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An effective and efficient approach for simulating the mechanical behaviour of metal foam filled tubular structures

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Towards the perfect structure...

Side crash test of a FIAT 500

Foam filled metal tubes

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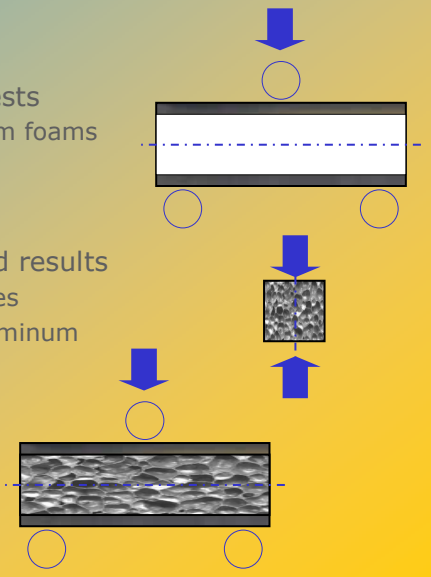
Outline of the presentation

- Introduction to metal foams
- FEM simulation approaches
- Description of experimental tests
  - Axial compression of aluminum foams cylindrical specimens
  - 3 point bending of empty and foam filled round tubes
- Description of FEM models and results
  - 3 point bending of empty tubes
  - Axial compression of pure aluminum foams cylindrical specimens
  - 3 point bending of foam filled round tubes
- Conclusions



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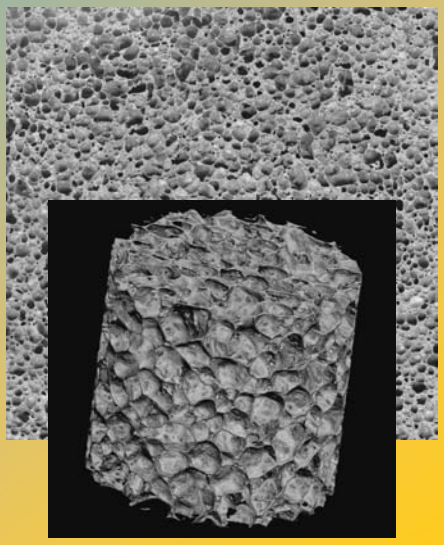
Introduction to metal foams

CELLULAR METALS

- are heterogeneous materials formed by a three-dimensional metallic matrix with gas-containing pores occupying more than 70 vol-% (relative density ρ_r less then 0.3) i.e. honeycombs, foams, sponges.
- They are made up of an interconnected network of solid struts or plates which form the edges and faces of cells.



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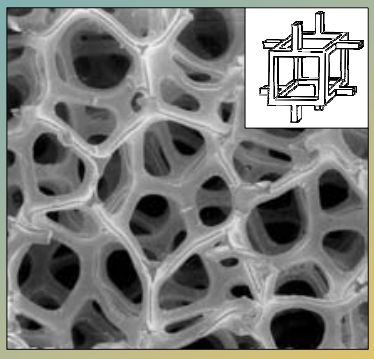
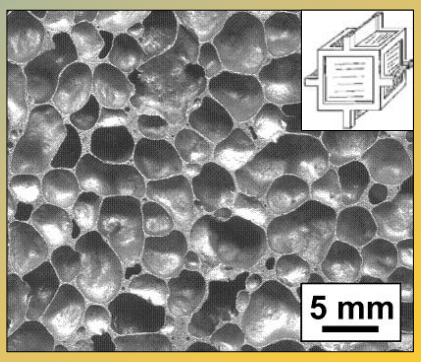
Morphology: sponges or foams

- OPEN cell





- metallic sponge
  - (… or sometimes open-cell foam)

- metallic foam
  - … or closed-cell foam

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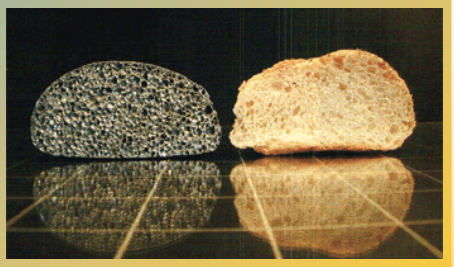
How metal foams are produced



Zinc foam (8 cm width)

bread (8 cm width)

Decomposition of foaming agents (TiH2) **in semi-solids** (aluminium) **at high temperature** (625 °C)

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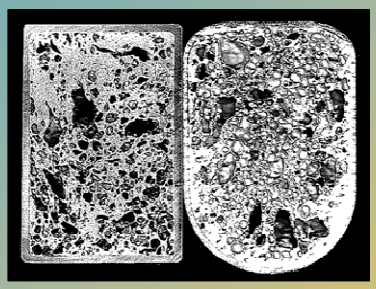
Morphology: shape of unit cells

contained expansion



Apparently:

- the smaller, the rounder…
- Free expanded cells are more regular

Furnace temperature

625 °C

free expansion

2 min | 3 min | 4 min | 5 min | 6 min | 7 min | 8 min | 9 min

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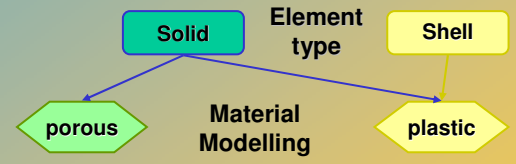
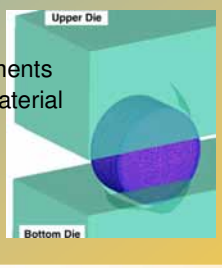
FEM: Simulation approaches

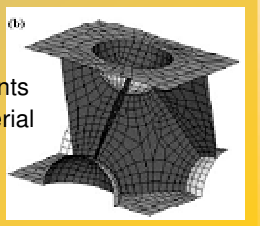
- **Material Modelling**
  - **Porous**: homogeneous material with porous or crushable constitutive law
  - **Plastic**: physical modelling the voids through the mesh with elastic-plastic or rigid-plastic constitutive law



Solid elements
Porous material



Shell elements
Plastic material



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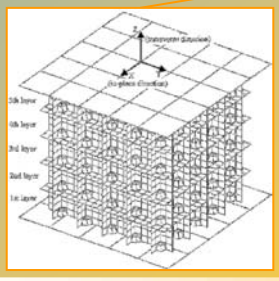
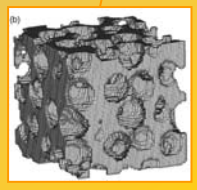
FEM: Simulation approaches

- **Geometrical Modelling**

Material Modelling

- **porous**
  - **full** — Full solid geometry modelled with solid elements
  - **layer** — Full geometry made of stratification of solid layers
- **plastic**
  - **euc** — Voids reproduced as repetitions of equal unit cells
  - **suc** — Voids reproduced as a repetition of similar unit cells with statistically distributed shapes
  - **tom** — Realistic geometry reproduced as a reconstruction of tomographic or photographic data





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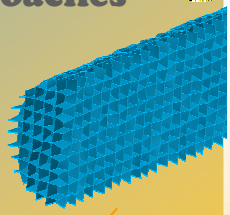
FEM: Simulation approaches

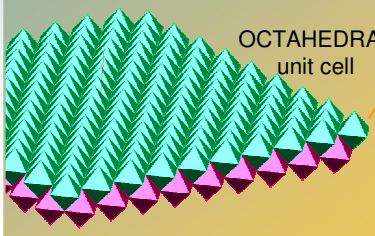
objective of the present work

- to simplify the geometrical modelling of the unit cells, in order to reduce the total number of required elements and to simplify the mesh generation process, without significant loss of accuracy

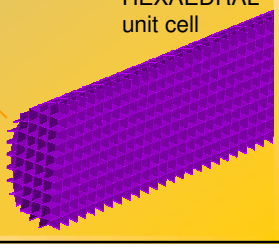
- **plastic**
  - **euc** — Voids reproduced as repetitions of equal unit cells
  - **suc** — Voids reproduced as a repetition of similar unit cells with statistically distributed shapes



OCTAHEDRAL unit cell



HEXAEDRAL unit cell



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Experimental tests: 3 point bending

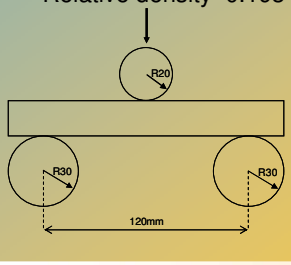
- Experiments on tubes
  - T: thermally treated
  - V: empty-as received
  - S: foamed filled

Tubular skin:

- 0.97 mm thickness AISI 304 round tubes with 39.9 mm outer diameter

Foam filling:

- Casting aluminium AlSi10 + 0,8%wt TiH_2
- Relative density 0.193



- **Punch speed**
  - 3mm/min
- **Pre-load**
  - 50N

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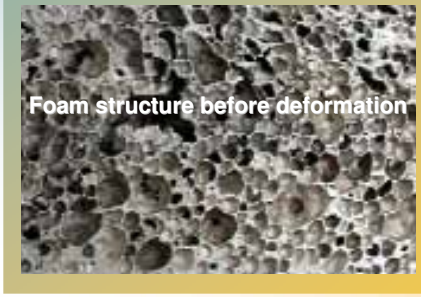
Experimental tests: 3 point bending

Maximum load increase after foam filling

- from 5523 to 31079 N **+462 %**

Weight increase after foam filling

- from 182 to 299 g **+64 %**



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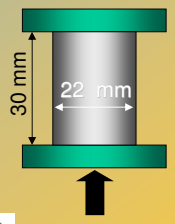
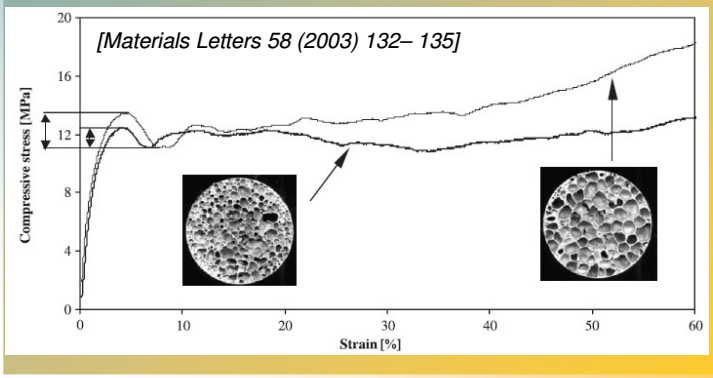
Experimental tests: axial compression

- Experiments on cylindrical foam samples
  - Diameter 22 mm
  - Length 30 and 60 mm

Foam structure:

- Casting aluminium AlSi10 + 0,7%wt TiH_2
- Relative density 0.193





- **Punch speed**
  - 1mm/s

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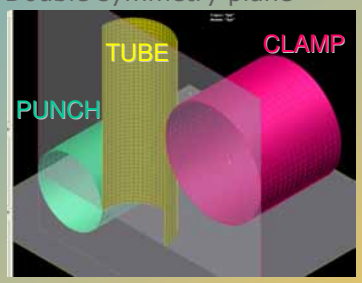
3 point bending of empty tubes

- **Description of FEM model**
  - Tube modeled with 1500 shell elements
  - Double symmetry plane



  - Material modeled with
    - Normal anisotropy with r>1
    - Krupkowsky law
      - K=1.08 GPa
      - n=0.218
      - ε_0=0.011

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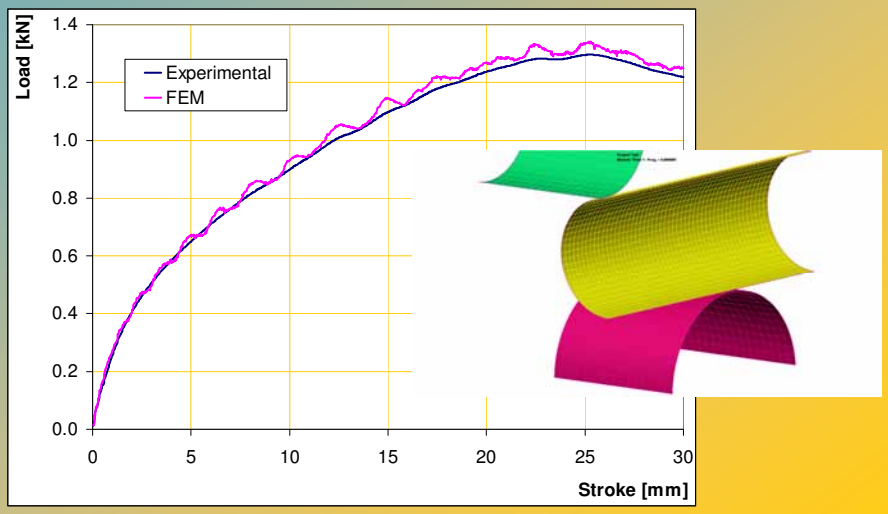
3 point bending of empty tubes

- Results of simulations



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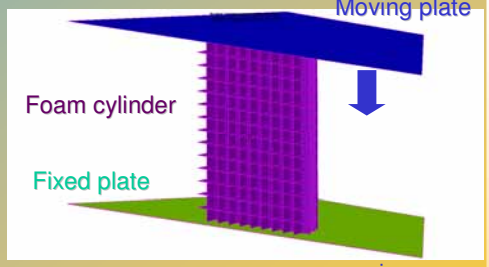
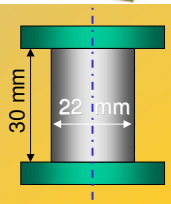
Axial compression of metal foam samples

- Description of FEM model
  - Single symmetry plane
  - Foam modeled with
    - regular hexahedral unit cells with about 1700 quadrangular shell elements
    - constant wall thickness: *0.151 mm*
      - selected as to obtain the correct value of mass: *2.86 g* and relative density: *0.193*
  - Self-contact modeled between foam with itself
  - Material modeled as isotropic elastic-plastic
    - Krupkowsky law
      - K=0.1 GPa
      - n=0.05
      - ε_0=0.01





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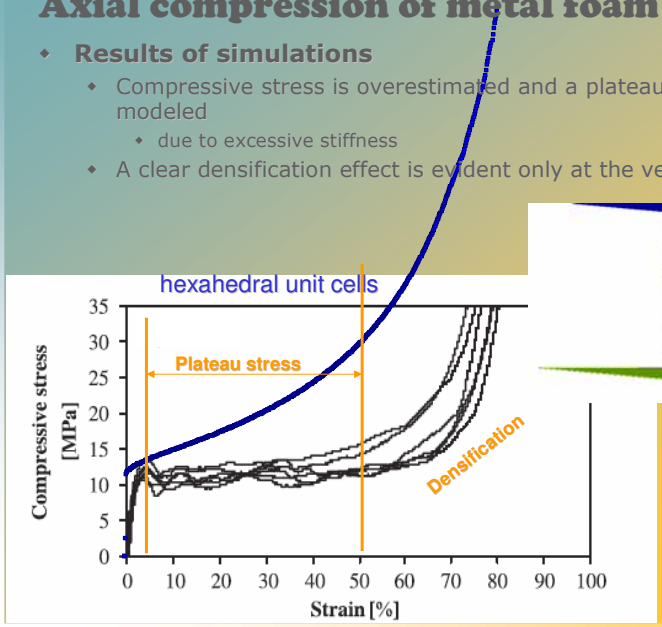
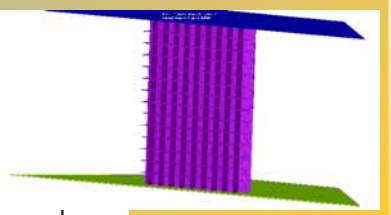
Axial compression of metal foam samples

- **Results of simulations**
  - Compressive stress is overestimated and a plateau stress effect is not modeled
    - due to excessive stiffness
  - A clear densification effect is evident only at the very end of simulation





Sample height 30 mm

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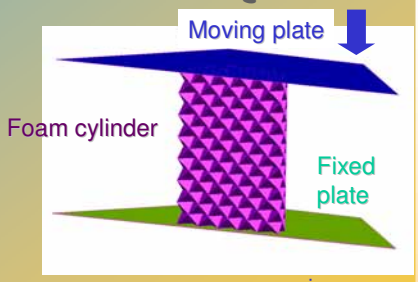
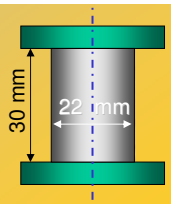
Axial compression of metal foam samples

- **Description of improved FEM model**
  - Foam modeled with
    - regular octahedral unit cells, each made by 8 triangular shell elements
      - Circularity: 0.85
      - Equivalent diameter: 2.5 mm
    - about 2500 elements
      - with constant wall thickness: *0.117 mm*
      - selected as to obtain the correct value of mass: *2.86 g* and relative density: *0.193*
  - All other conditions are kept constant





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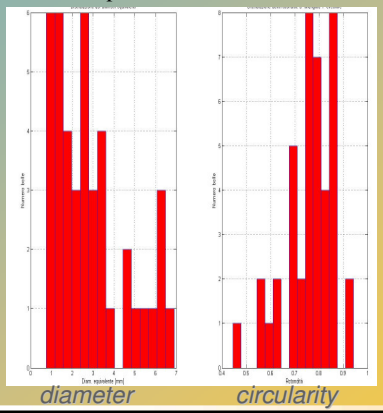
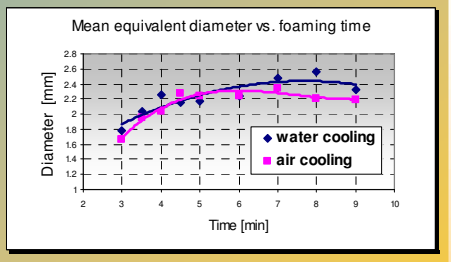
Some issue about cell size and shape

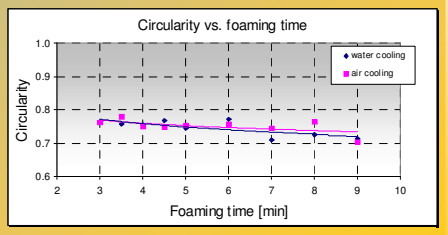
- Experimental values
  - *average diameter is about 2.5 mm*
  - *circularity is about 0.72*
  - *distribution is obviously random*

$$C = \frac{4\pi A}{p^2} \qquad D_{eq} = \frac{4A}{p}$$



diameter *circularity*





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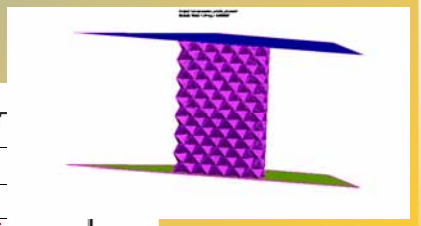
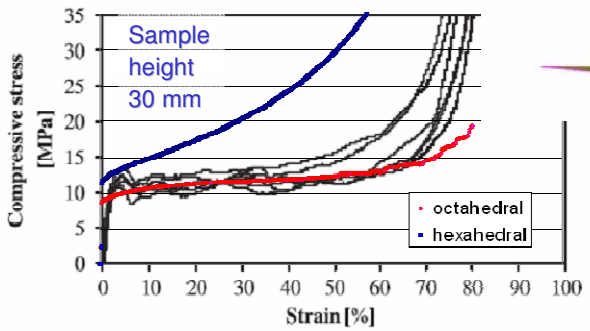
Axial compression of metal foam samples

- **Results of simulations**
  - Average compressive stress is well estimated and a plateau stress effect is now modeled
    - due to reduced stiffness of octahedral cells
  - A clear densification effect is evident after 65% reduction, slightly retarded





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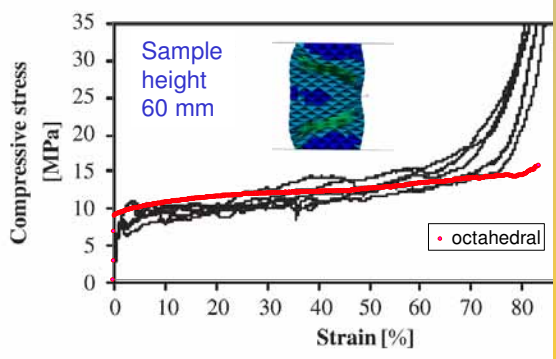
Axial compression of metal foam samples

- **Results of simulations**
  - Although localization of strain is not exactly simulated as in the experiment, very good results are obtained also for increased specimen length to 60 mm



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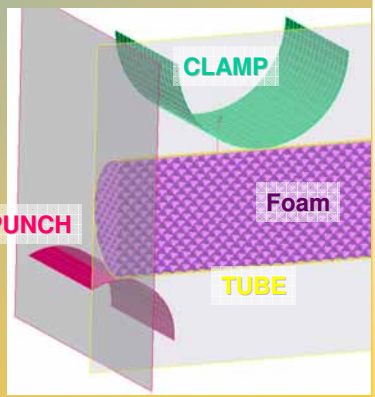
3 point bending of foam filled tubes

- **Description of FEM model**
  - Double symmetry plane
  - Tube modeled
    - with 2480 quadrangular shell elements
    - material with normal anisotropy (r>1) and Krupkowsky law
  - Foam modeled
    - with regular octahedral unit cells made by 8 triangular shells
      - 23460 triangular shell elements
    - constant wall thickness
      - selected as to obtain the correct value of mass: *28.1 g* and relative density: *0.193*
    - Material modeled as in the previous cases



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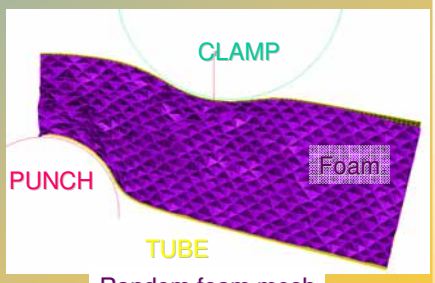
3 point bending of foam filled tubes

- **Description of modified FEM models**
  - Foam modeled with **random** octahedral unit cells made by 8 eleents
    - 23460 triangular shell elements
    - Random mesh is generated by perturbation of nodes in order to model the variance of cell diameter and circularity
  - constant wall thickness
    - selected as to obtain the correct value of mass: *28.1 g* and relative density: *0.193*
  - All other conditions are kept constant



Random foam mesh

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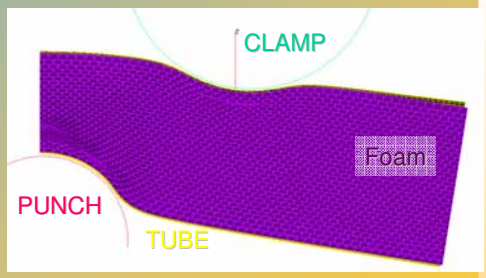
3 point bending of foam filled tubes

- **Description of modified FEM models**
  - Foam modeled with **smaller** regular octahedral unit cells
    - 199200 triangular shell elements
    - Equivalent cell diameter is decreased from 2.5 to 1.3 mm
  - constant wall thickness
    - selected as to obtain the correct value of mass: *28.1 g* and relative density: *0.193*
  - All other conditions are kept constant



smaller foam cells

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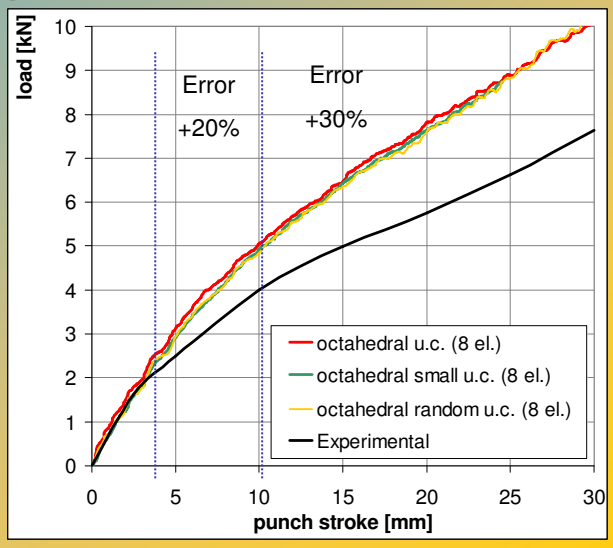
3 point bending of foam filled tubes

Results of simulations

- Accuracy is very good up to a stroke of about 4 mm
- For larger stroke values, overestimation error goes up to 20% and 30%
- Errors are probably due to much localised deformation
- Results are not very sensitive to a change in the cells diameter and circularity
  - Best results are obtained with random mesh



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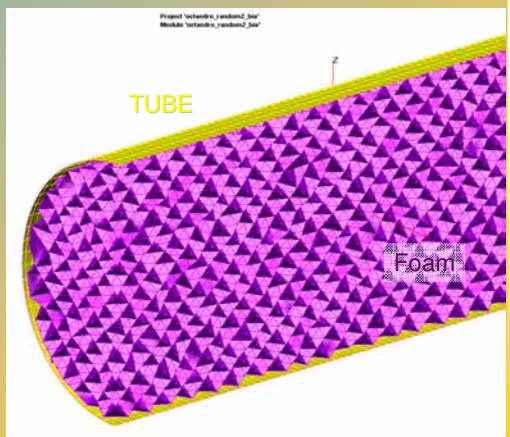
3 point bending of foam filled tubes

- **Description of improved FEM models**
  - Foam modeled with regular octahedral unit cells
  - Each wall of the octahedron is made up of 4 elements, for a total of 32 elements per cell
    - constant wall thickness
      - selected as to obtain the correct value of mass: *28.1 g* and relative density: *0.193*
    - All other conditions are kept constant



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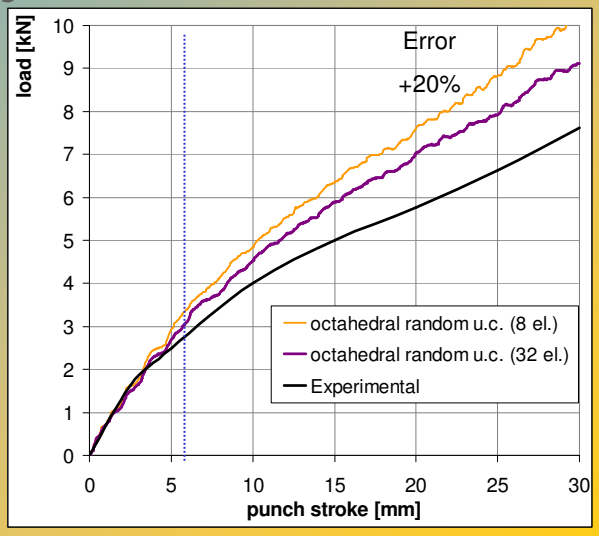
3 point bending of foam filled tubes

Results of simulations

- Accuracy is very good up to a stroke of about 6 mm
- For larger stroke values, overestimation error goes up to a maximum of 20%
- Adding more elements on the same cell walls helps reducing the total stiffness of the foam structure without increasing the model preparation time and with acceptable increase of solving time



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Conclusions and future work

- **Conclusions**
  - **Axial compression of foam samples**
    - can be very effectively modeled with simple regular unit cells
    - octahedral cells with triangular shell elements outperform hexahedral cells with quadrangular elements
  - **Bending of empty steel tubes**
    - is (obviously) effectively modeled with quadrangular shell elements
  - **Bending of foam filled structures**
    - can be modeled with octahedral unit cells either made by 8 or 32 elements each
    - due to localized deformation, accuracy is not as good as in axial compression
    - Best results are obtained with randomization of nodal positions and 32 elements per shell
    - simulation results are not very sensitive to a change in cell size
- **Future work**
  - material models with stress saturation, softening or damage
  - More accurate stochastic modeling of cell size