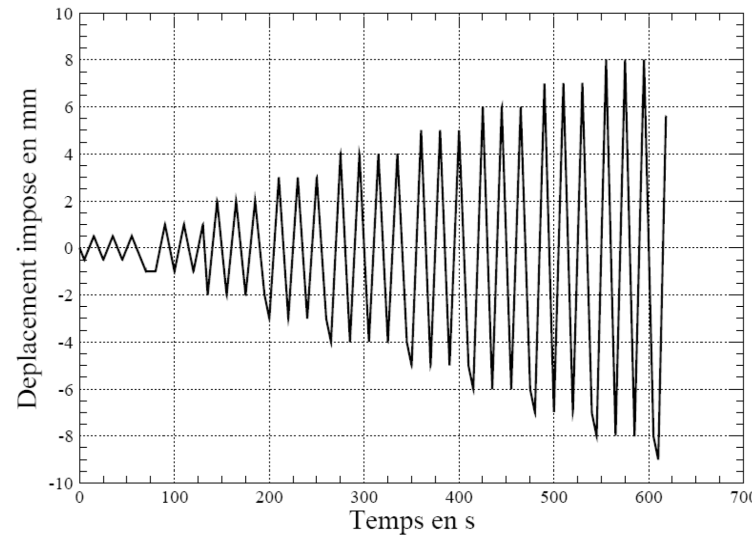


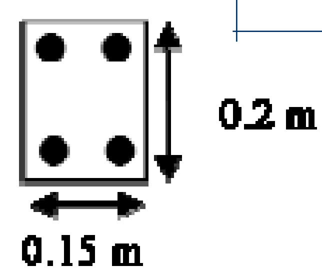


Cyclic loading : Simulations (MF)/Experiments



Loading path





● Steel reinforcement: $\phi = 0.012$ m

Fiber beam model :

- 30 beam elements
- Section, 5x5 fibers

Experiments from LMT Cachan : F. Ragueneau et al - 2010

Seismic application: SMART 2013 (CEA-EDF)

1. Mock-up representative of a building of a power plant
   - 1/4 scale - weight = 45t
   - asymmetrical structure
   - bidirectional loading
2. Loading program:

Phase 1 : artificial signal in respect of the design spectra

Phase 2 : natural earthquake (Northridge)

Phase 3 : Northridge replica

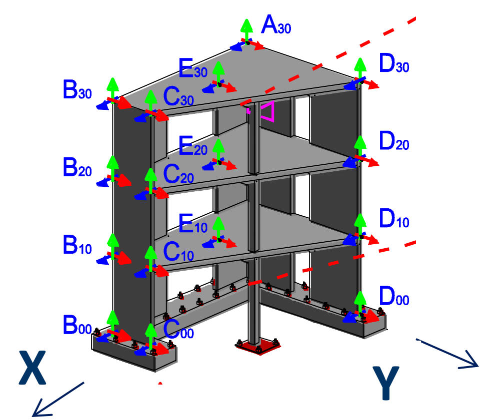
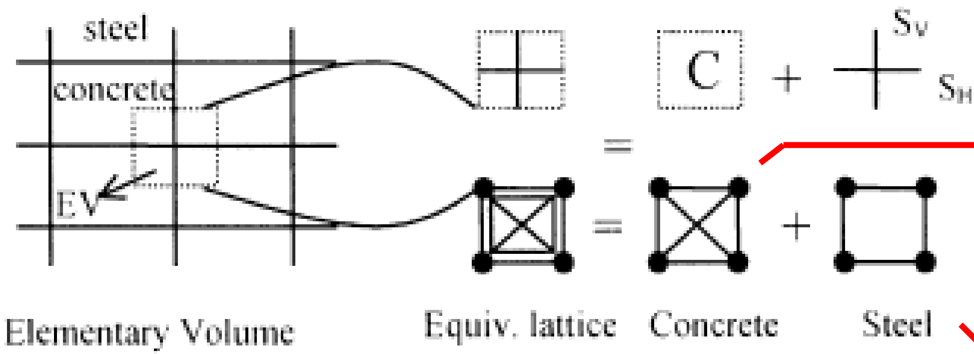


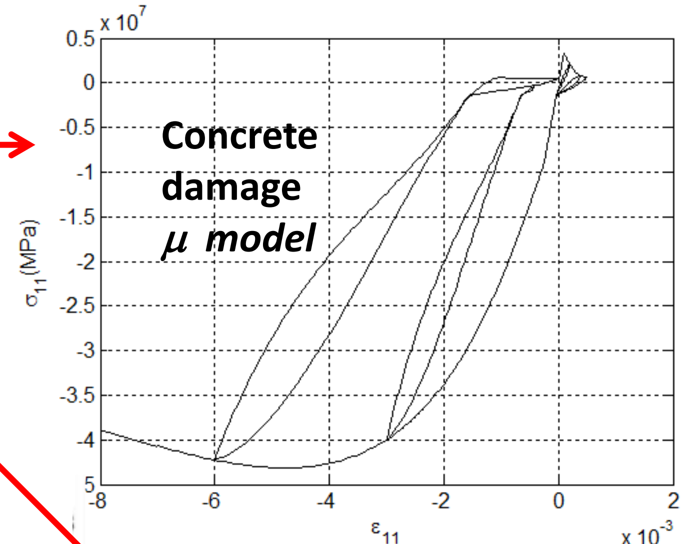
Schéma de la maquette

T. Chaudat, P-E Charbonnel – SMART 2013 Experimental campaign, 2014

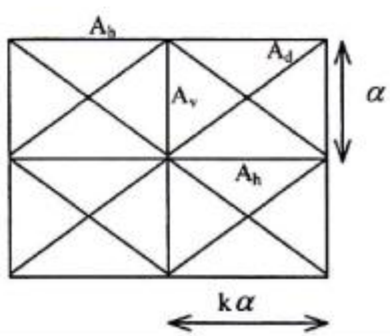
Shear wall simplified modelling: lattice « equivalent reinforced concrete»

Principle





Concrete bars of the truss



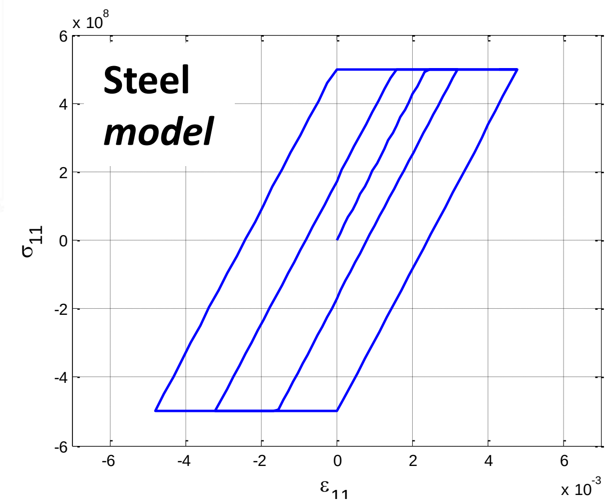
$$A_v = \frac{3}{8}\frac{3k^2-1}{k}at$$

$$A_h = \frac{3}{8}(3-k^2)at$$

$$A_d = \frac{3}{16}\frac{(1+\kappa^2)^{3/2}}{k}at$$

Area of the bars

from Hrennikoff (1941)



Kotronis P., Mazars J., Simplified modelling strategies to simulate the dynamic behavior of RC walls, J. of Earthquake Engineering, Vol 16, n°5, 2005

Out of plane deformations

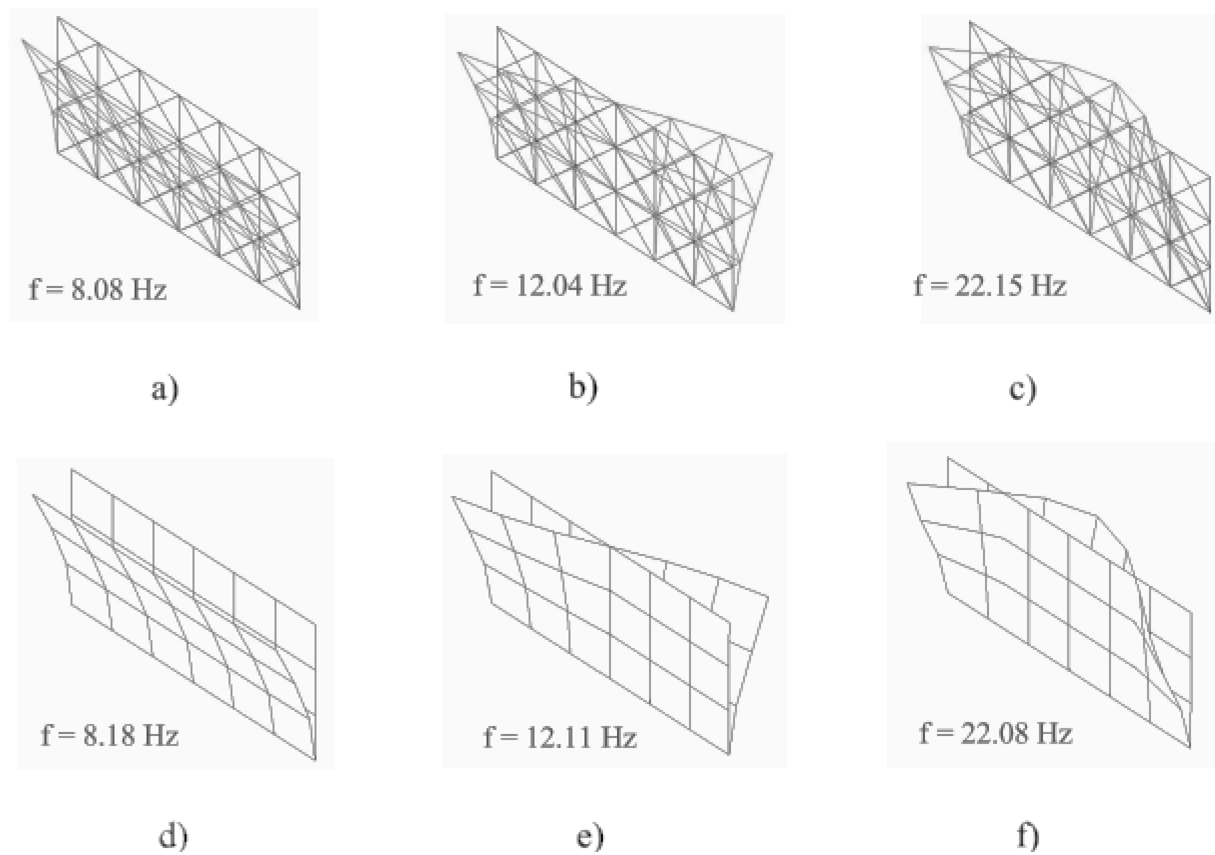
(M. di Biaso, S. Grange, Rapport benchark SMART 2013)

vertical additional bars are added (*section area = 0*)

bending and torsion inertia identified from a FE modal analysis

Modal analysis
of the « ERC » wall

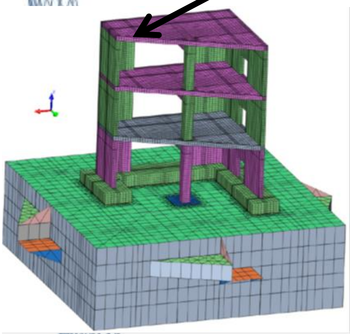
Modal analysis
FE shell elements

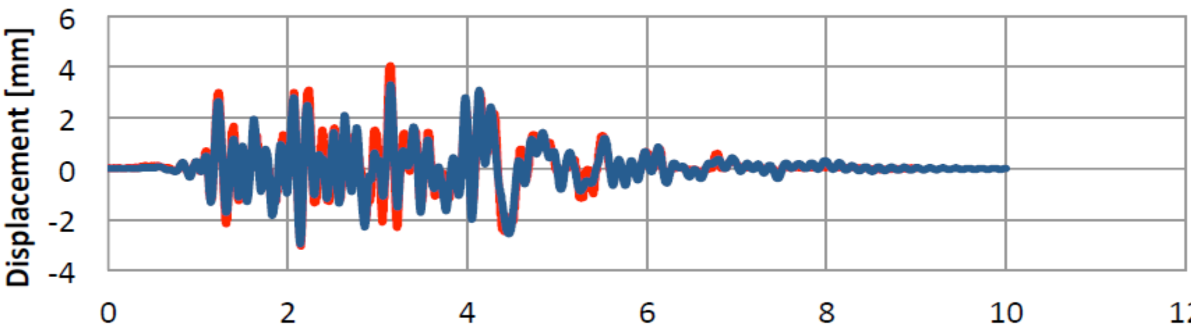


SMART 2013 (EDF-CEA) : Benchmark results

(B. Richard et al., benchmrark report SMART 2013)

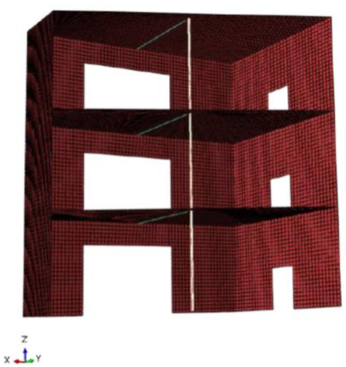
Point C, level 3 – direction X - design earthquake (0.22g)

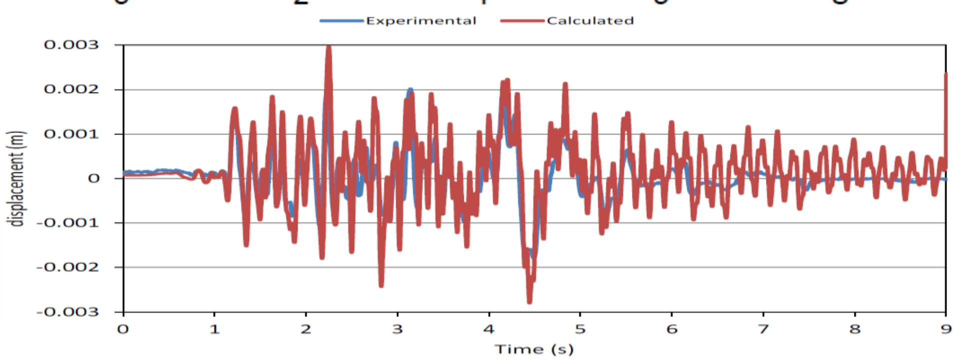




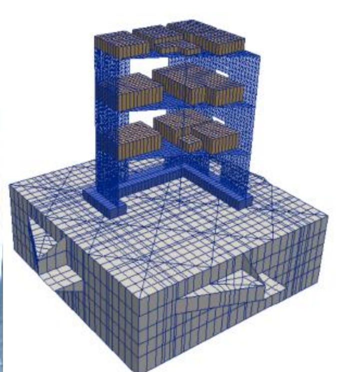
3D: solid elements (71600)
(Labib et al. 2014)

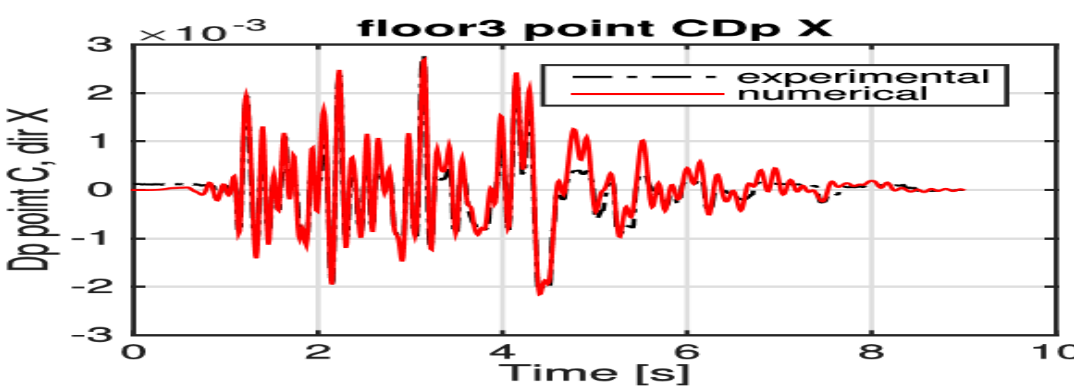
Experimental
Numerical





2D: beam elements(230) & shell elements (8600)
(Crespo et al., 2014)





1D (present modeling):
MF beam elements(69) & lattice elements (10800 bars)
(de Biaso, Grange , 2014)

Performance of the « 1D » calculation
SMART 2013 *(M. di Biaso, S. Grange, Benchark report SMART 2013)*

Beams and columns = NL multifiber beams; Walls = NL Equivalent Reinforced Concrete truss; Slabs = linear shell

pts C

Mode 1

Exp: 6.47Hz
Calcul: 6.28Hz

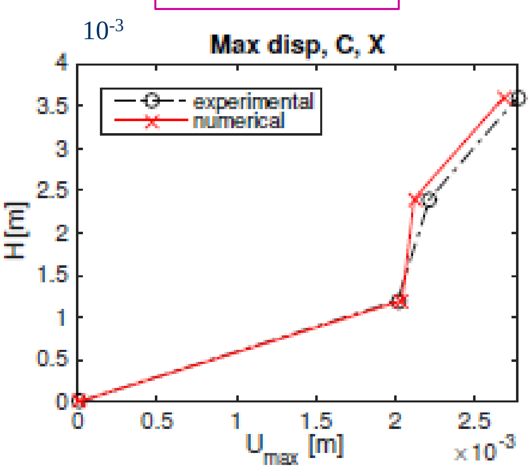
Mode 2

Exp: 9.13Hz
Calcul: 7.86Hz

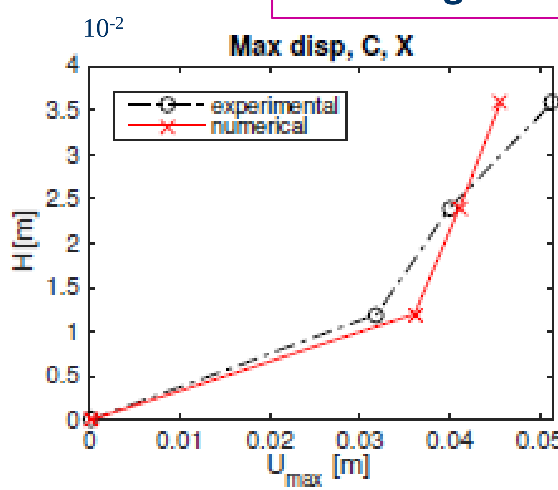
Mode 3

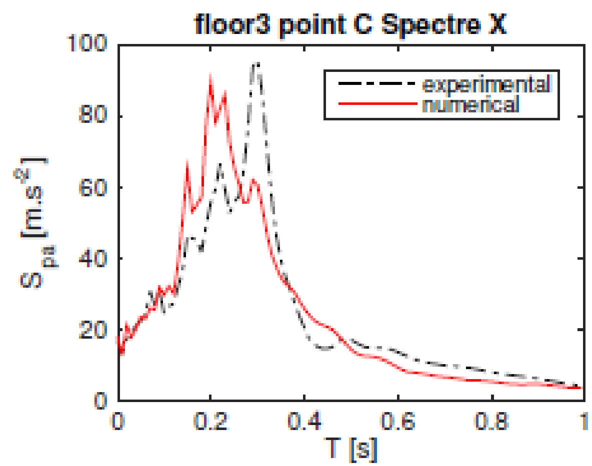
Exp: 17.85Hz
Calcul: 16.5Hz

Design earthquake (0.22g)



Northridge earthquake (1.1g)

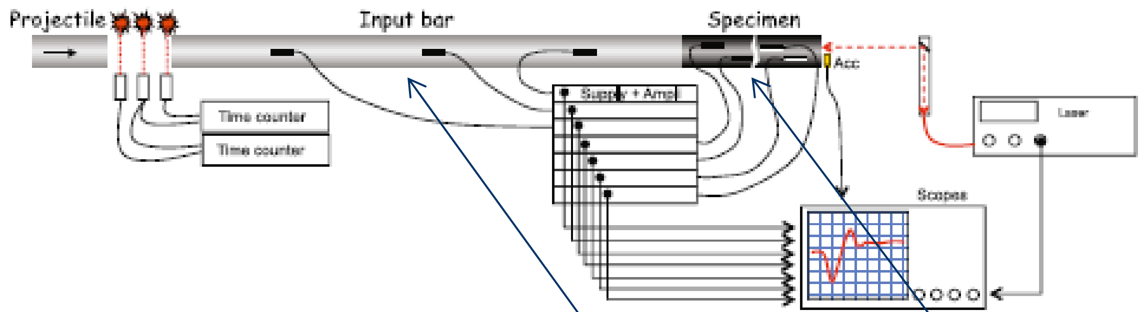


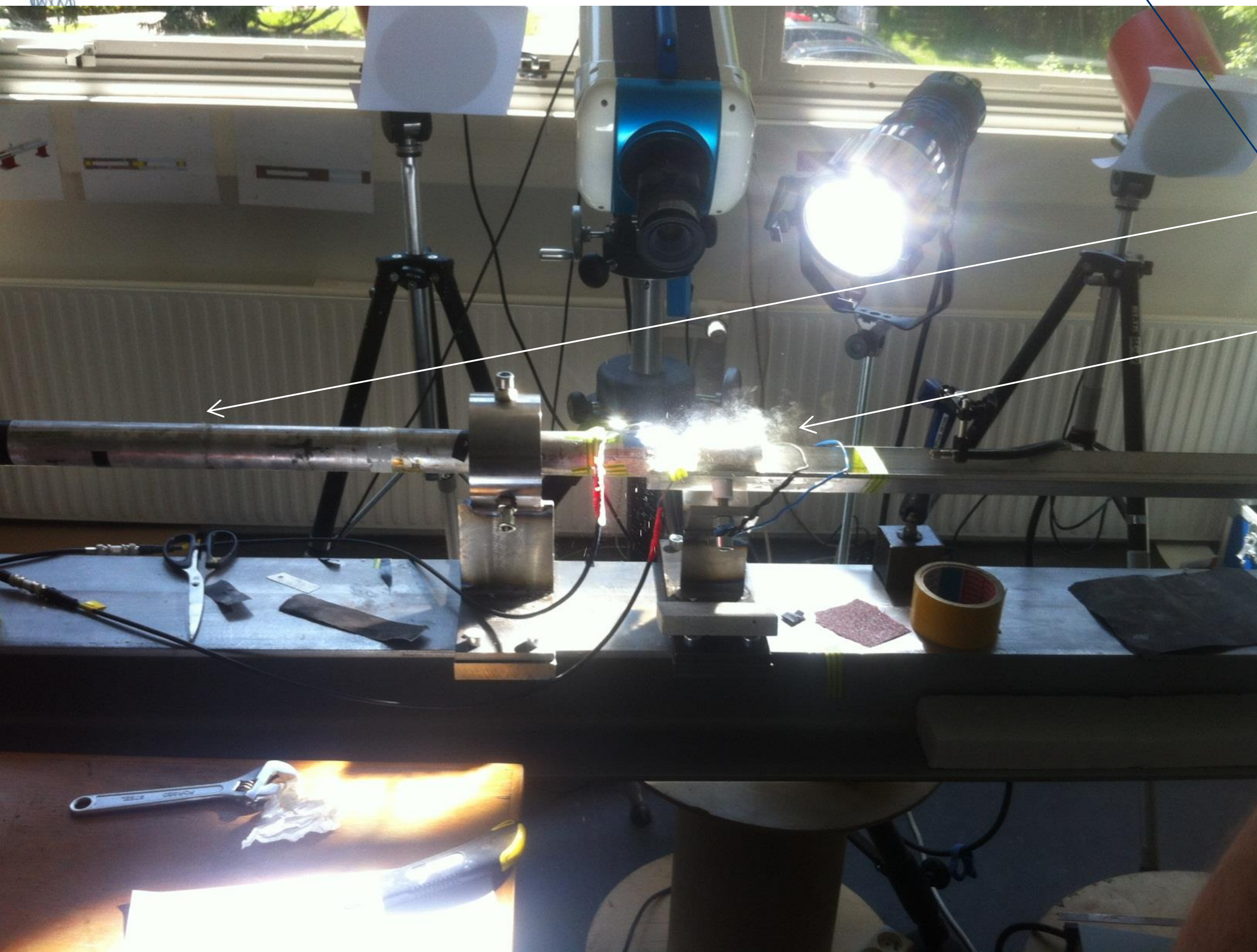


Mazars J., Grange S., Modélisation du fonctionnement des ouvrages en béton armé sous séisme, congrès AFPS, Paris 2015

High velocity loading
Spalling test

(Forquin et al. 2011)

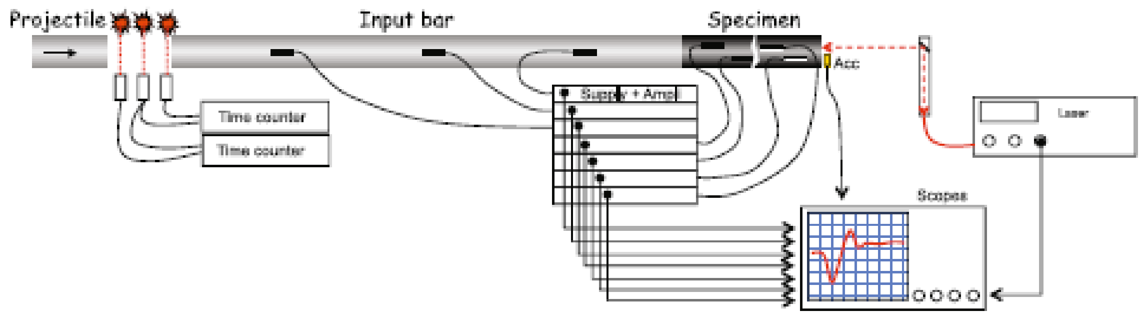


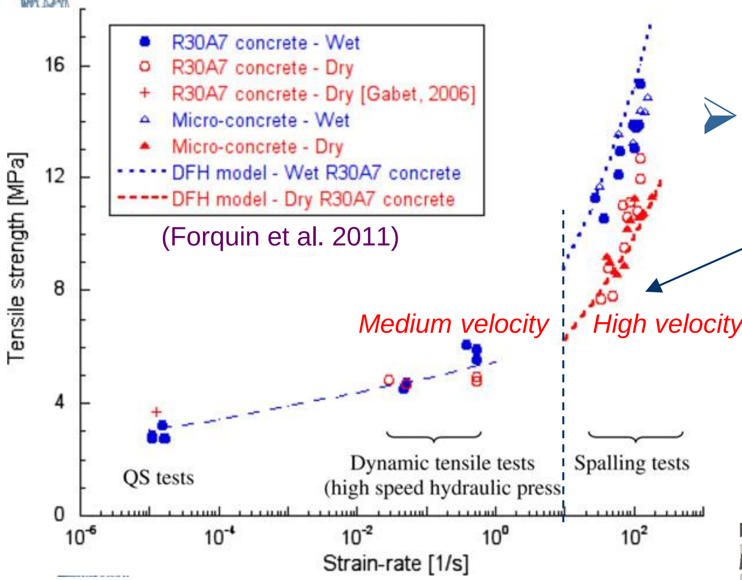


Hopkinson bar

Specimen

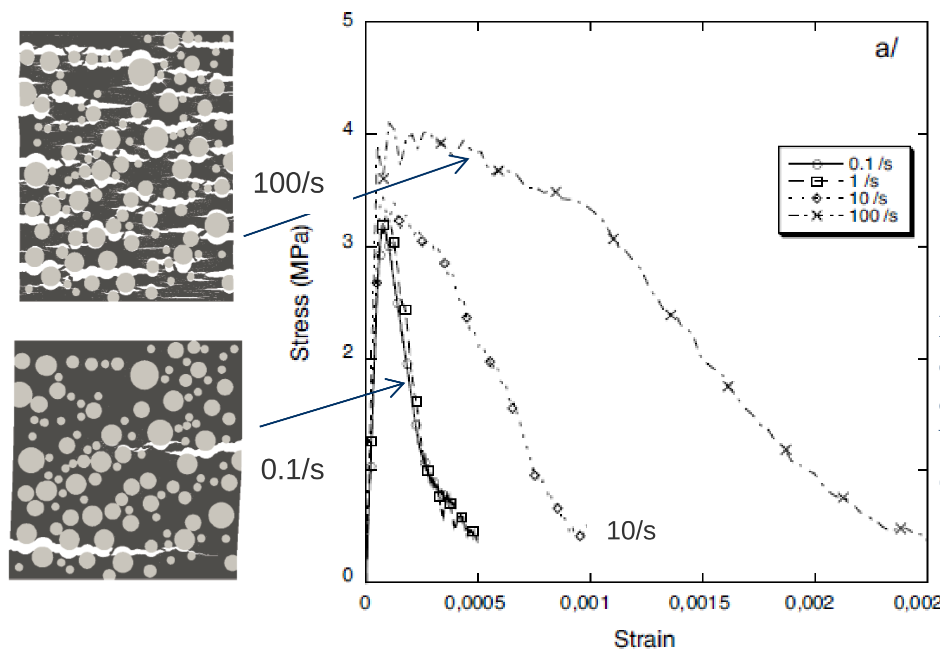
High velocity loading
Spalling test





➢ Experimental observations :

1. *Tensile strength increases with strain rate*
2. *Strain rate changes fracture processes*
   - Induces multi-fracturing
   - Increases fracture energy



Mesoscopic model : effect of srain rate on the tensile behaviour (Gatuingt et al 2013)

Tensile behavior evolutions with strain rate

Strain rate effects taken into account using the retarded damage concept

$$R_t = \varepsilon_{t0}^{d} / \varepsilon_{t0}^{s}$$

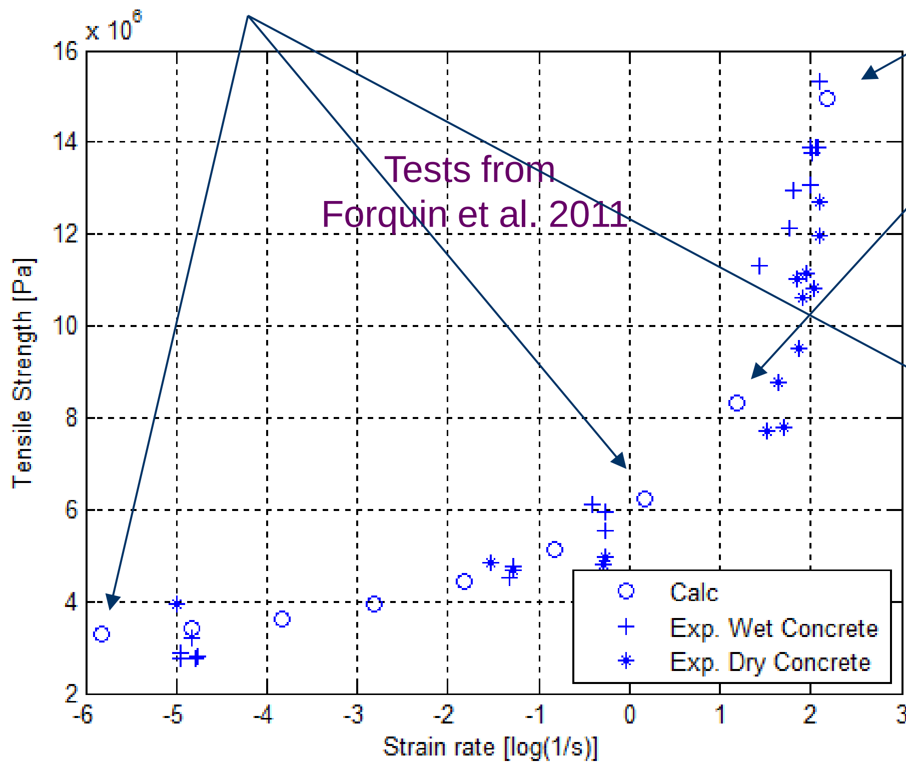
Two domains :

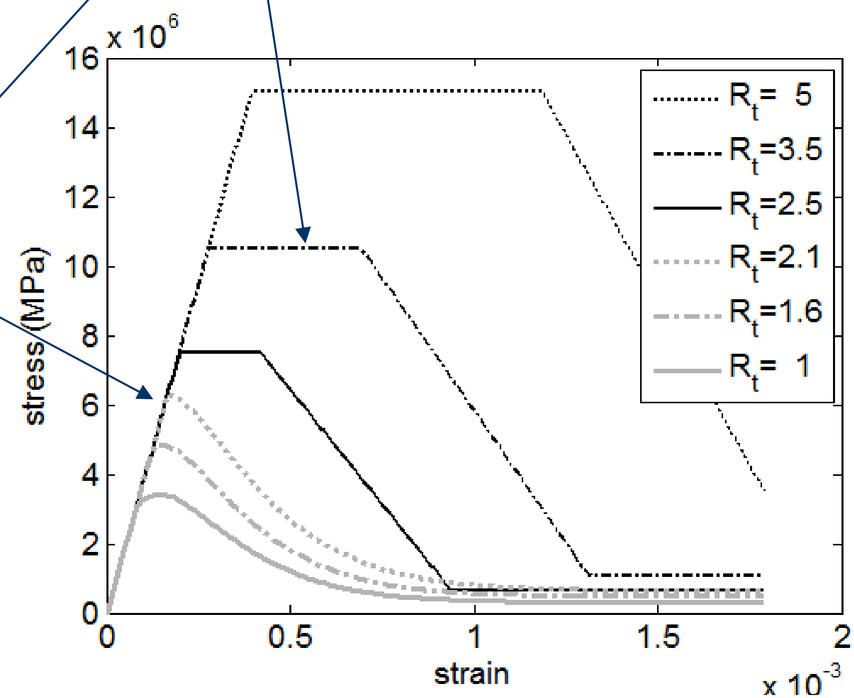
Low and medium velocity ($\dot{\varepsilon}$ <10/s)

$$R_t = 1.0 + a_t \dot{\varepsilon}^{bt}$$

High velocity ($\dot{\varepsilon}$ >10/s)

$$R_t = \min\left[c_t\, \dot{\varepsilon}^{dt}, M_t\right]$$

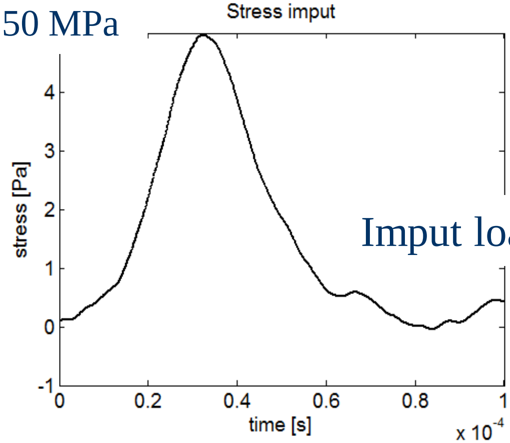




Erzar B., Forquin P., 2011, Experiments and mesoscopic modelling of dynamic testing of concrete, Mechanics of Materials 43

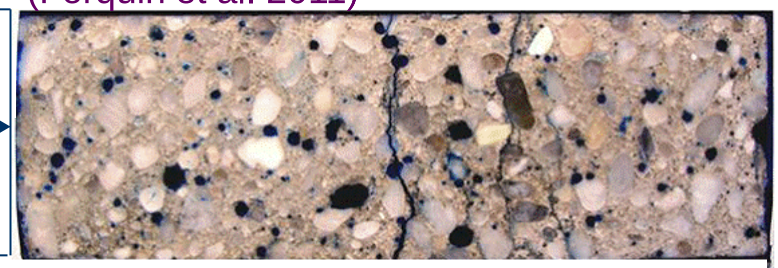
Spalling test : Simulation (explicit 1D)

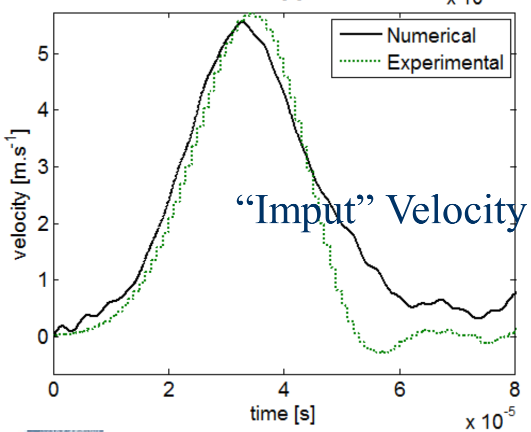
σ maxi
50 MPa

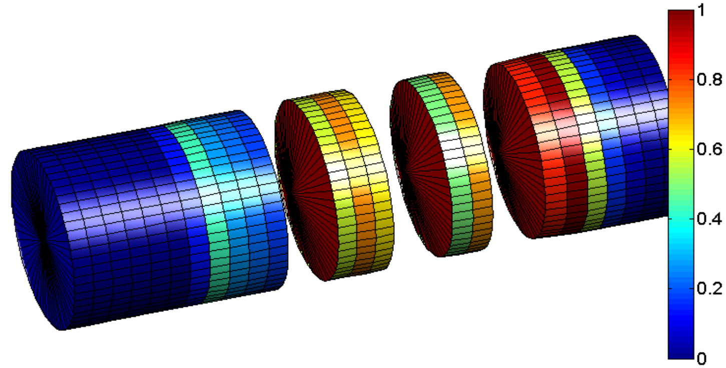


(Forquin et al. 2011)

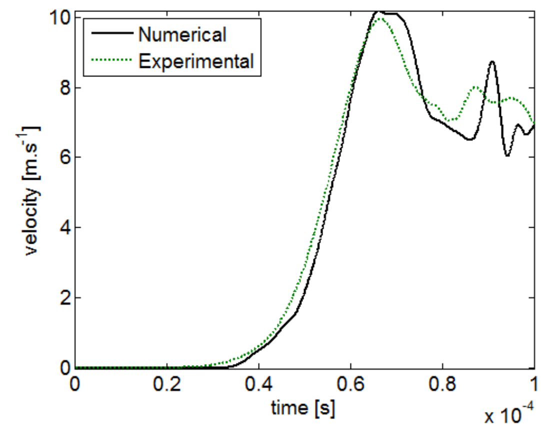
Imput loading

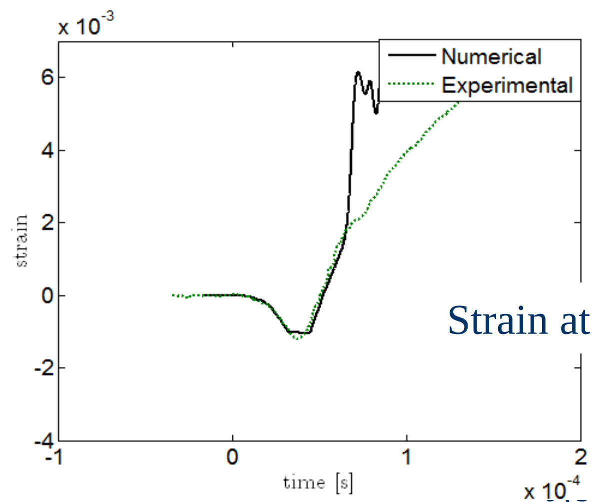






"Output" Velocity





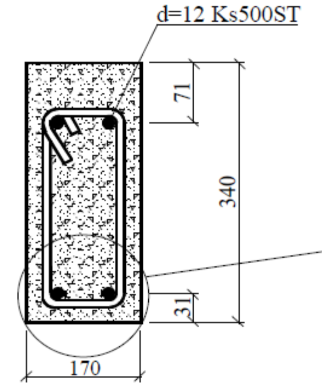
Strain at mid specimen

Erzar B., Forquin P., 2011, Experiments and mesoscopic modelling of dynamic testing of concrete, Mechanics of Materials 43

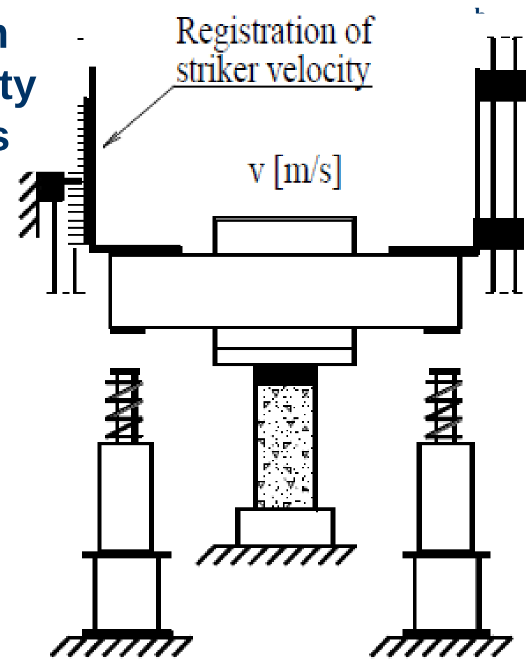
Experiment from Swedish Defence Research Agency (FOI)

Impact on a RC beam : Medium velocity loading

Ågårdh L, Magnusson J, Hansson H, 1999



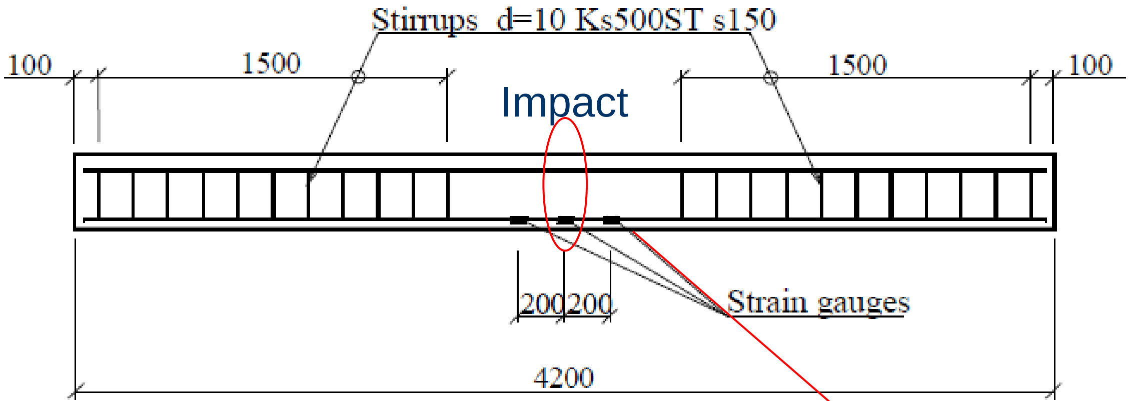
Mass : 718kg
Height: 2.68m
Impact velocity 6.7m/s

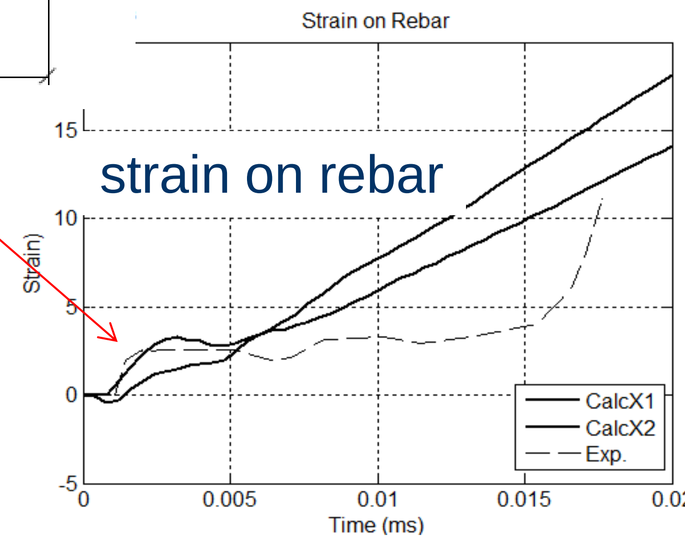


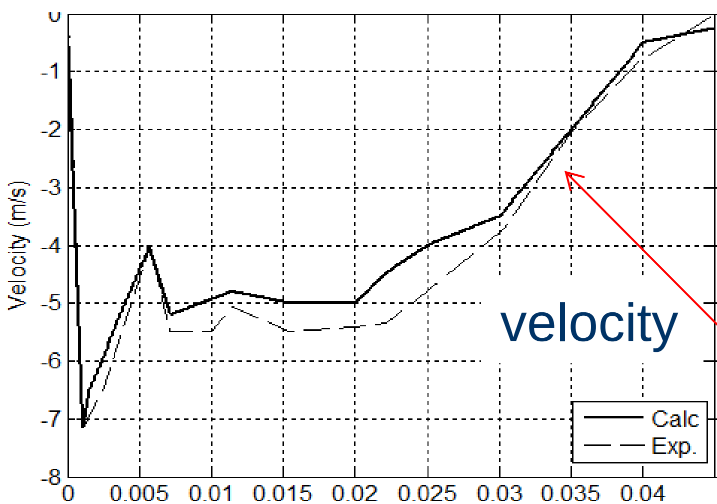
Ågårdh L, Magnusson J, Hansson H:."High Strength Concrete Beams Subjected to Impact Loading, an Experimental Study". Defence Research Establishment, Sweden. FOA-R--99- 01187-311—SE.1999.

Experiment/ MF calculation

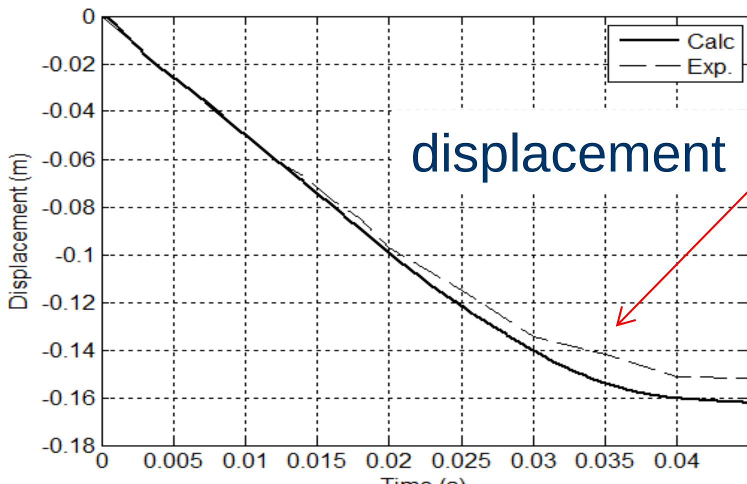
(30 beam elts, 10x2 fibers)

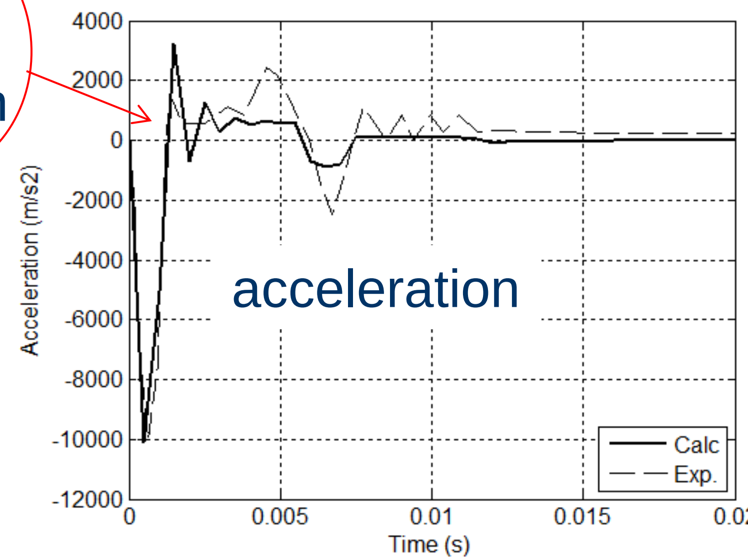






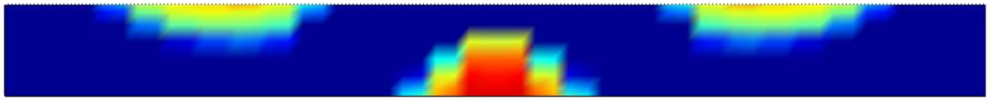
Impact section



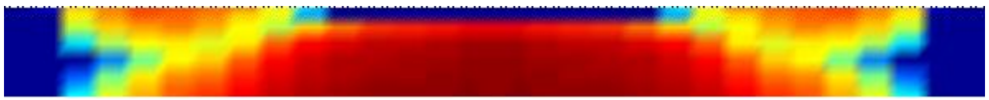


Experiment/ Calculation…
… again

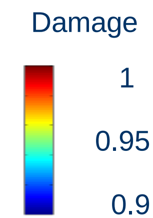
Tension damage contour

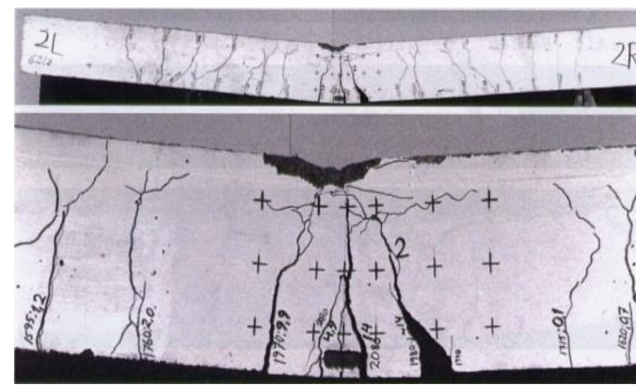


t= 2 10^{-3} s



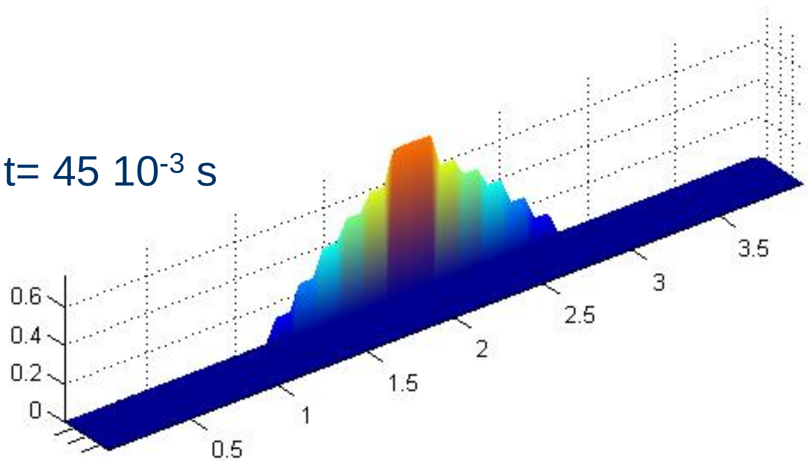
t= 45 10^{-3} s

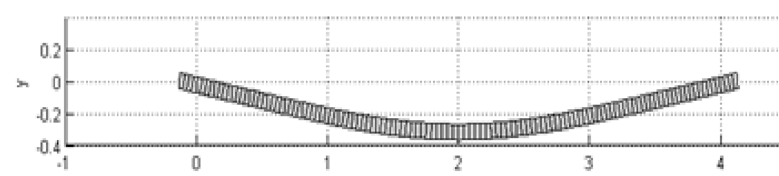




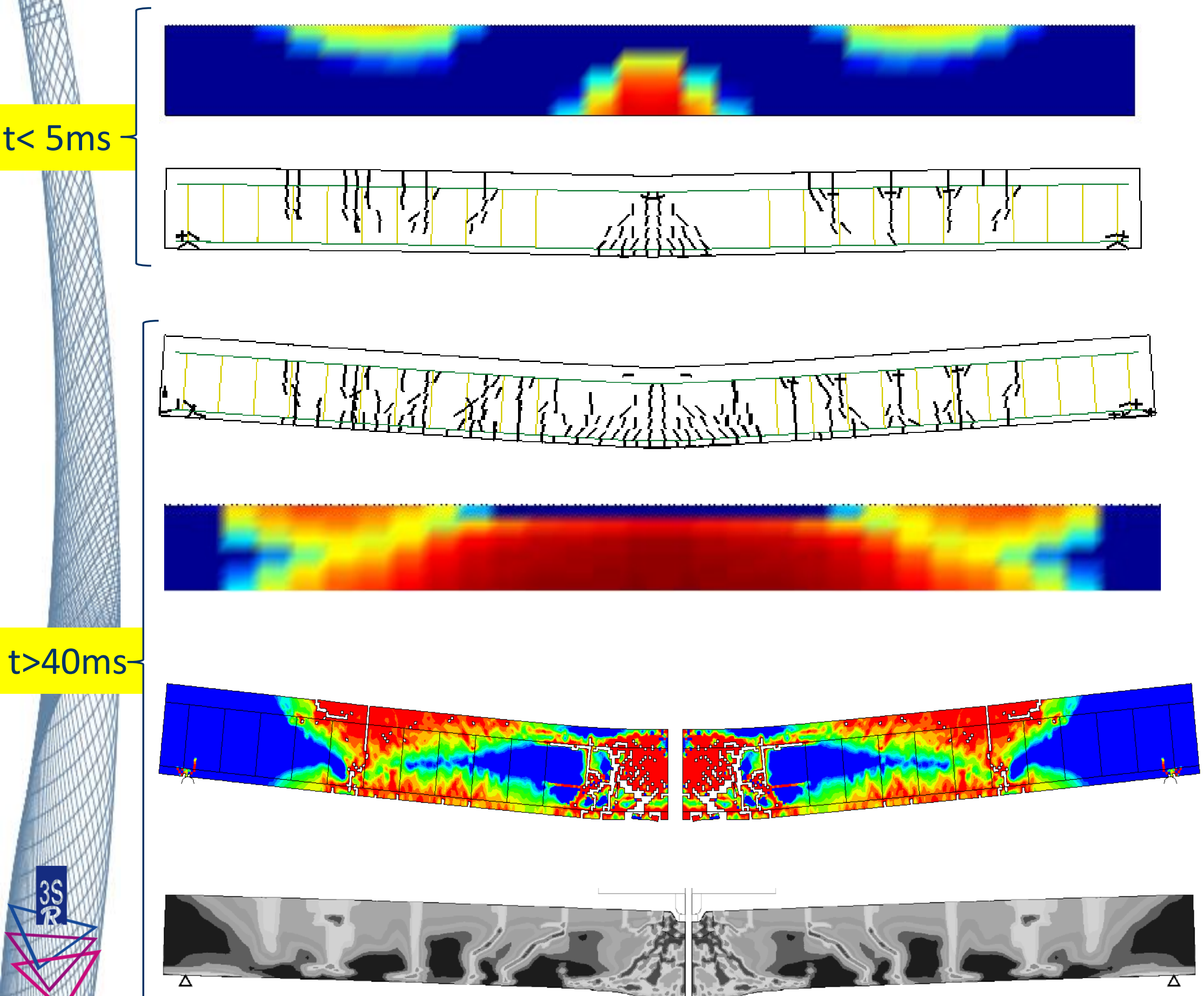
Compression damage contour

t= 45 10^{-3} s





Comparison of various calculations



1. **Present simplified modelling (1D)**
2. **Tuan Ngo and Priyan Mendis (RC impulsive model – 2D- 2005)**
3. **Present simplified modelling (1D)**
4. **Pontiroli et al (2D) PRM model 2004**
5. **M. Unosson - K&C concrete model (2D) 2001**

Conclusions

Central question: *is simplified modelling (MF beams, lattice elements) able to describe the response to low, medium and high velocity?*

Yes, but some requirement are needed

1. **Have relevant models :**
   - **Damage model for concrete including major behaviour effects (crack-closure, permanent strains, hysteretic loop,…)**
   - **Including the steel – concrete debounding effects**
2. **Take care to localization problems**
3. **Introduce strain rate effects**
   - **Retarded damage concept + Fracture energy evolution (2 domains) :**
     - **low and medium velocity (<10/s)**
     - **high velocity (>10/s)**
   - **Adapted dynamic solver**

…… major advantage : robustness and very low computer cost