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# Dynamic analysis of a multi-contact problem with clearances, application to the SFR fuel pins bundle.

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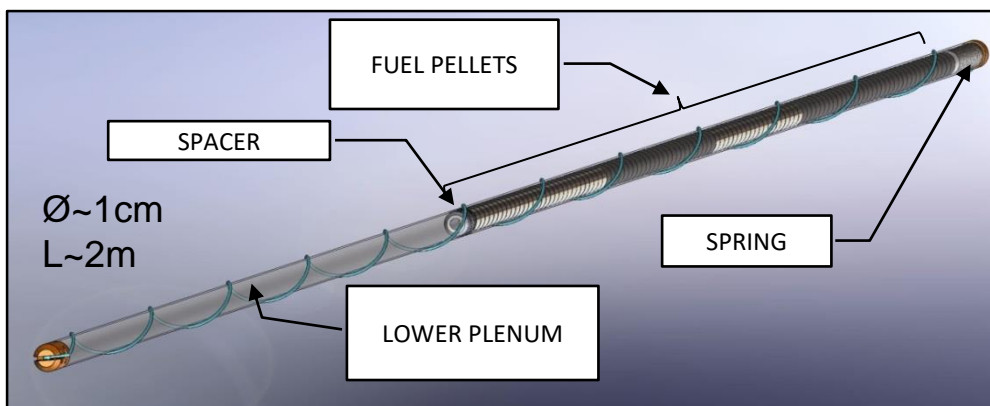
September, 11<sup>th</sup> 2017

EURODYN2017 – X<sup>th</sup> international conference on structural dynamics

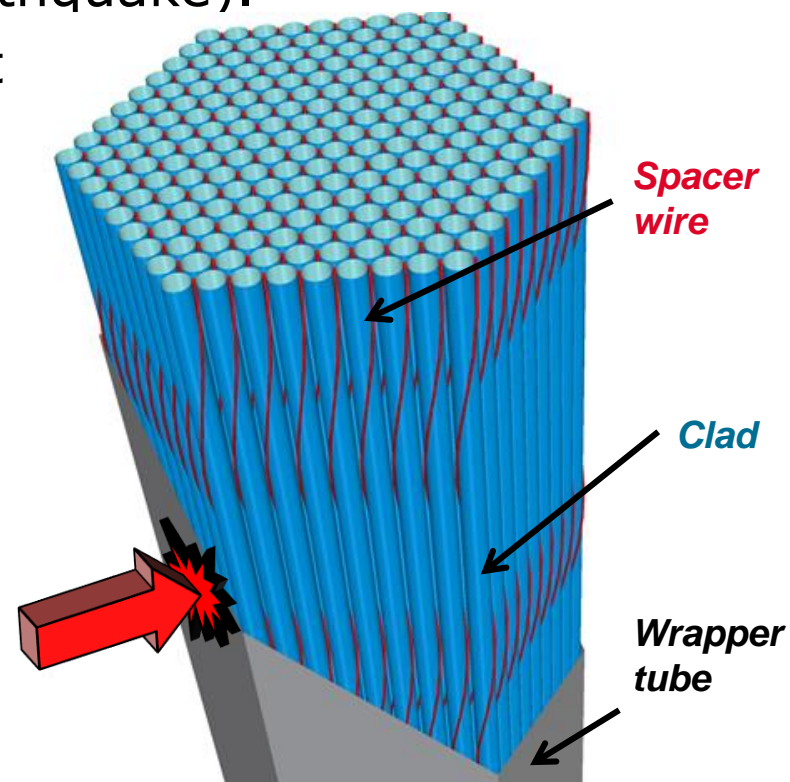
# Introduction

## ■ Goal

- Characterize the non-linear dynamical behavior of the ASTRID pins bundle with mounting gaps for different loads (handling, transport, earthquake).
- Ensure the integrity of the first containment barrier.



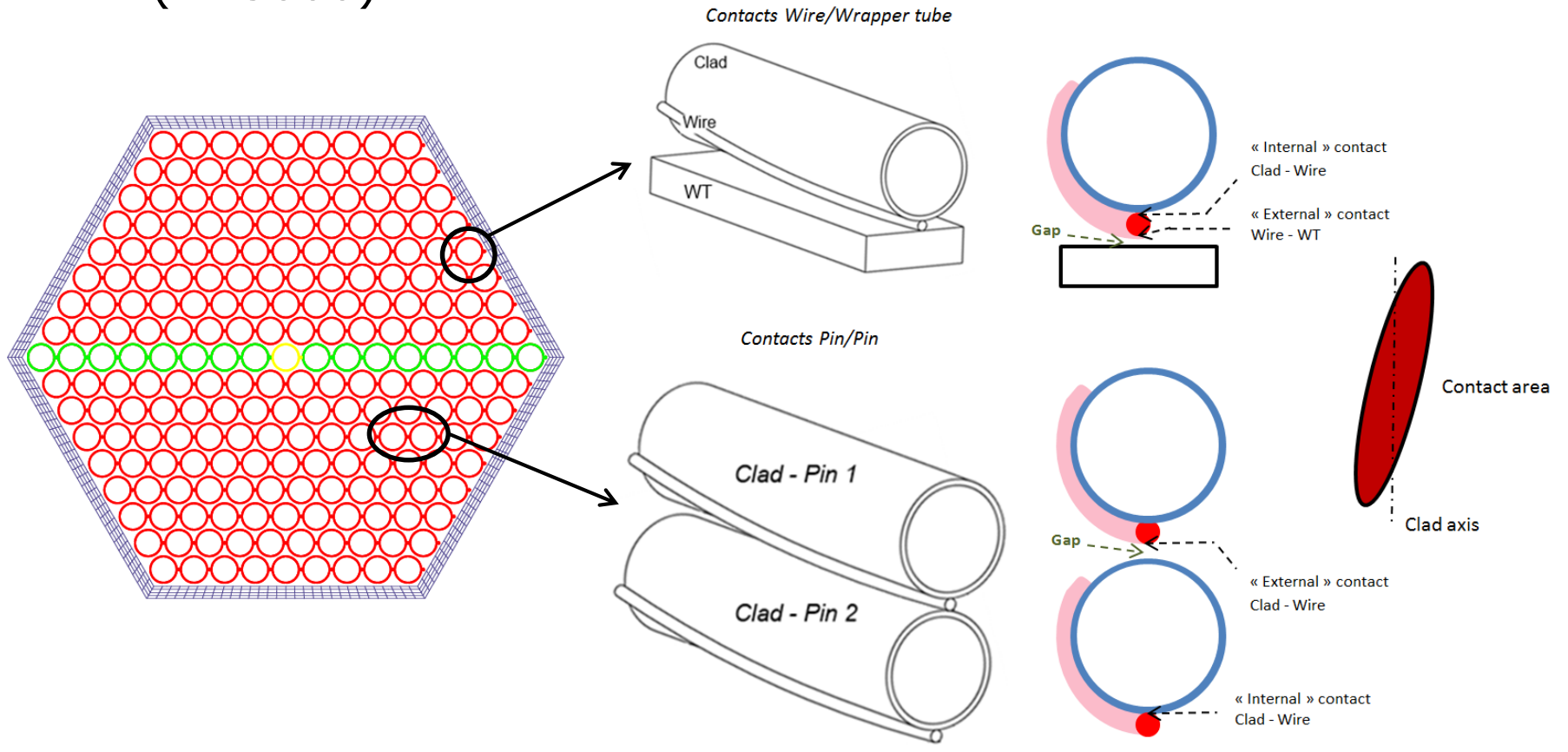
*A fuel pin*



*A fuel sub assembly*

# Introduction

- A large number of pins (217) and localized contact zone (~15000)

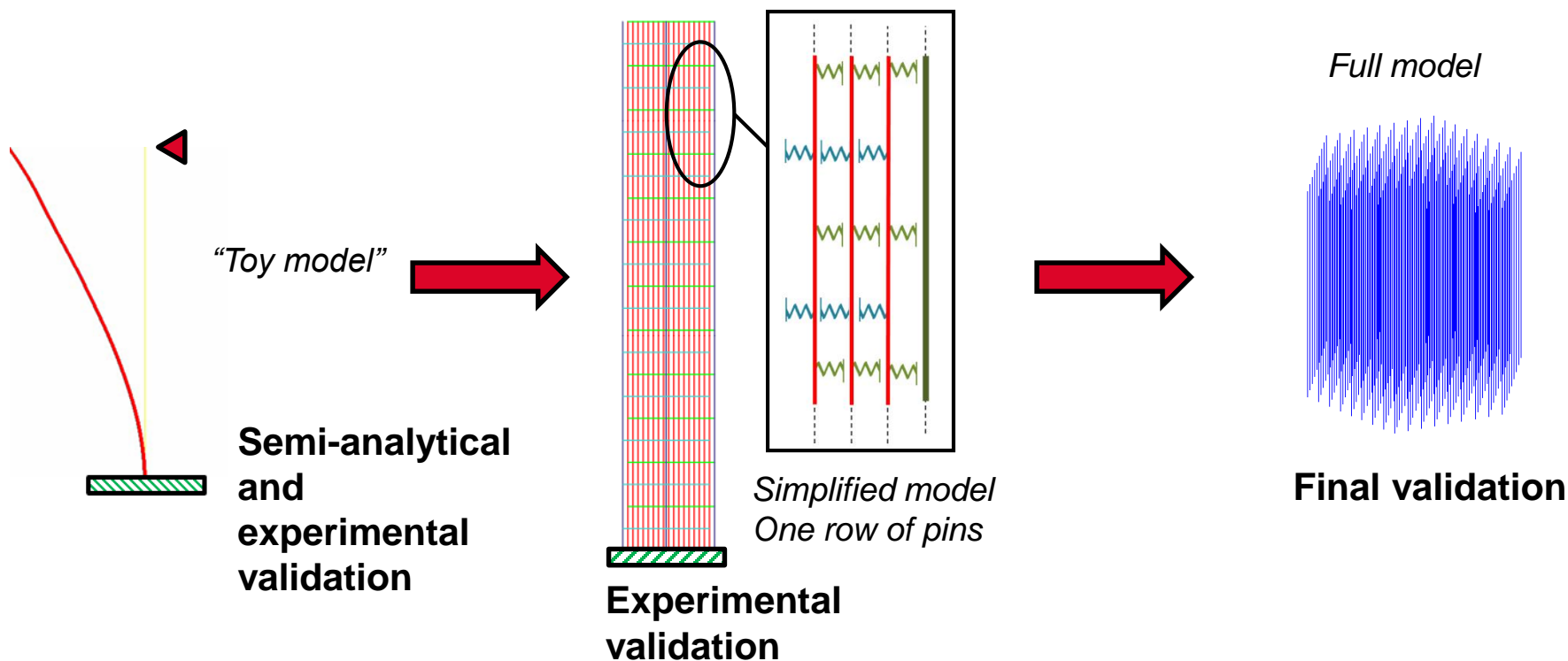


# Introduction

## — Hypothesis:

- Timoshenko beams
- Small deformations

## — Methodology of numerical method validation



# Clamped beam colliding on a spring

## ■ Numerical method (Cast3M finite element software)



- Explicit integration scheme (central difference method)
- Modal analysis without contacts
- Resolution of the fundamental equation of the dynamic on the modal base

$$\Phi^t M \Phi \ddot{q} + \Phi^t C \Phi \dot{q} + \Phi^t K \Phi q = \Phi^t F_{ext} + \Phi^t F_{shock}(u, \dot{u}).$$

- Modal recombination for each time step on contact points to estimate contact forces  $F_{shock}$
- Sub-structuring for the full model

# Clamped beam colliding on a spring

## ■ Semi-analytical method

### ■ Modal basis analysis of two basic problems



### ■ Resolution of the fundamental equation of the dynamic on the modal base

$$\ddot{q}_i + 2\xi_i\omega_i\dot{q}_i + \omega_i^2 q = 0$$

$$q_i(t) = e^{-\xi_i\omega_i t} (A_i \cos(\omega_d t) + B_i \sin(\omega_d t))$$

$$A_i = \frac{\int_{\Omega} u_0 \cdot \Phi_i}{\int_{\Omega} \Phi_i \cdot \Phi_i}; \quad B_i = \frac{\int_{\Omega} v_0 \cdot \Phi_i}{\omega_i \int_{\Omega} (\Phi_i \cdot \Phi_i)} + \frac{\xi_i}{\omega_i \sqrt{1 - \xi_i^2}} A_i \quad ; \quad \omega_d = \omega_i (1 - \xi_i^2).$$

$$u_f(x, t) = \sum X_{fi}(x) q_{fi}(t) \quad \longleftrightarrow \quad u_s(x, t) = \sum X_{si}(x) q_{si}(t)$$

Switching time ?

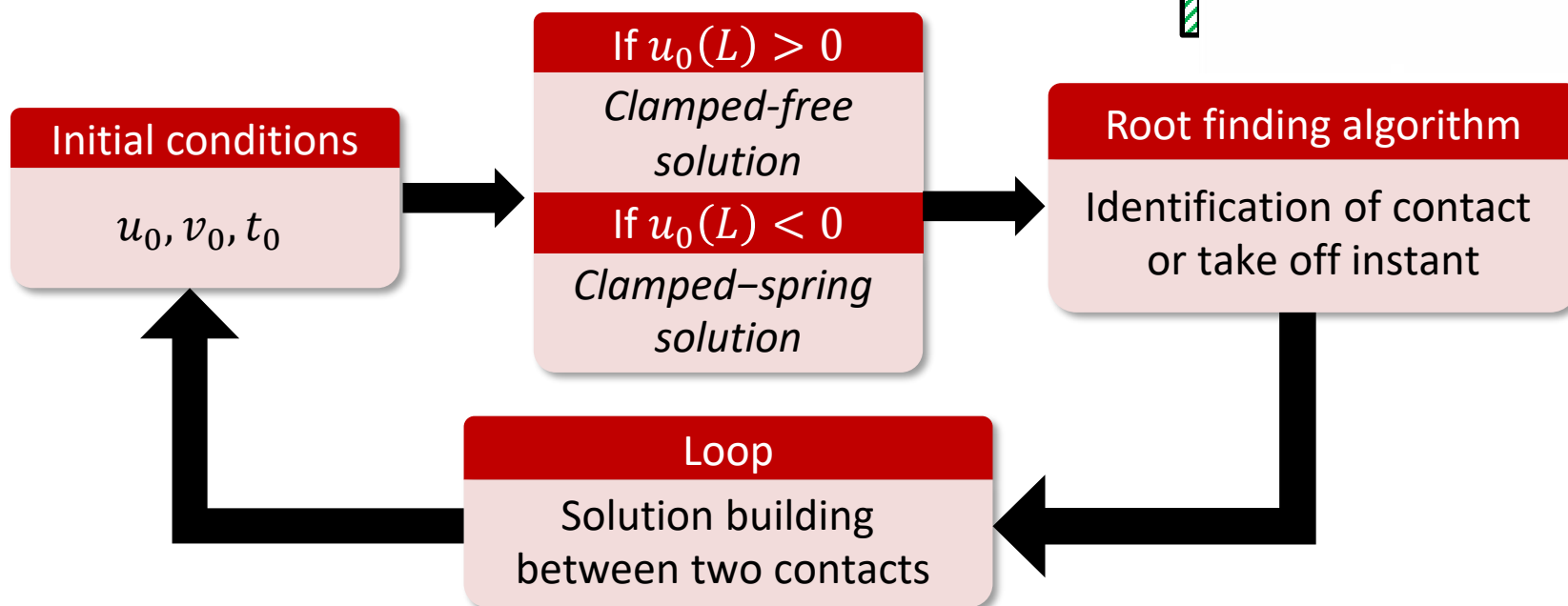
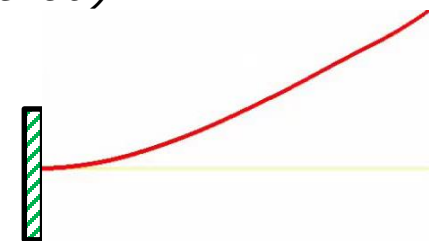
# Clamped beam colliding on a spring

## ■ Semi-analytical method

- Root finding algorithm to find the switching time

$$t_{n+1} = t_n - \frac{f(t_n)(t_n - t_{n-1})}{f(t_n) - f(t_{n-1})} \quad (\text{Secant method})$$

- Creation of the solution

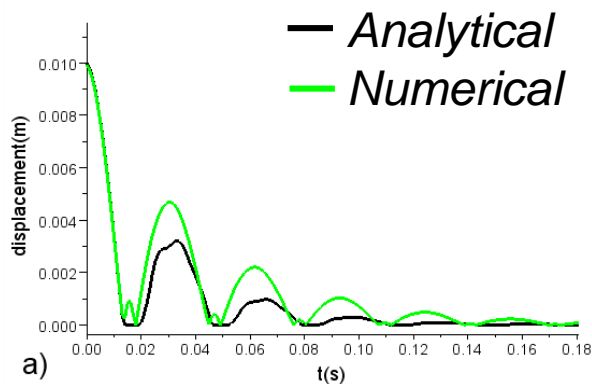




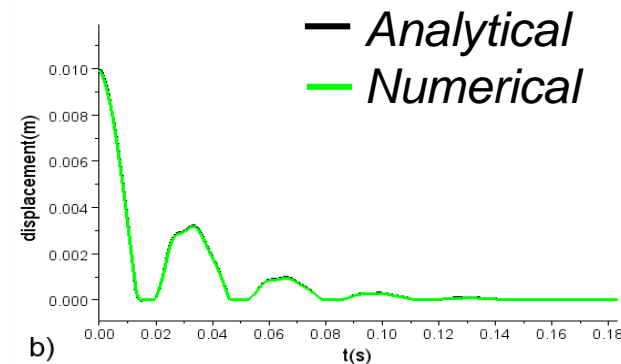
# Clamped beam colliding on a spring

## Results : displacements

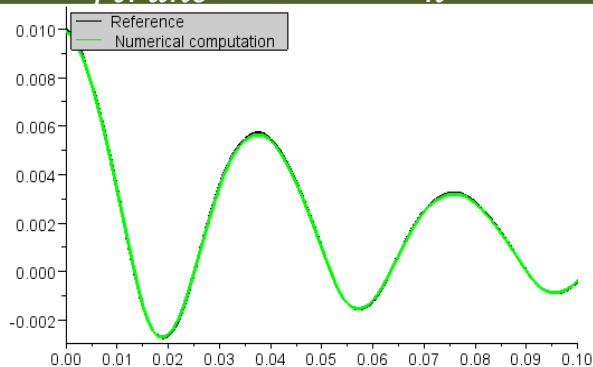
$$R_{ftrunc} = 10 / R_k = 3000$$



$$R_{ftrunc} = 300 / R_k = 3000$$



$$R_{ftrunc} = 300 / R_k = 5$$



$$R_k = \frac{K_{spring}}{K_{bending}},$$

Hardness of the contact

$$R_{ftrunc} = \frac{f_{trunc}}{f_1}$$

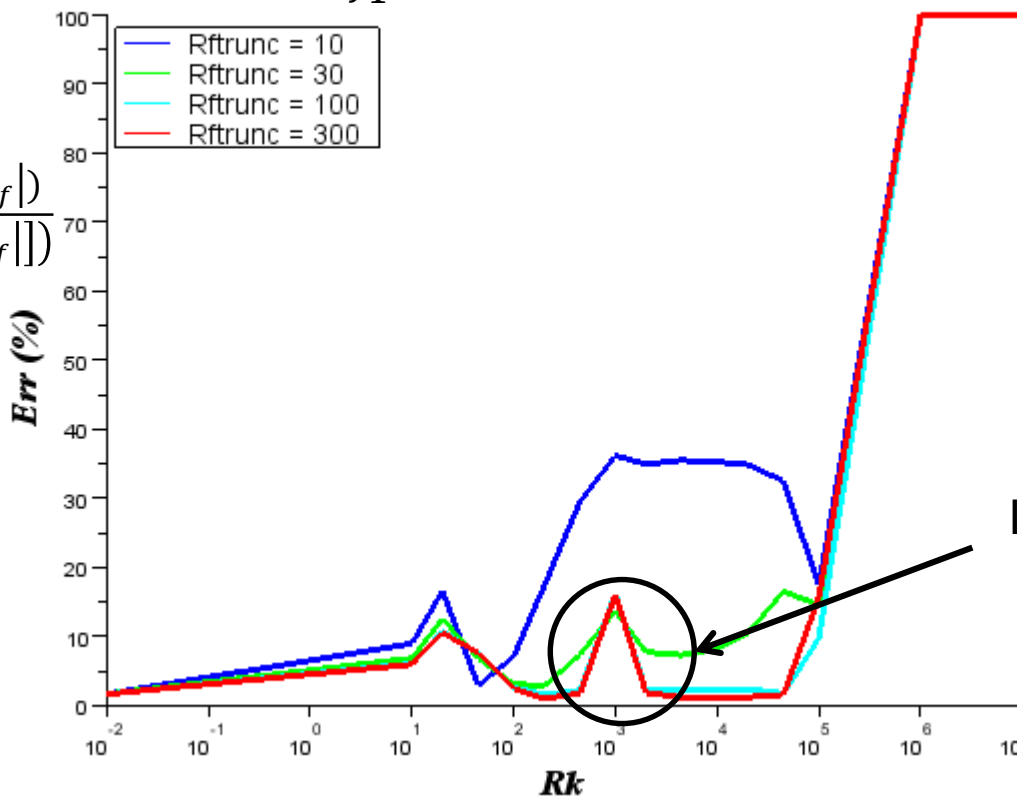
# Clamped beam colliding on a spring

## Validation – Frequency truncation

$$R_{ftrunc} = \frac{f_{trunc}}{f_1}$$

reference = semi-analytic method

$$\text{Err} = \frac{\max(|\Gamma_{num} - \Gamma_{ref}|)}{\max(|\Gamma_{num}|, |\Gamma_{ref}|)}$$



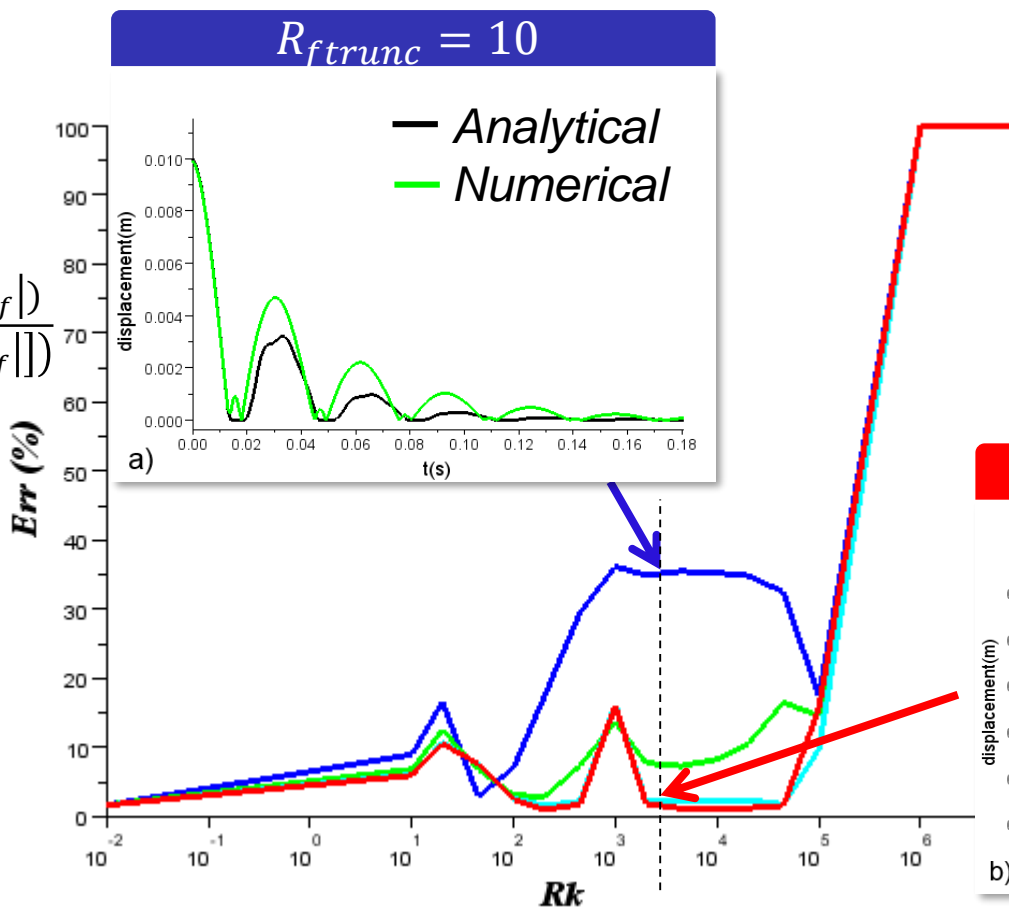
Local error when  
 $t_{contact} \approx t_{bending\ waves}$

$$R_k = \frac{K_{spring}}{K_{bending}}$$

# Clamped beam colliding on a spring

## Validation - Frequency truncation

$$\text{Err} = \frac{\max(|\Gamma_{num} - \Gamma_{ref}|)}{\max(|\Gamma_{num}|, |\Gamma_{ref}|)}$$

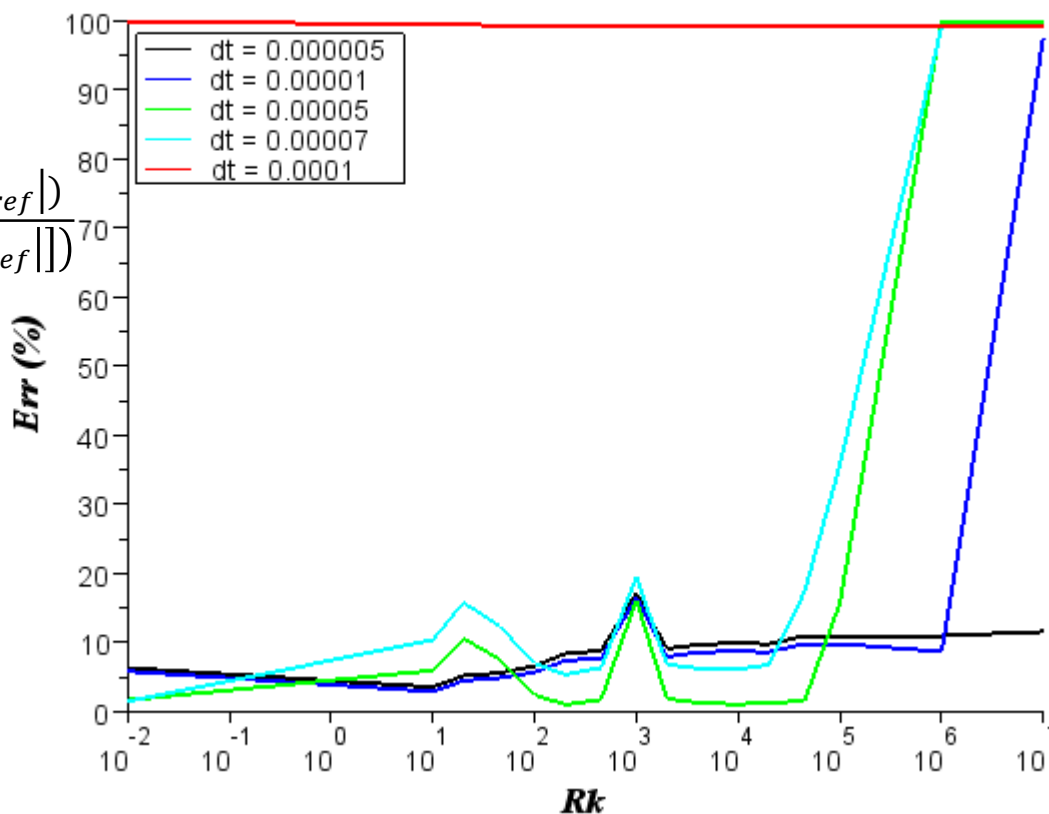


- A high frequency truncation is necessary when  $R_k$  is high.

# Clamped beam colliding on a spring

## Validation – Time step

$$\text{Err} = \frac{\max(|\Gamma_{num} - \Gamma_{ref}|)}{\max(|\Gamma_{num}|, |\Gamma_{ref}|)}$$



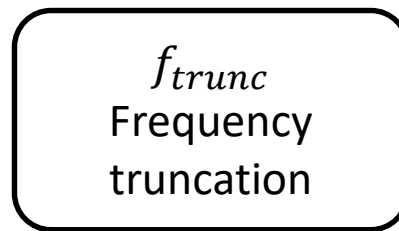
- A small time step is needed for a high  $R_k$
- A small time step doesn't mean a greater accuracy.

# Clamped beam colliding on a spring

$$\frac{1}{\pi} \sqrt{\frac{k_s}{m}}$$

*Frequency of the shock  
of a mass m*

$\ll$



$<$

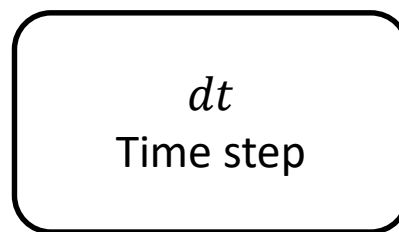
$$\frac{1}{4dt}$$

*Explicit scheme condition*

$$0,8 dt_{maxi}$$

*A small time step doesn't  
involve a greater accuracy*

$<$



$<$

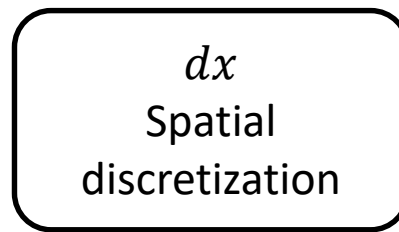
- $\frac{1}{4f_{trunc}}$
- $\frac{\pi}{2} \sqrt{\frac{m}{k_s}}$

*Explicit scheme*

*Time shock*

$\emptyset$

$<$



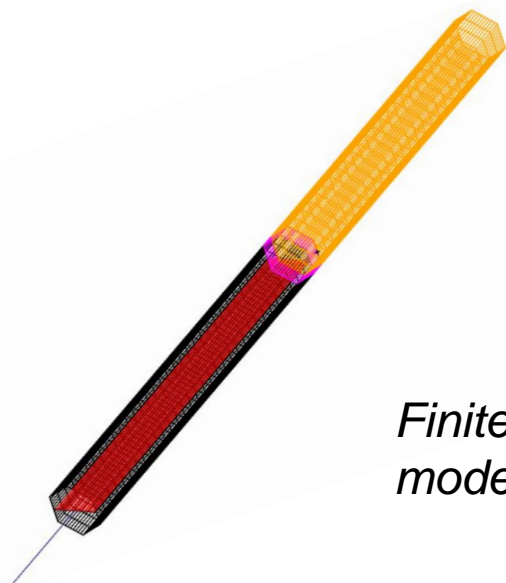
$<$

$$\frac{\lambda_{mini}}{4} = \frac{c_{bend}}{4f_{trunc}}$$

*Bending wave propagation*

# Dynamical behavior of a tube bundle

## ■ Application to the SFR tube bundle

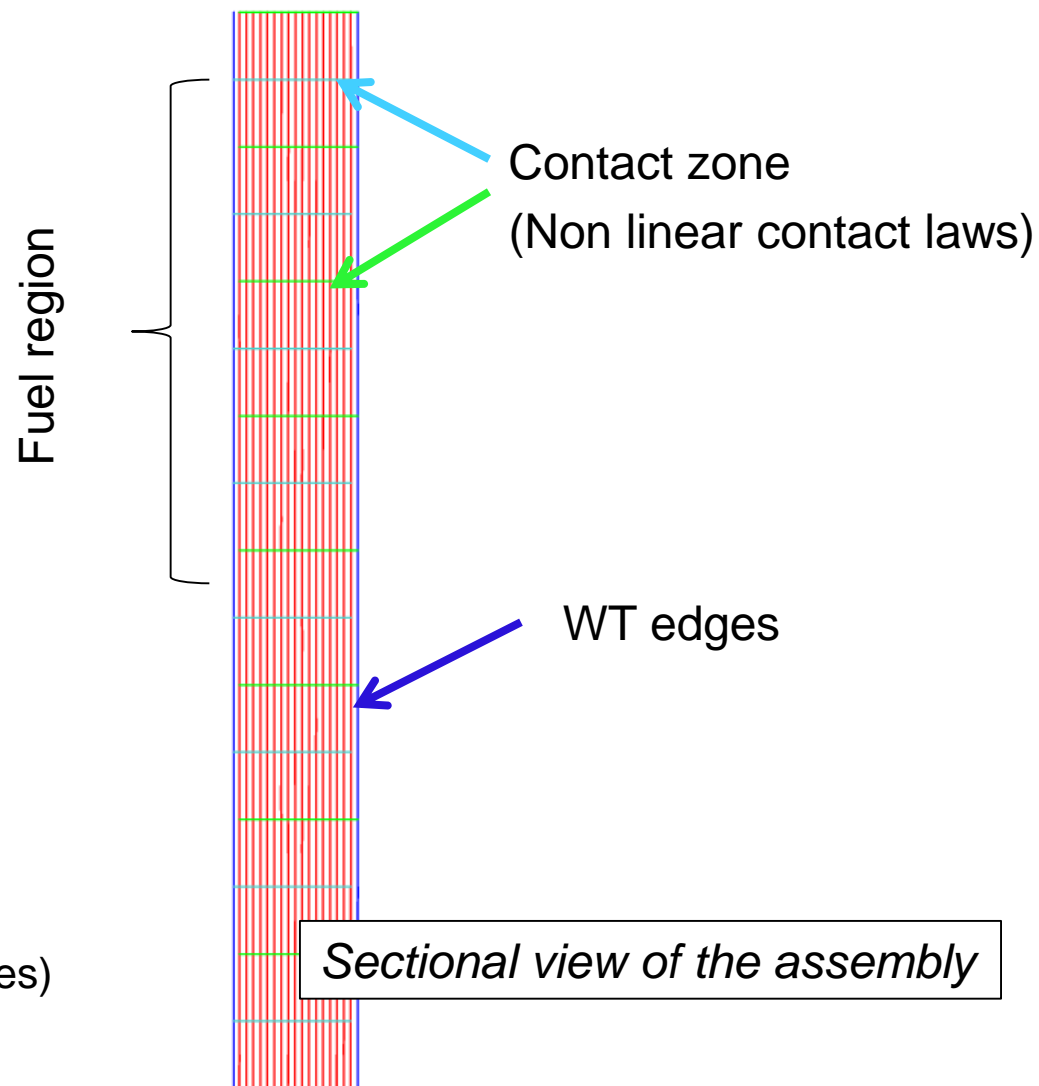


*Finite element model*

■ Fuel pins : Timoshenko beams

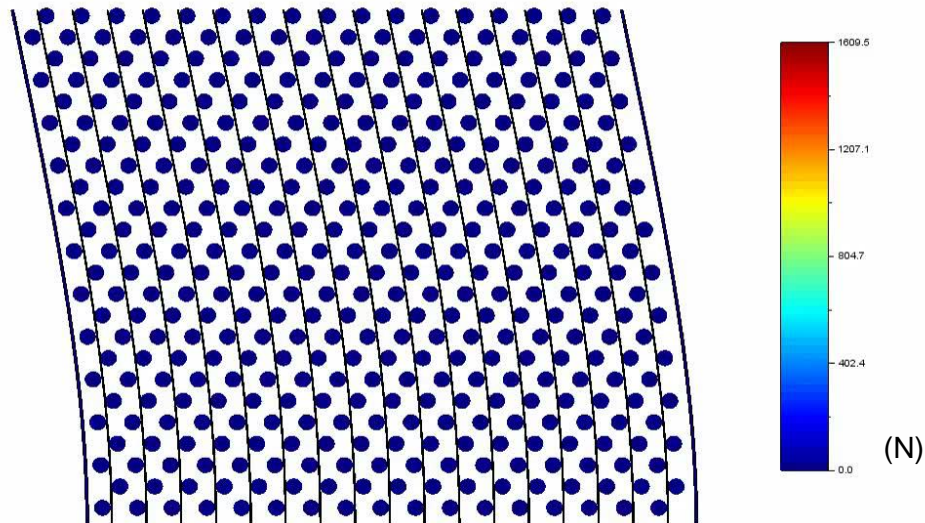
■ Wrapper tube : Shells

One row modeled (~500 contact zones)



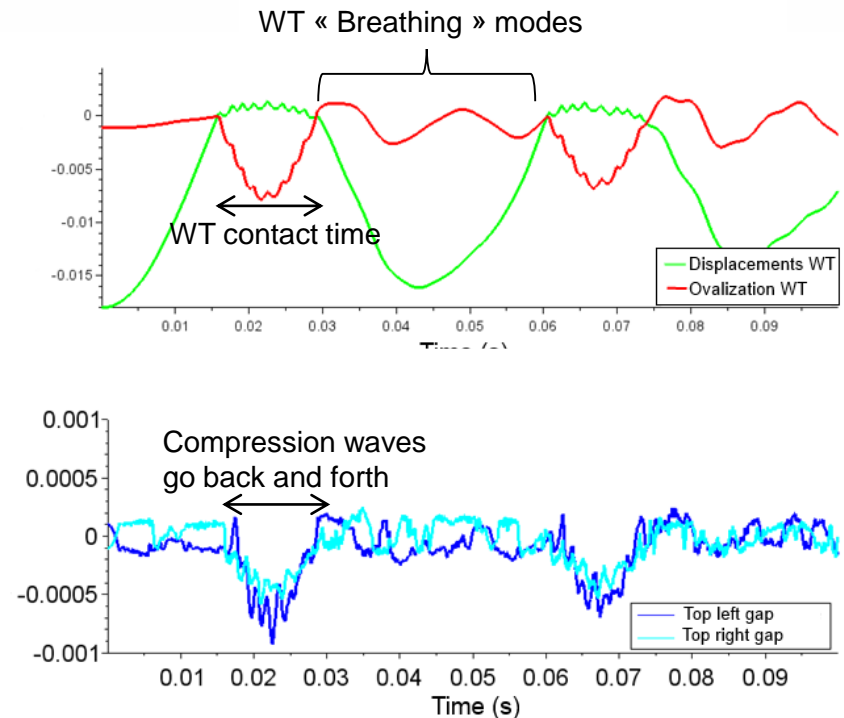
# Dynamical behavior of a tube bundle

## Release of an assembly in bending on a rigid stop



### Several phenomena at different time scale

- WT contact time (~20ms)
- WT breathing waves (~15ms)
- Compression waves in the bundle (~3ms)
- Bending waves in the bundle (~5ms)
- Local phenomena in a contact zone if there is a gap (<0.5ms)



# Dynamical behavior of a tube bundle

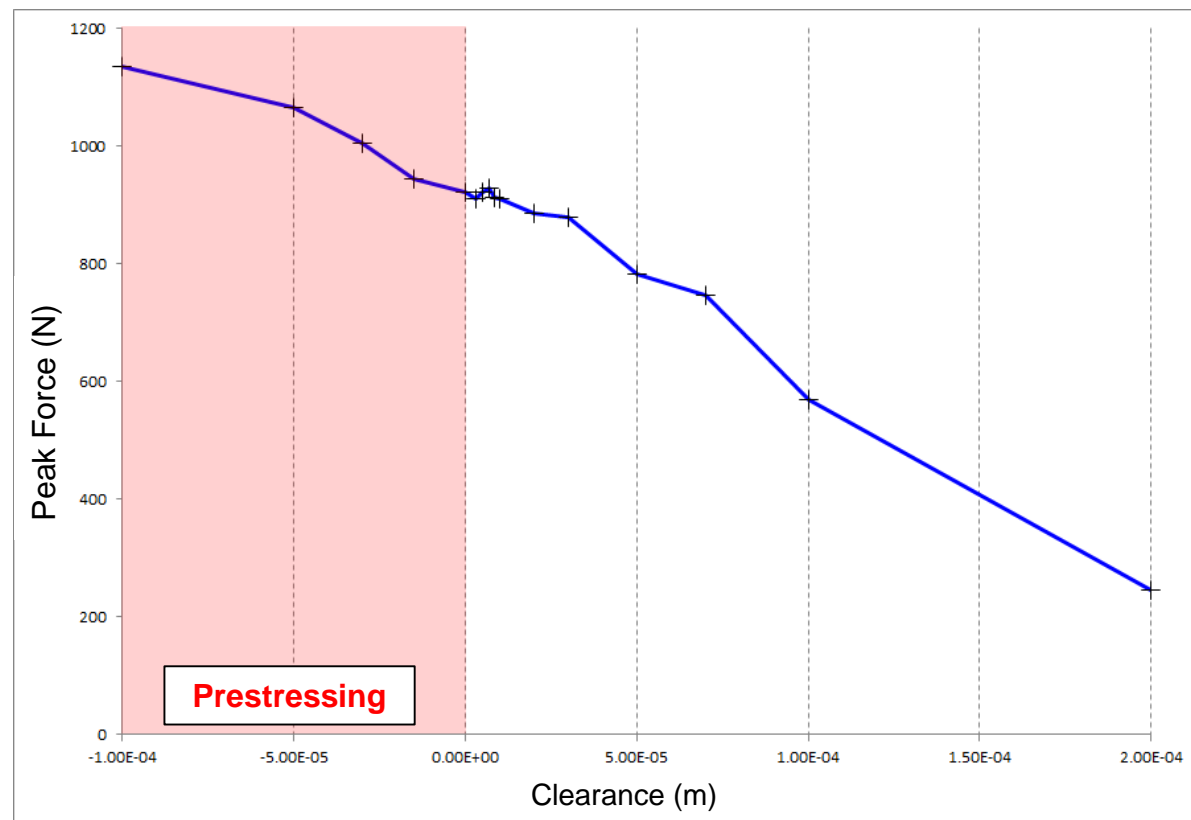
## ■ Peak force depending on clearance

■ Linear decrease with clearance

■ Similar to a Newton's cradle behavior

*Donahue 2008*

*Hutzler 2004*





# Conclusion and outlook

## ■ Analytical validation of a contact problem

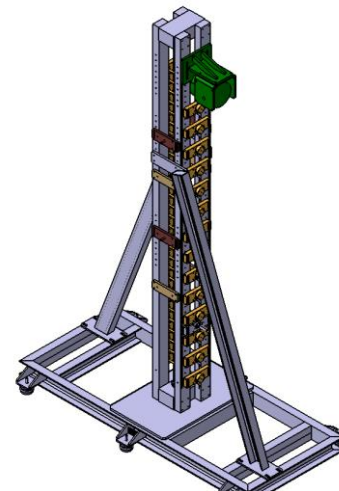
- Semi-analytical solution
- Numerical method choice
- Creation of a validity domain of the numerical model

## ■ Application to a pin bundle

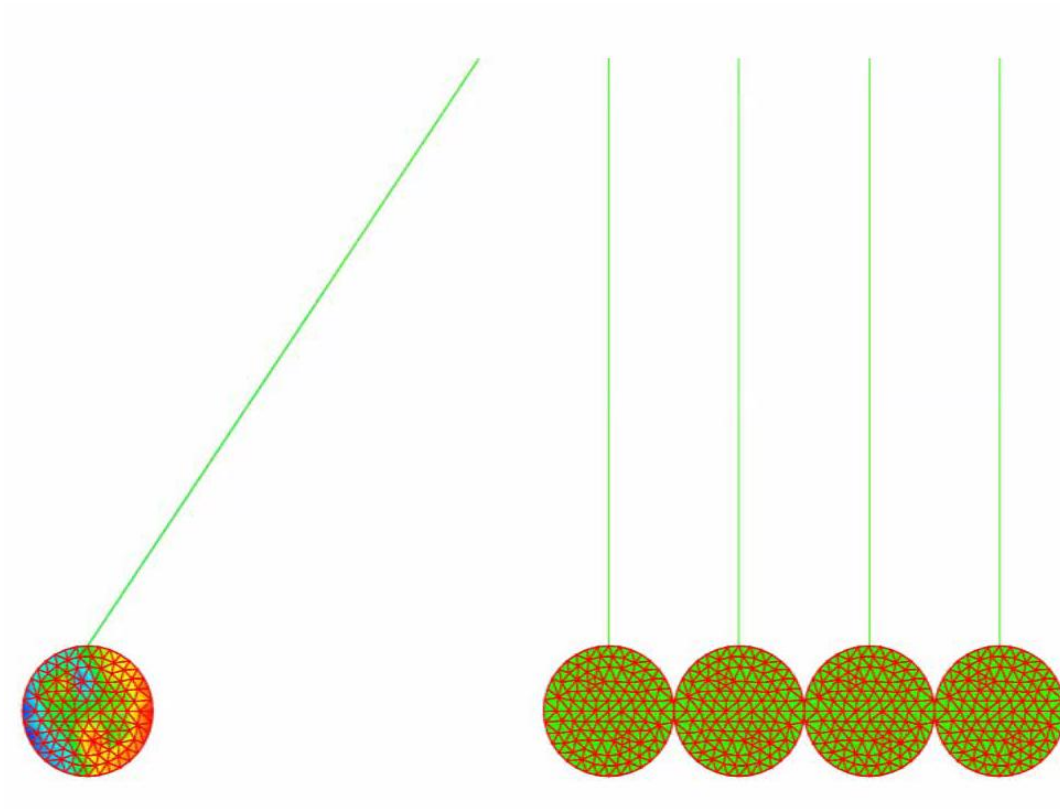
- Several phenomena highlighted.
- Beneficial impact of clearance size for an homogeneous distribution.

## ■ Outlooks

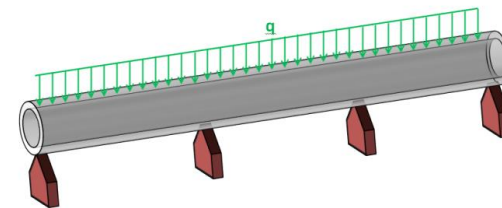
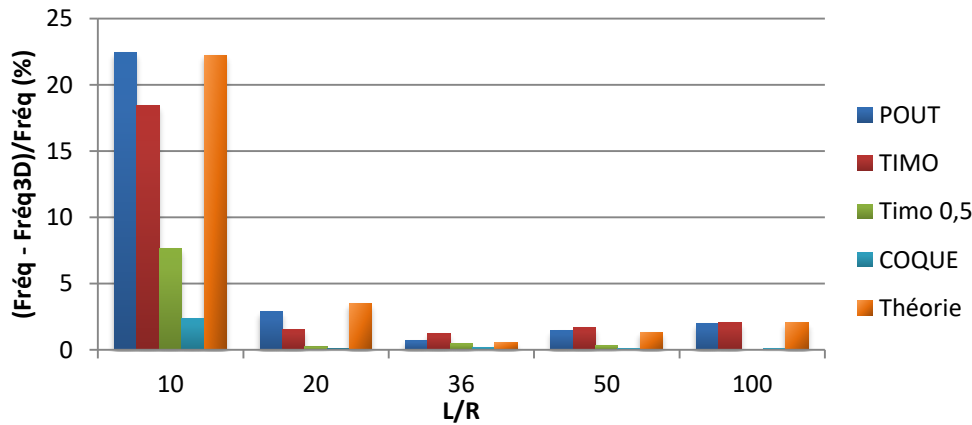
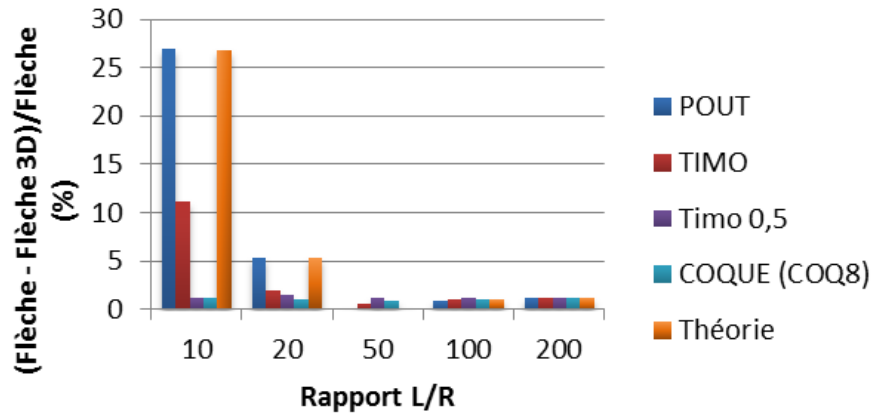
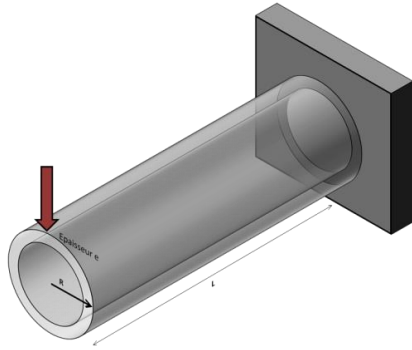
- Study of heterogeneous distribution of clearances.
- Experimental validation
- Influence of the fluid



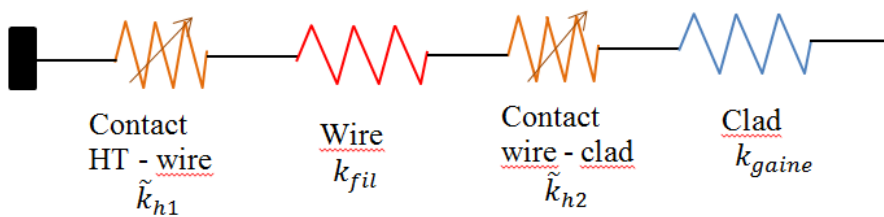
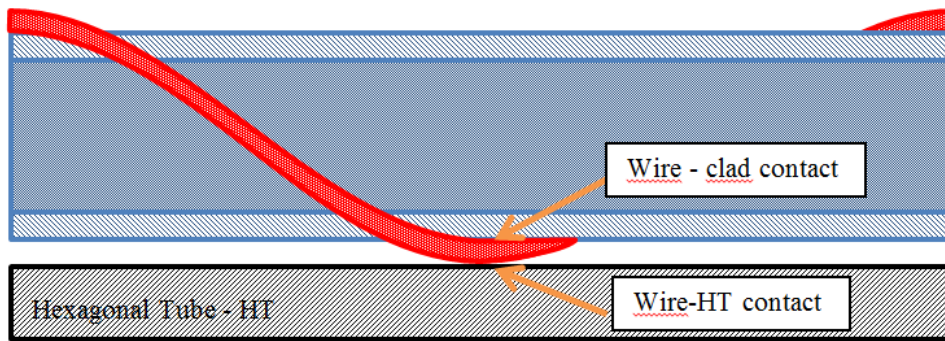
Thanks for your attention.



## Rationale of the selection of timoshenko beam.



- Contact law



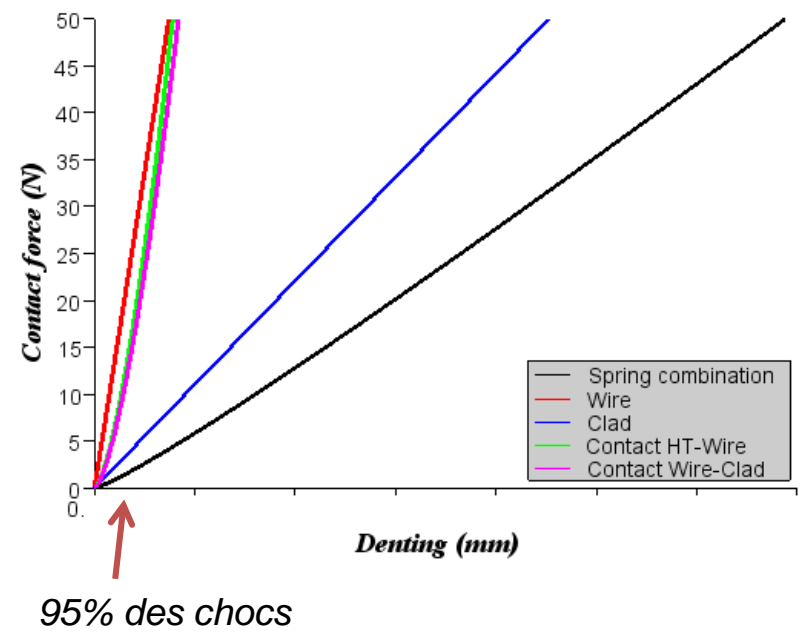
**Hertzian spring**

$$F = \tilde{k} \delta^{\frac{3}{2}}$$

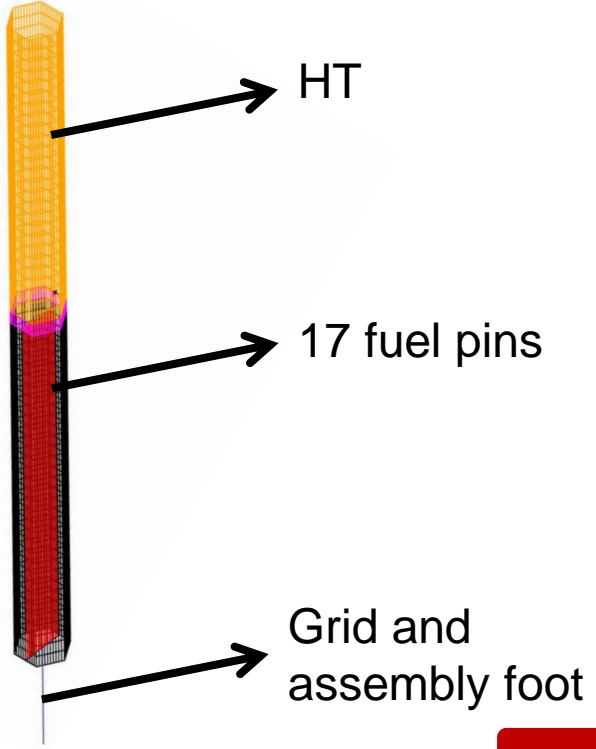
**Linear spring**

$$F = k \delta$$

- Non-linear stiffness : Hertz theory
- Shell stiffness : [Millard 1981] , [Madureira 2004,2010,2015]



- Sub-structuring



**Modal analysis**  
 $\Phi_{HT}, \Phi_{pin_1}, \dots$

**Connectivity mode**  
 $\Psi_{c1}, \Psi_{c2}, \dots$

$$x = \Sigma \Phi_i q_i + \Sigma \psi_j q_{Lj},$$
$$B_r = [\Phi, \Psi]$$

$$\hat{K} = B_r^t K B_r \quad \text{et} \quad \hat{M} = B_r^t M B_r$$

**Modal analysis on  $\hat{K}$  and  $\hat{M}$**   
*Eigenvalues and Eigenvectors written on  $B_r$*



**Modal recombination**  
*Eigenvalues and Eigenvectors written on physical basis*