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# DEM simulations of punch tests for the mechanical characterization of cortical meshes

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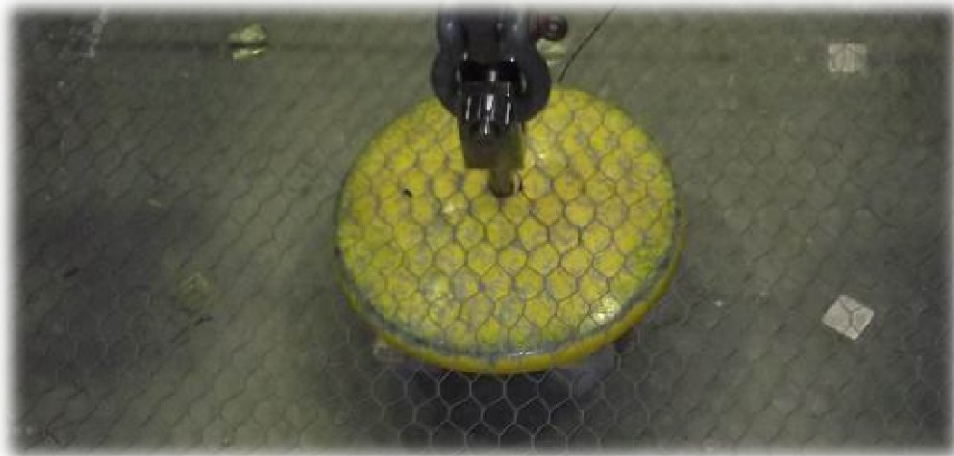
**Conclusive Remarks**

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Protection of instable slopes through the application on steel meshes.

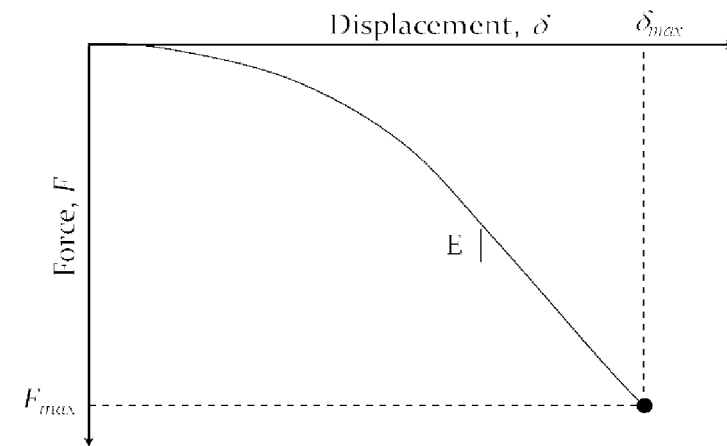
- Knowledge of the landslide phenomenon
- Knowledge of the mechanical behaviour of the mesh
- Knowledge of the interaction between backfill material and steel mesh



## EXPERIMENTAL LABORATORY STUDIES

Laboratory punch test (UNI 11437-2012) is useful to study the overall mechanical behavior of the product under defined conditions

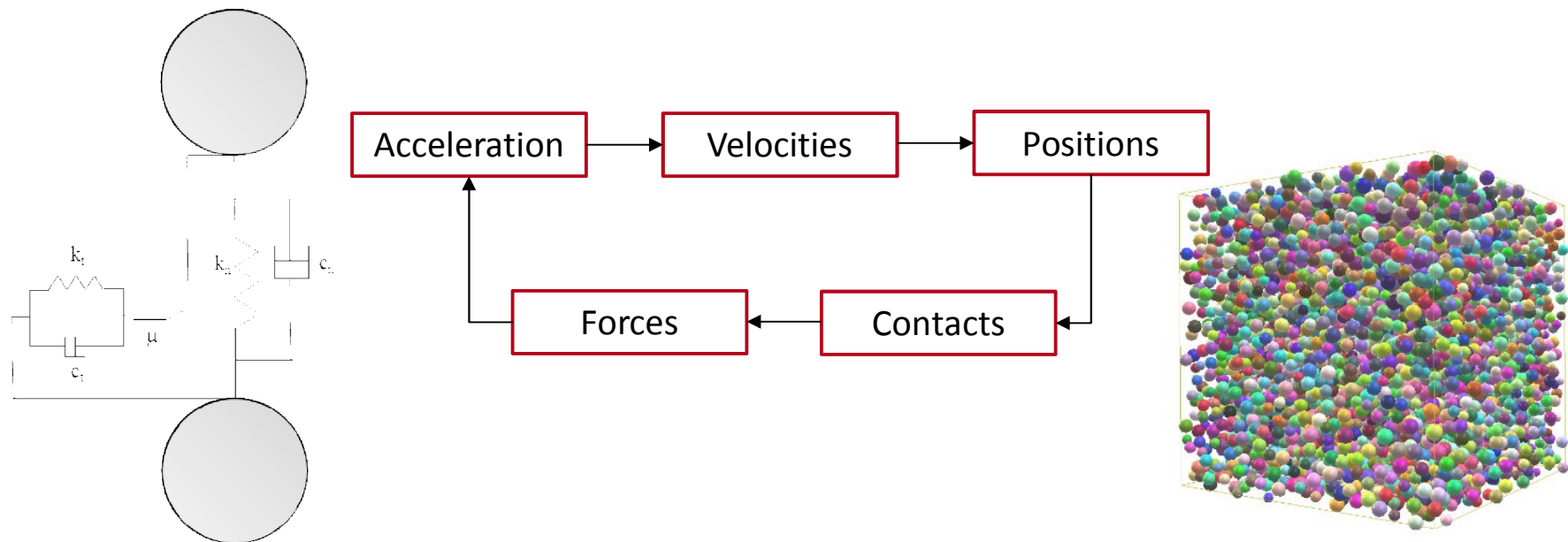
- Study of the overall mechanical behaviour (load-displacement curve);
- Investigation of typical failure modalities;
- Detailed observation of local deformation of the steel mesh;



Typical trend of force - displacement curve during a punch test

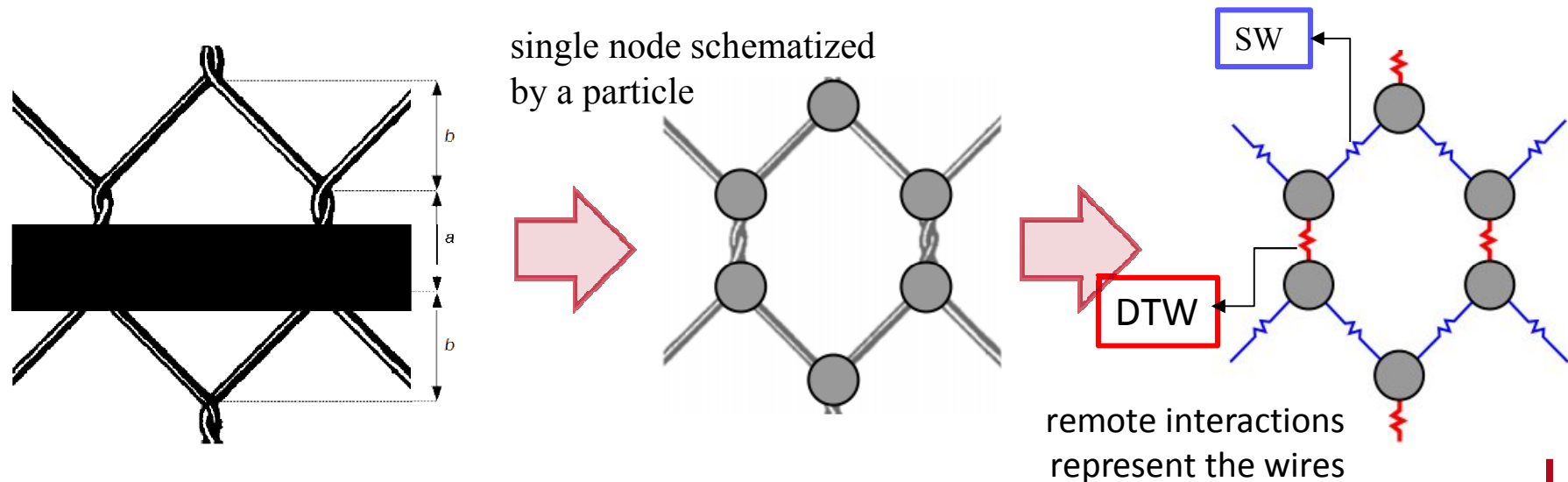


- Allows to simulate the physical system with a discrete number of independent bodies
- Bodies interact each other by specific contact or remote interaction laws
- New values of local variables are updated by the integration of the equations of motion
- Allows to study the system under large deformations





From the real wire mesh to the numerical model a simplification shall be introduced (Nicot et al. 2001, Bertrand et al. 2008, Thoeni et al. 2013)



3 different approaches are considered for the interaction laws:

1. Full Model (Deterministic Model)
2. Simplified Model (Deterministic Model)
3. Stochastic Model

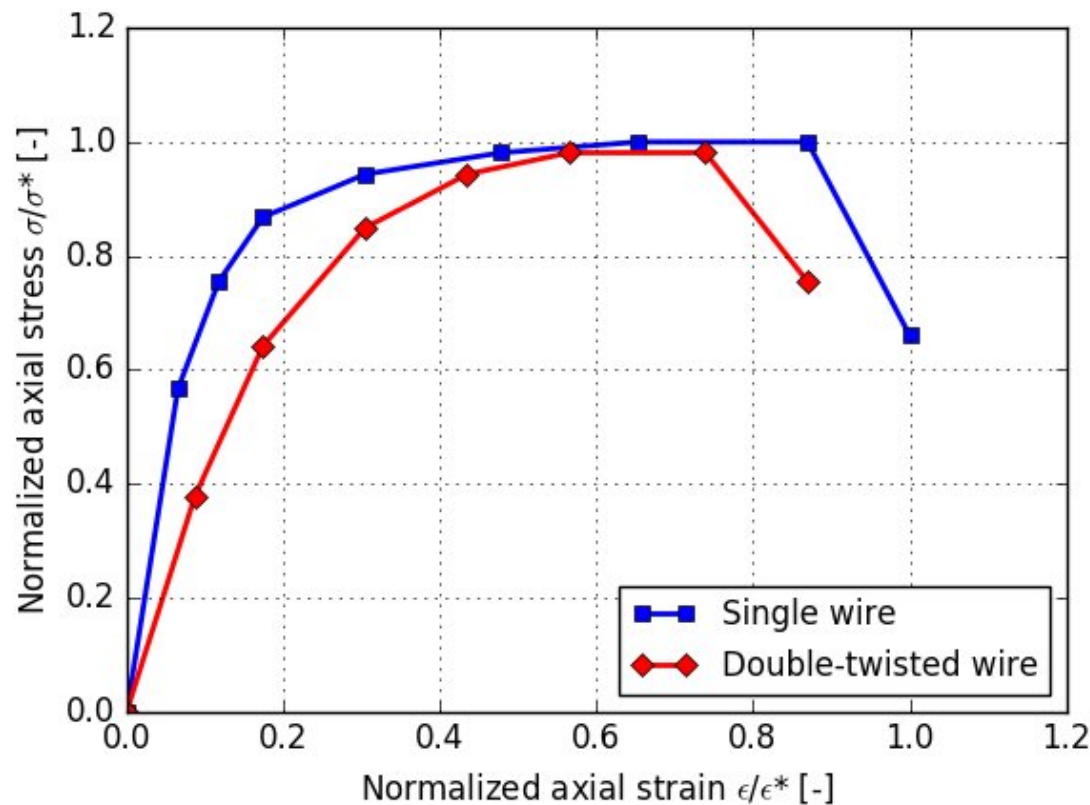
Specific interaction laws are defined for each type of wire:

- Single wire (SW)
- Double twisted wire (DT)



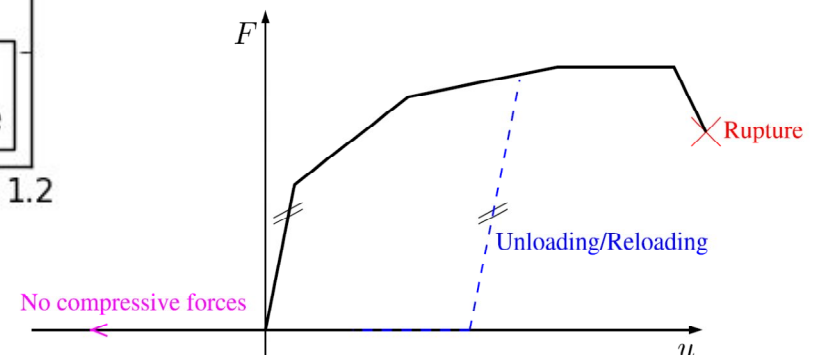
## Model 1 - Thoeni 2011 (Deterministic Model)

Two different relationships for Single Wire (SW) and Double Twisted wires (DT) are used (formally equals to EWM, Elementary Wire Model).



## Elementary Wire Model - EWM

The interaction law is directly defined by a piece-wise linear force-displacement curve which is derived from the stress-strain curve of a wire.

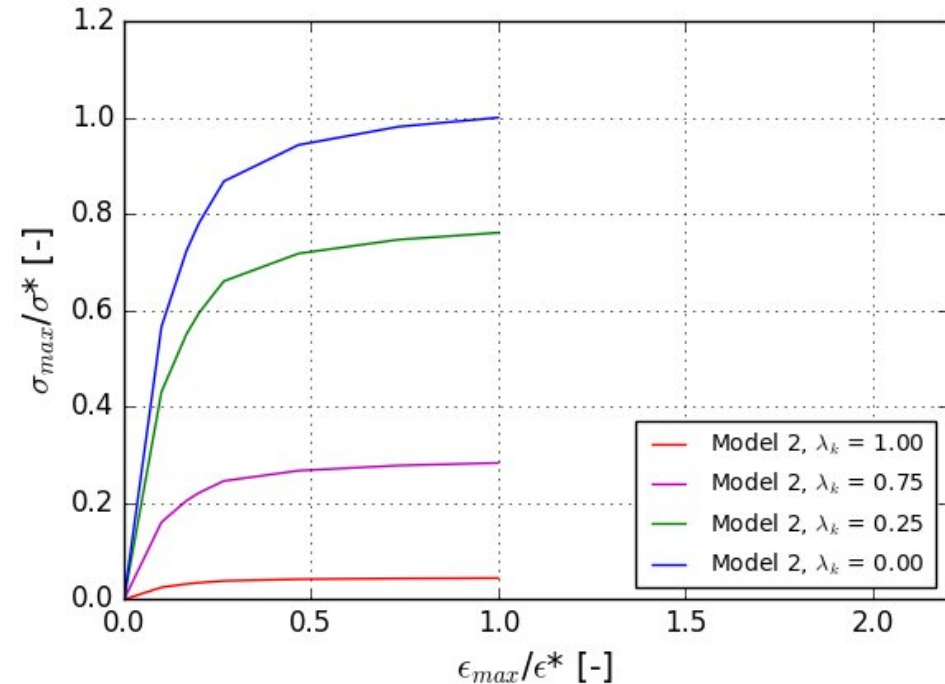
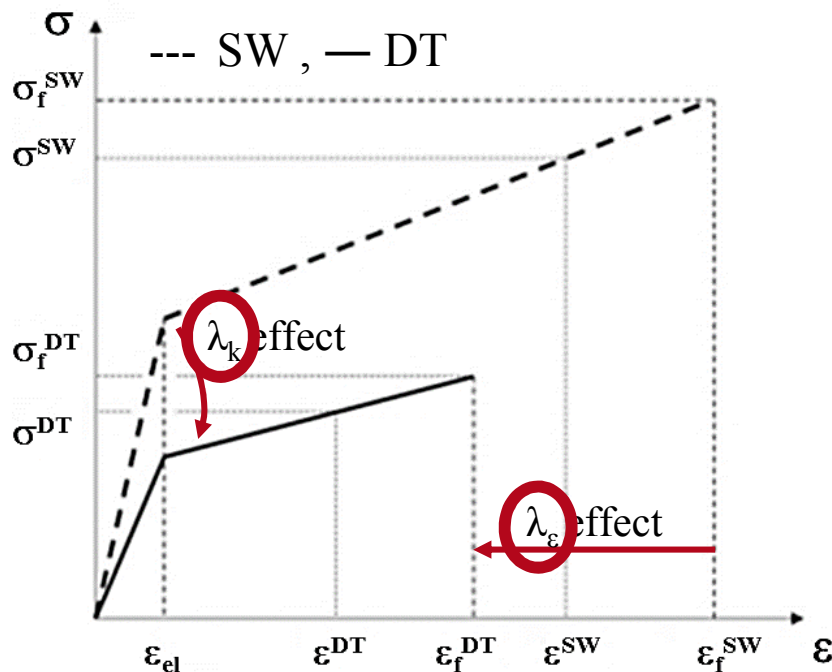




## Model 2 - Bertrand 2005 (Deterministic Model)

The relationship of DT's interaction (e.g.  $\sigma$ - $\epsilon$  curve) is derived directly from the relationship of the SW. For this purpose the parameters  $\lambda_k$ ,  $\lambda_\epsilon$  are introduced.

- $\lambda_k$  acts on the initial stiffness of the DT
- $\lambda_\epsilon$  takes the strain reduction at failure into account





## Model 2 - Bertrand 2005 (Deterministic Model)

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- $\lambda_k$  acts on the initial stiffness of the DT
- $\lambda_\varepsilon$  takes the strain reduction at failure into account

$$k_e^{DT} = 2(\lambda_k k_h + (1 - \lambda_k)) k_e^{SW}$$

$$0 \leq \lambda_k \leq 1$$

The DT is assumed as an assembly of two overlapping helical wires or two springs.

$$\varepsilon_f^{DT} = \lambda_\varepsilon \varepsilon_f^{SW}$$

$$0 \leq \lambda_\varepsilon \leq 1$$

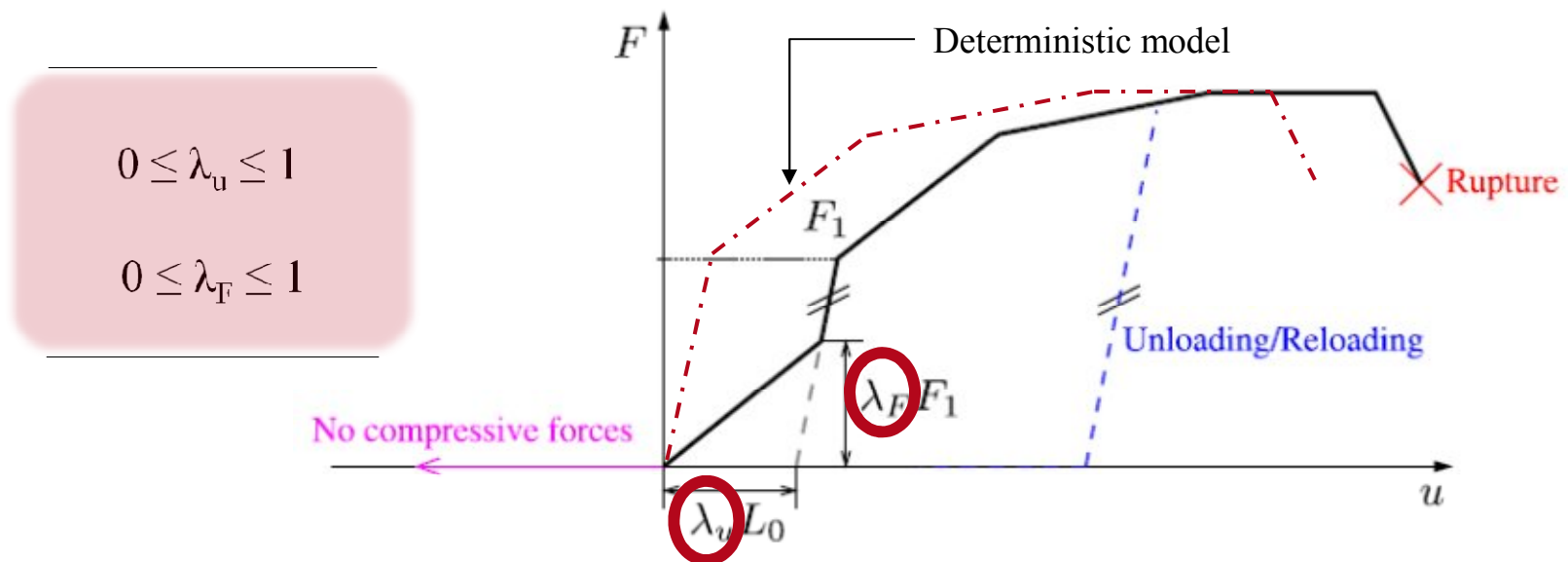
Due to plastic strains caused by the construction phase of DT



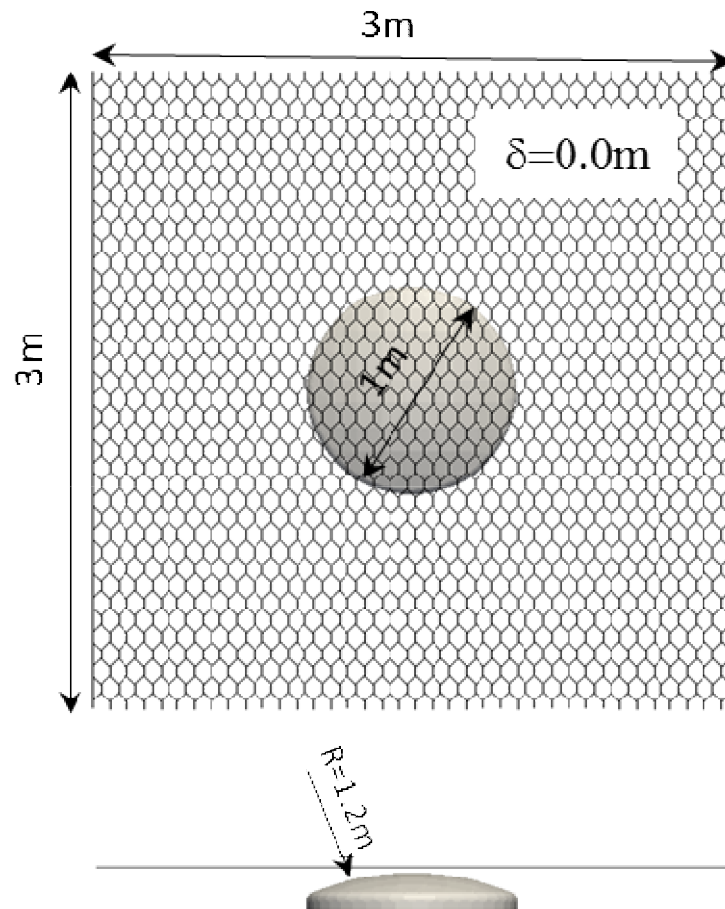
Model 3 - Thoeni 2013 (Stochastically Distorted Wire Model - SDWM)

The parameters  $\lambda_u$ ,  $\lambda_F$  are introduced in order to define the SDWM:

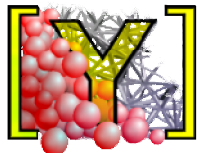
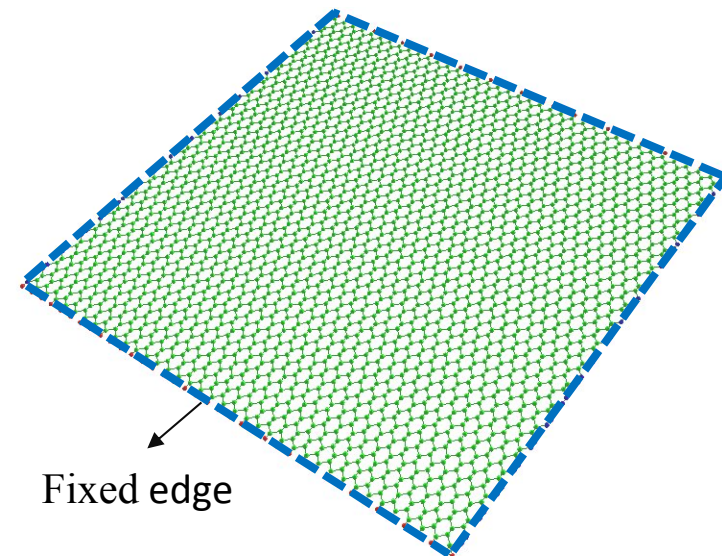
- $\lambda_u$  determines a horizontal shift to the force-displacement curve
- $\lambda_F$  determines the stiffness of the wire in the shifted area



A single panel is associated with a seed number, each seed number generates a new distribution (triangular distribution) of the properties in the mesh related panel.



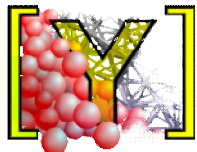
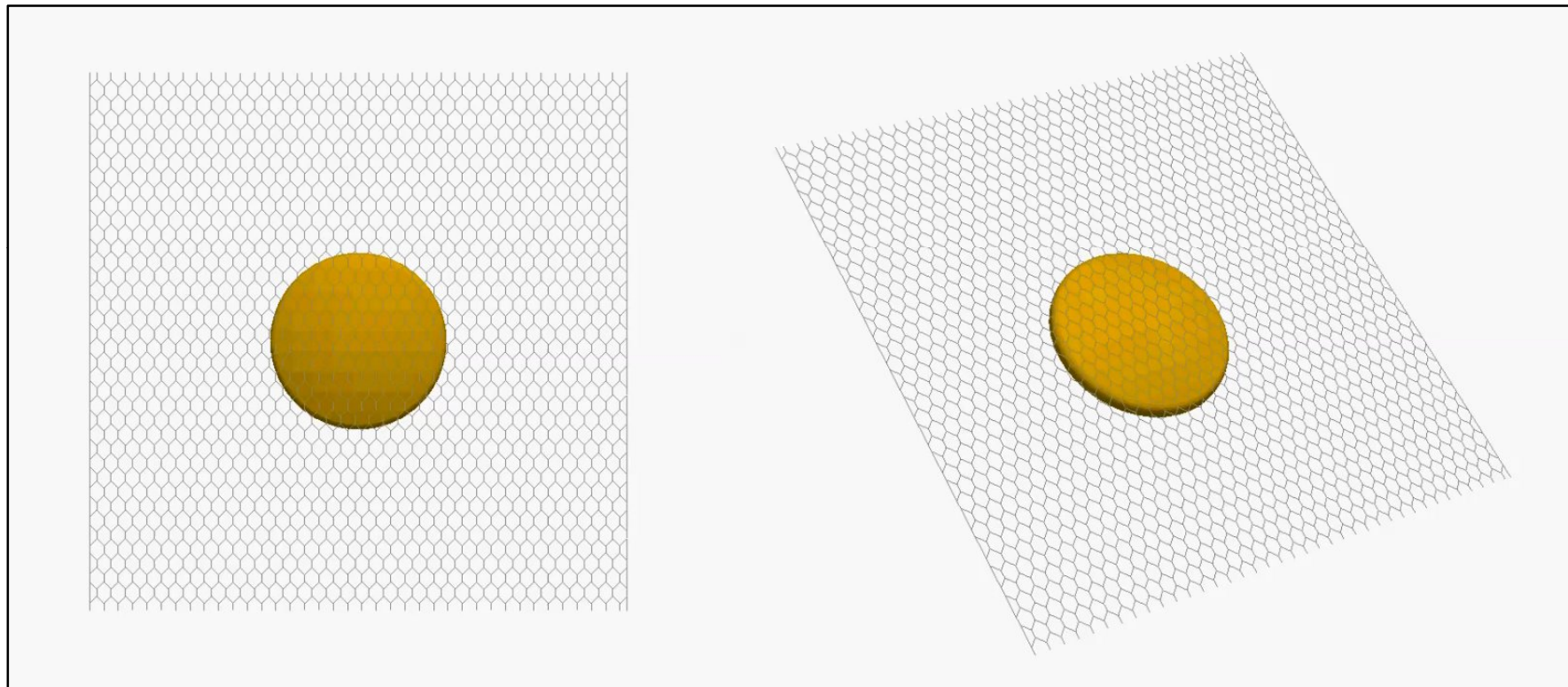
- Geometry is conform to UNI 11437-2012
- Punching element is represented by frictionless triangular facets
- Punching element is lifted with an imposed vertical velocity
- Edges of wire mesh are fixed



All simulations are performed with the open-source code Yade



Example of the typical overall behavior obtained from DEM with Yade

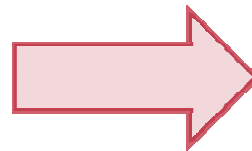
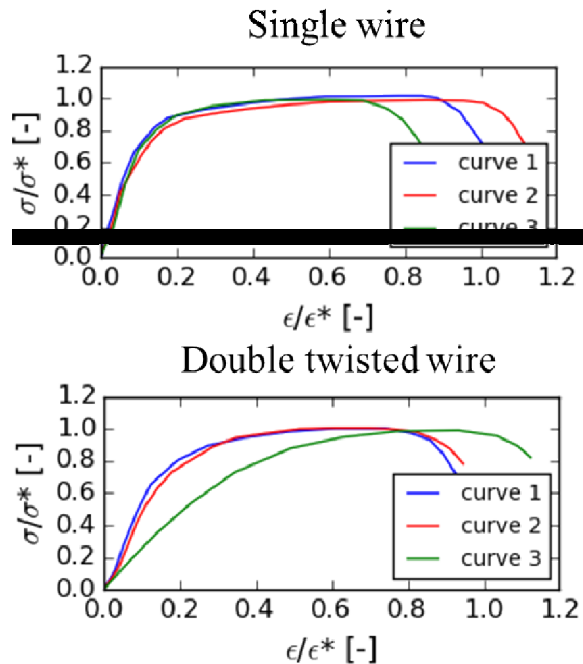


All simulations are performed with the open-source code Yade



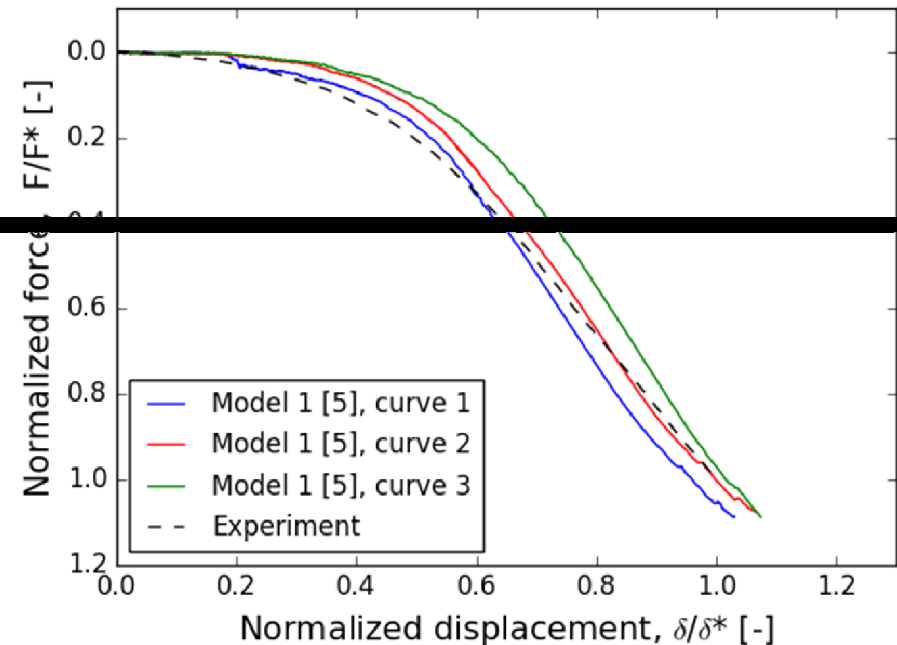
Influence of stress-strain curve is investigated using three different experimental curves.

## *Material Model 1*



## *Material Model 1*

### *Numerical Modelling of the Punch Test*

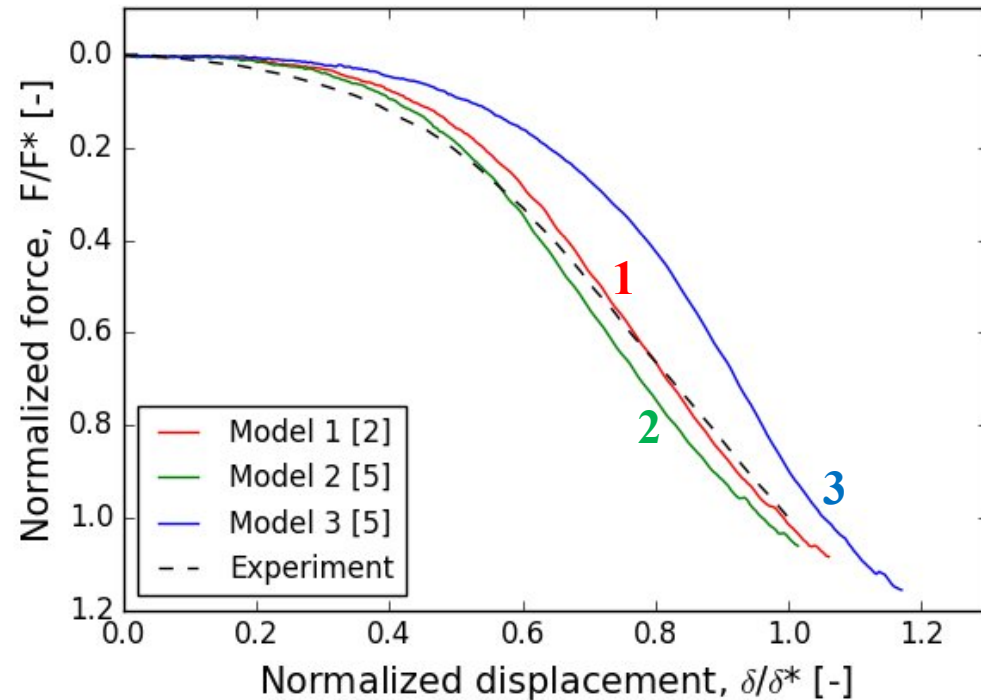
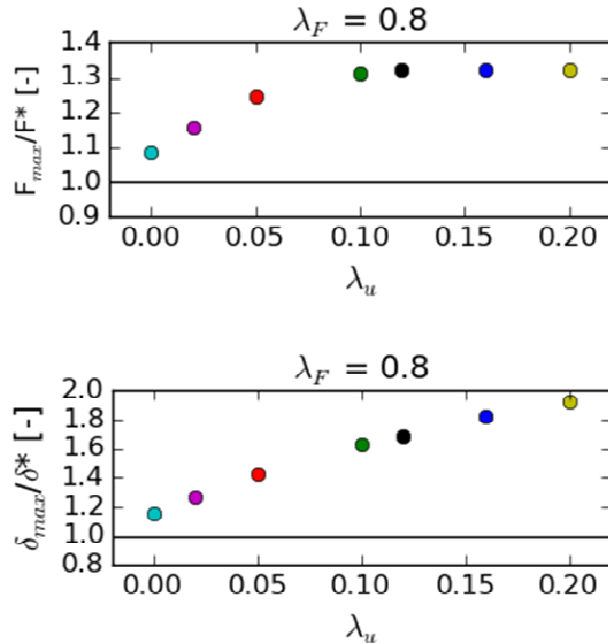


The sensitivity of the model on the stress-strain curve of constitutive elements is relevant. The variability obtained from numerical simulations is compatible with that obtained from laboratory tests.

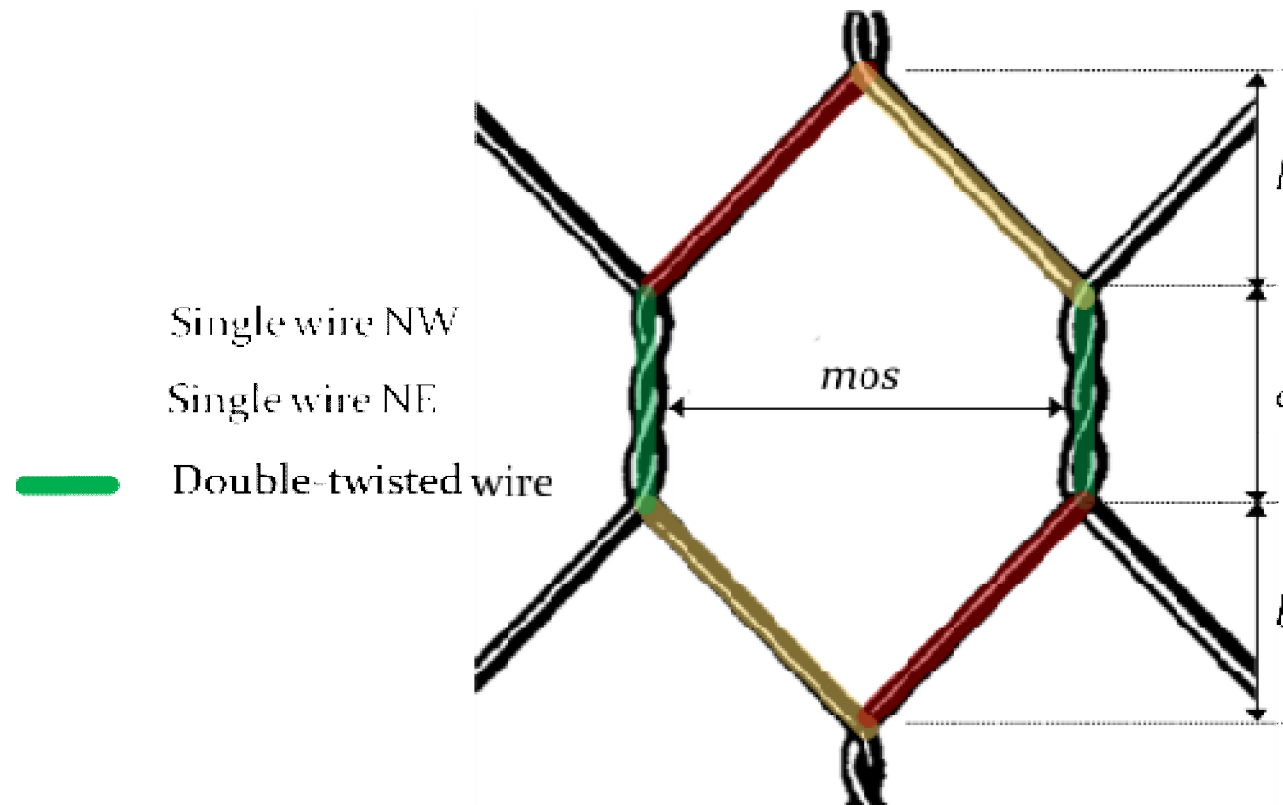


Experimental results of punch test are suitable to calibrate the models.  
The calibrated results of all model are presented:

### *Material Model 3* *Sensitivity Analysis*



In order to be able to compare the models, the same stress-strain curve, respectively for SW and DT, are used with each model.



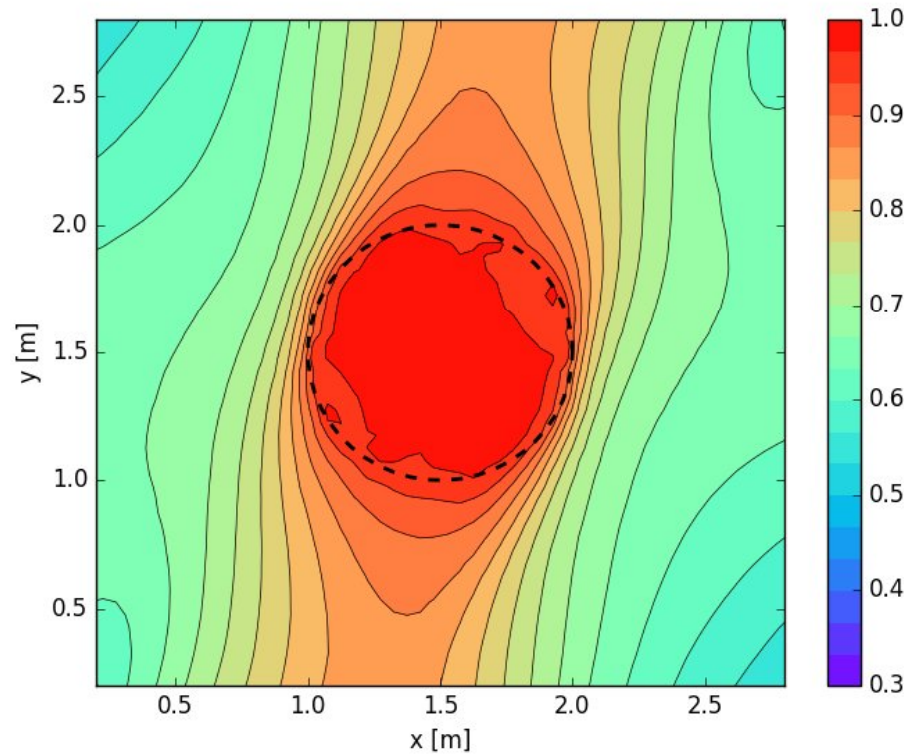
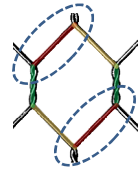
Each component is separately studied for a better understanding of both detailed and overall mechanical behavior



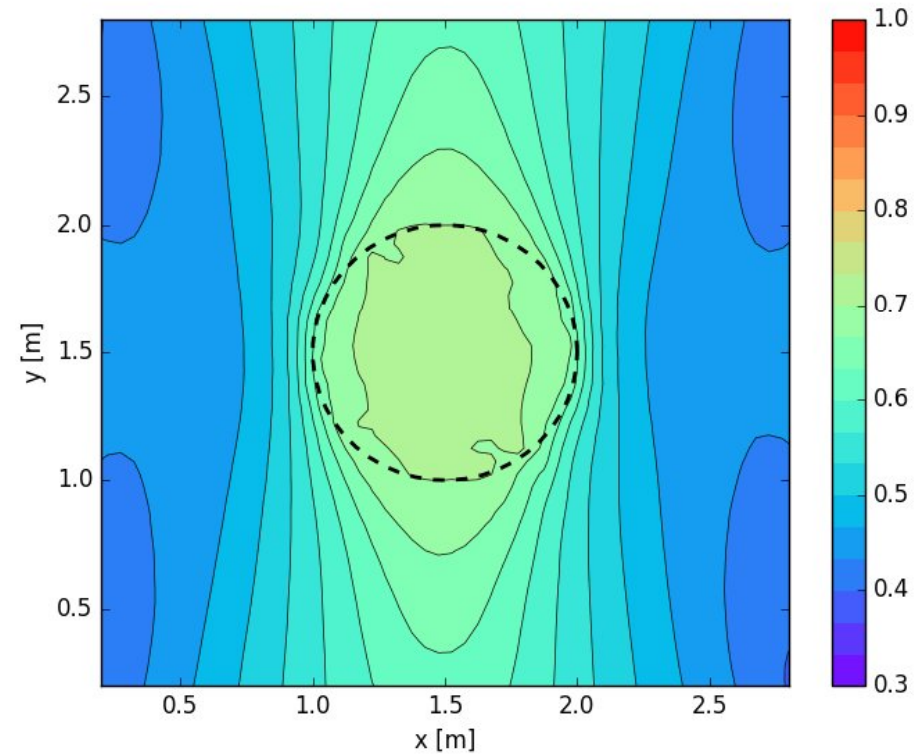
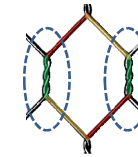
# Results of Numerical Models

## Distribution of Tensile Stresses

Single wire  
(NE)



Double Twisted wire  
(NS)



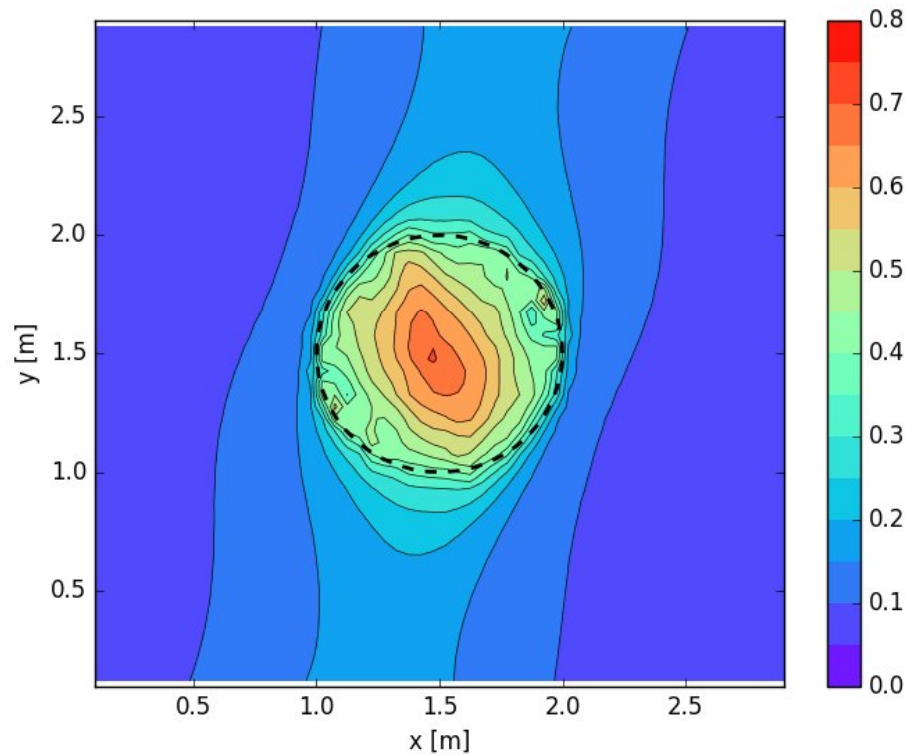
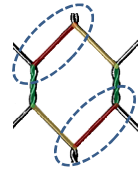
The computed stresses are normalized over the maximum characteristic strength of the element



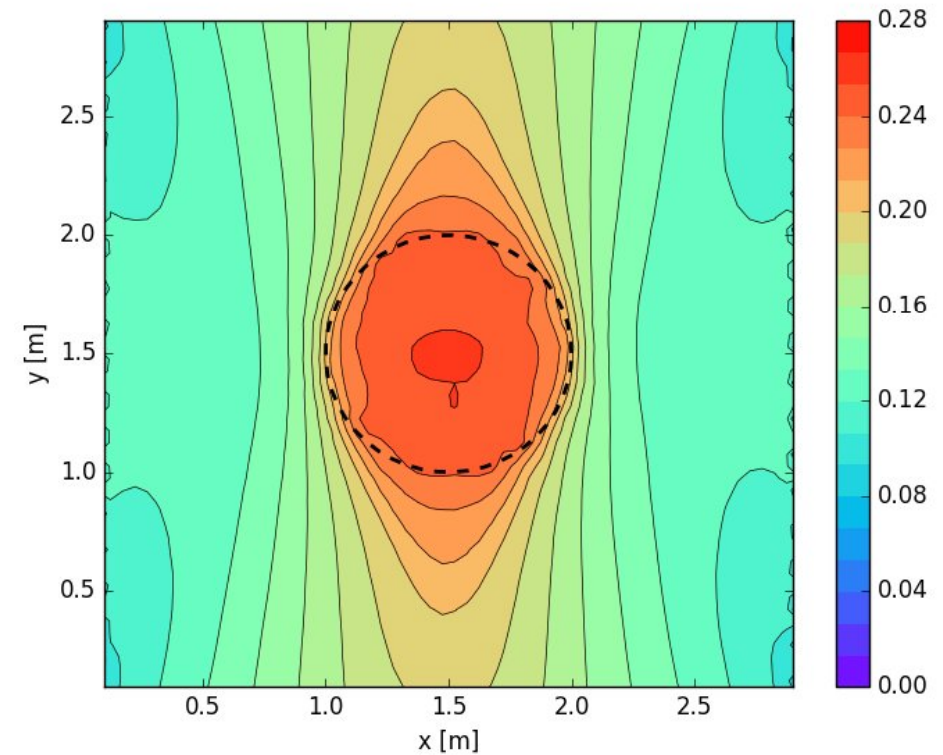
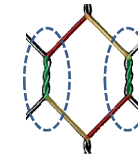
# Results of Numerical Models

## Distribution of Tensile Strains

Single wire  
(NE)



Double Twisted wire  
(NS)

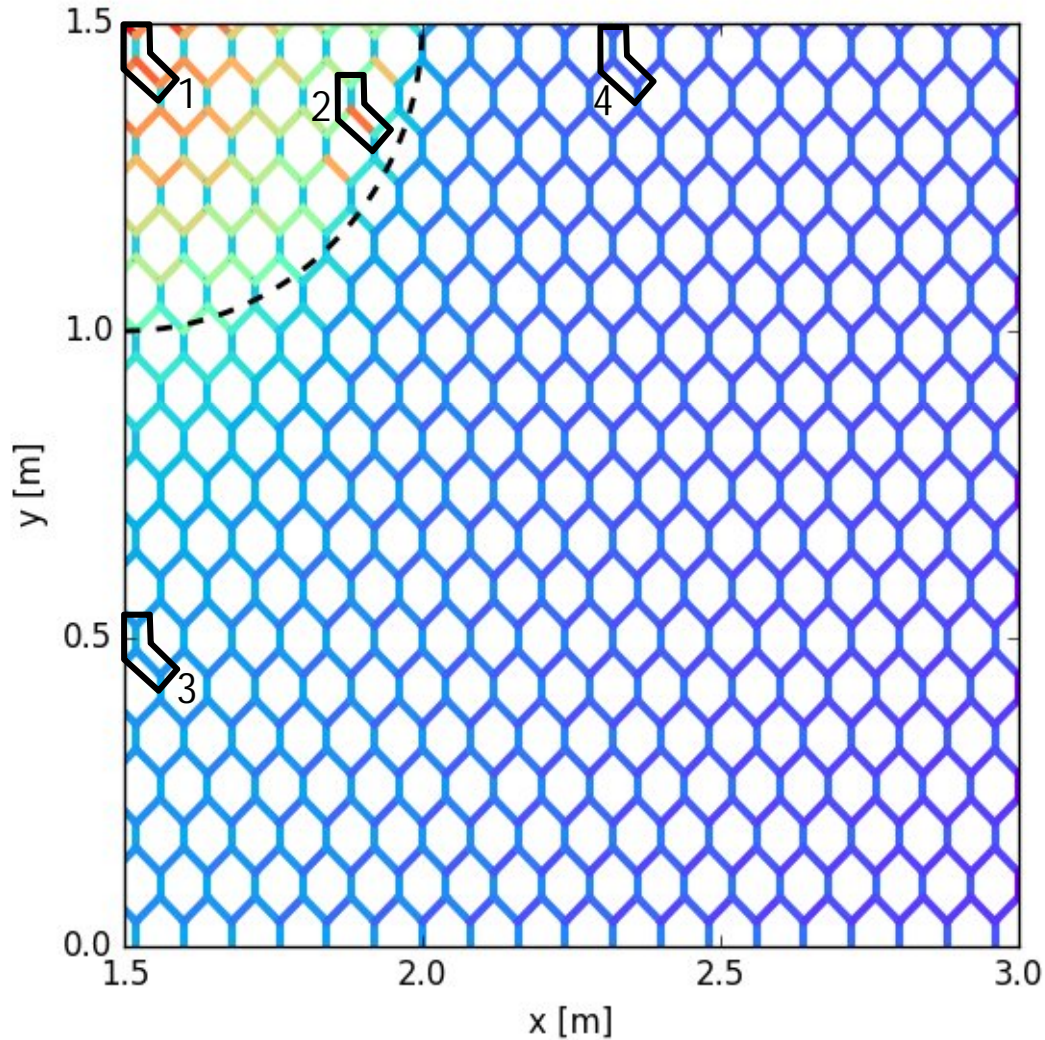


The computed strains are normalized over the maximum allowable deformation of the element considered

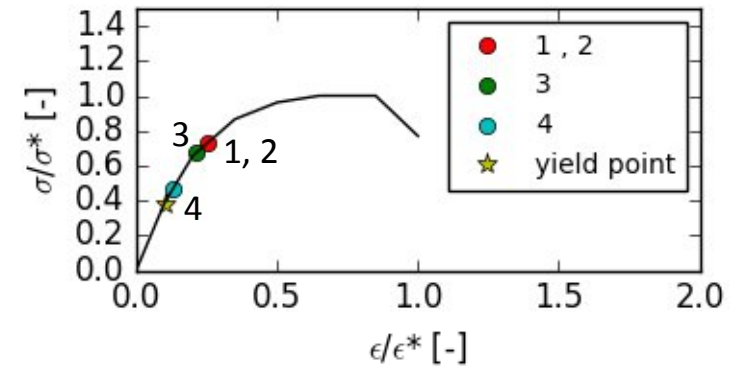


# Results of Numerical Models

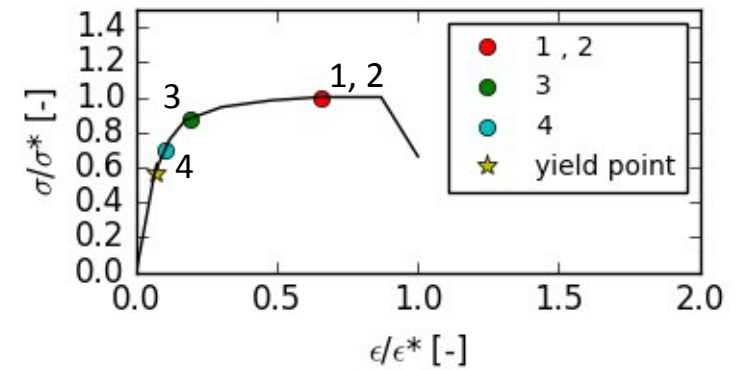
## Distribution of Tensile Strains



Double twist wire



Single wire





# Results of Numerical Models

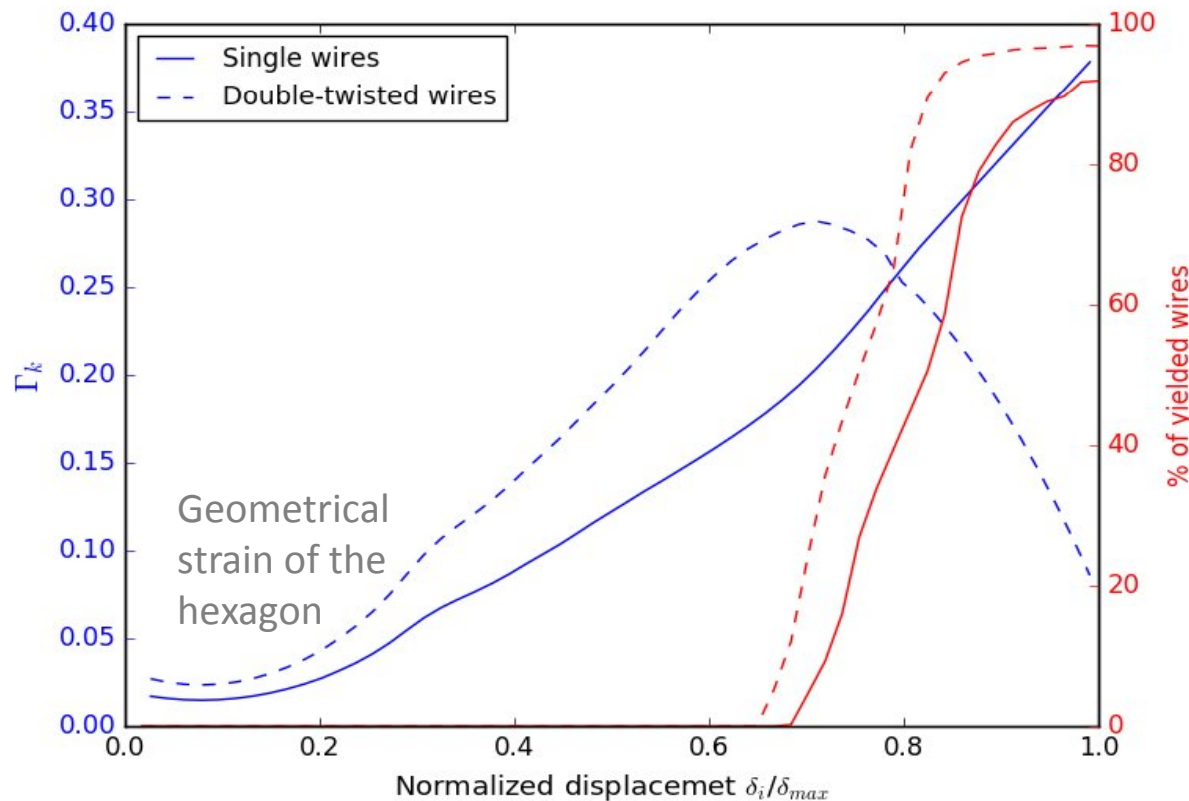
## Overall Behaviour of Wires

$$\Gamma_k = \frac{L_k(\delta_{i+1}) - L_k(\delta_i)}{L_{k,max} - L_{k,0}} \cdot \frac{\delta_{i+1} - \delta_i}{\delta_{max}}$$

*Wire behaviour*

*Punch element*

$\Gamma_k$  represents the mean increment of tensile strain held by the wires for a given unit amount of strain of the punching element



$L_{k,0}$  initial length of the k-wire

$L_k(\delta_i)$  length of the k-wire at the i-time

$L_{k,max}$  maximum length of the k-wire at i-time

$\delta_i$  displacement of the punch element at i-time

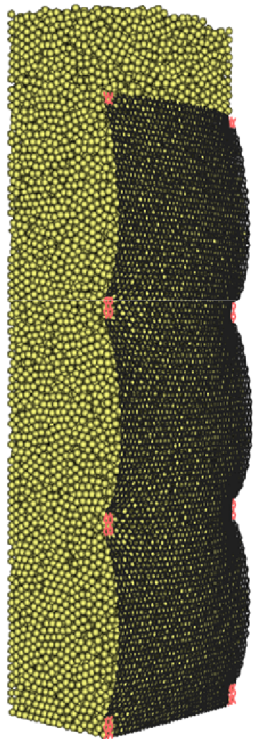
$\delta_{max}$  maximum displacement of the punch element



- A good agreement between experimental and numerical results is obtained for each strain level (small deformation, failure conditions, etc.)
- The intrinsic variability of the material could be considered and its influence on the mechanical behavior could be evaluated through different stress-strain curves (models 1 and 2)
- A stochastic model can be defined and calibrated starting from both kind of variability
- The intrinsic variability of the mesh geometry could be considered and its influence on the overall behavior could be evaluated assuming a random distribution of irregularities (model 3)
- A design optimization could be performed starting from stress and strain distributions on the mesh panel

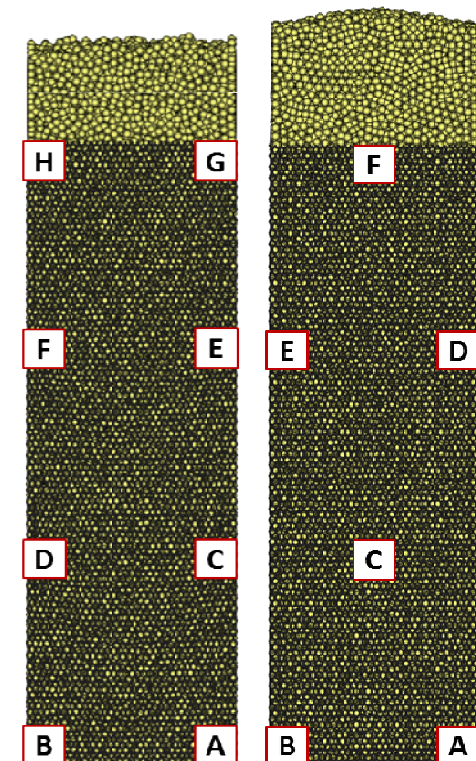


The forthcoming step is the creation of an numerical model of a real site condition. This “global model” will be based on the presented constitutive models.



- In-depth knowledge of the mechanical interaction between steel mesh and backfill material;
- Overall behaviour of the steel mesh depending on different loading conditions (different backfill material, different geometrical conditions, etc.);
- Influence and effectiveness of different geometrical configurations of constraining points (plates and nails);

These represent the fundamental bases to extend the result of the current study to a “full model” also suitable for the design of cortical meshes.





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## Elements of DEM Theory

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Analysis and Interpretation of Experimental Results



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Development and calibration of the DE Models



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Development and calibration of the DE Models