

Empilements aléatoires de sphères creuses : caractérisation, comportement et intégration dans les structures sandwich.

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SIMaP - GPM2
Grenoble INP - CNRS - UJF - France

21 Septembre 2009, Soutenance de thèse de Doctorat - Grenoble



Motivation

Matériaux architecturés
+
Structures sandwich

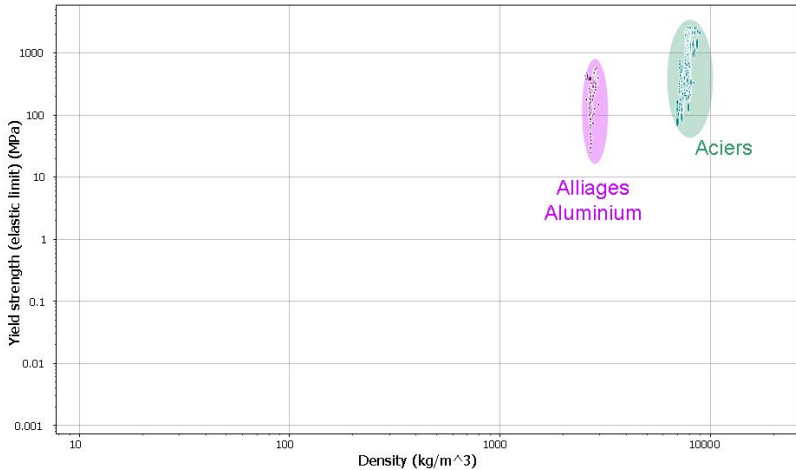
Pourquoi des matériaux
architecturés ?

Motivation

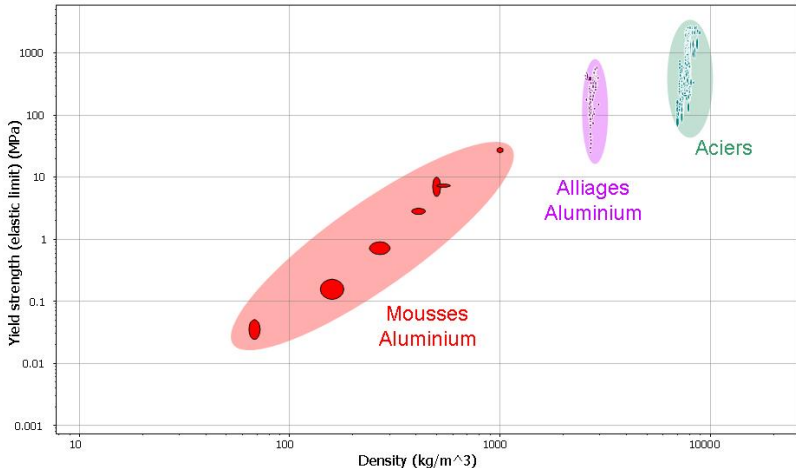
Matériaux architecturés
+
Structures sandwich

Pourquoi des matériaux
architecturés ?

Sélection des matériaux

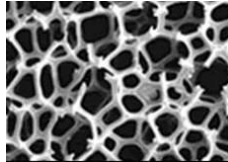
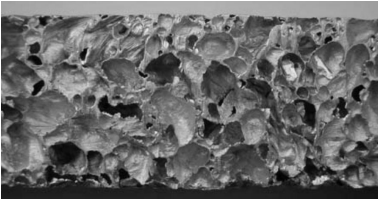


Sélection des matériaux

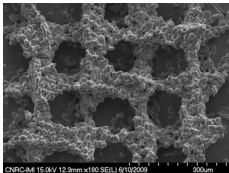


Mousses métalliques

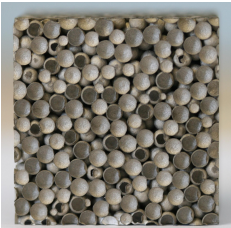
Exemples



Matériau multifonctionnel

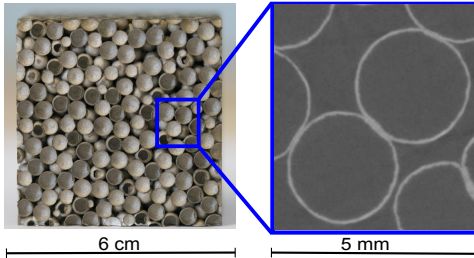


Empilements de sphères creuses

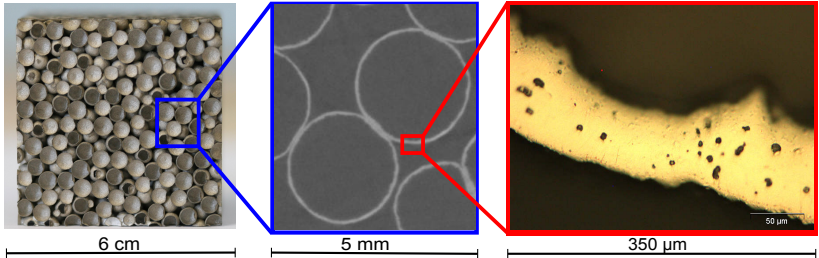


6 cm

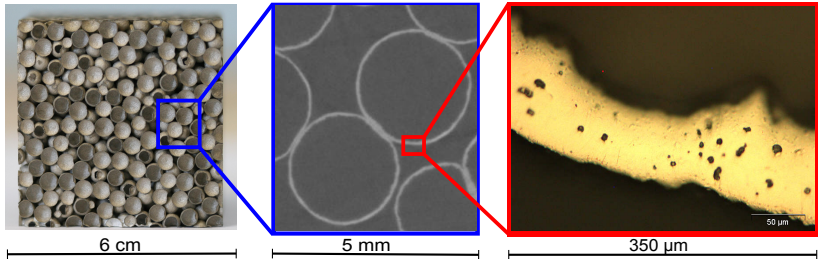
Empilements de sphères creuses



Empilements de sphères creuses

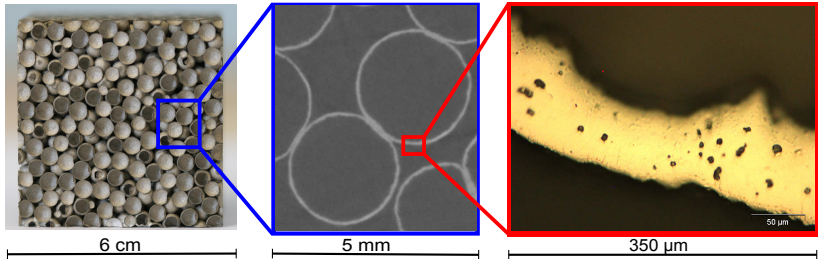


Empilements de sphères creuses



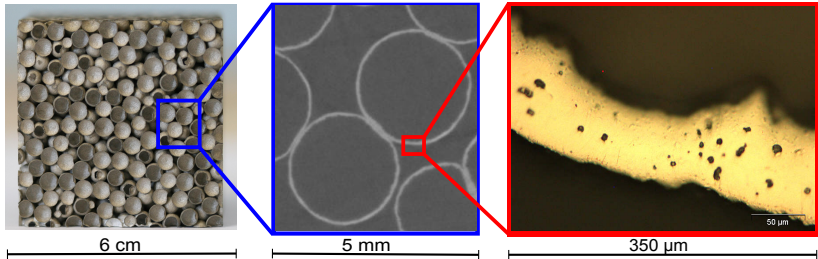
- 1 **Matériau cellulaire**
 - 2 Elaboration par métallurgie des poudres
 - 3 Mousse ouverte
 - 4 Mousse fermée
- Degrés de libertés de l'architecture
 - Taille de cellule, épaisseur de coque, taille de col

Empilements de sphères creuses



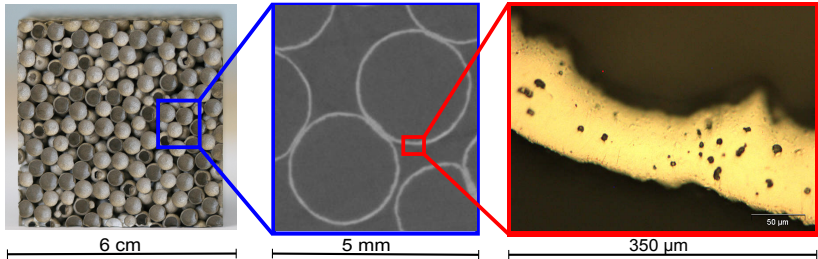
- 1 Matériau cellulaire
 - 2 **Elaboration par métallurgie des poudres**
 - 3 Mousse ouverte
 - 4 Mousse fermée
- Matériau constitutif
 - ➔ Températures élevées
 - ➔ Conductivité
 - Microporosité

Empilements de sphères creuses



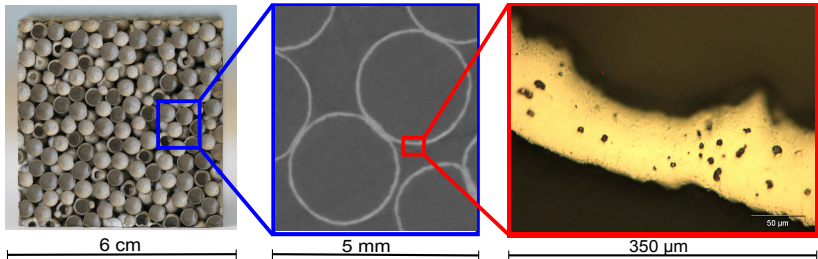
- 1 Matériau cellulaire
 - 2 Elaboration par métallurgie des poudres
 - 3 Mousse ouverte
 - 4 Mousse fermée
- Faible densité
 - Absorption acoustique

Empilements de sphères creuses

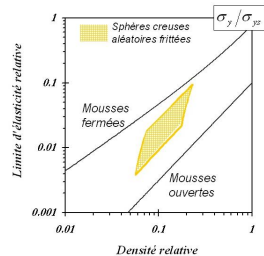


- ① Matériau cellulaire
 - ② Elaboration par métallurgie des poudres
 - ③ Mousse ouverte
 - ④ **Mousse fermée**
- Importante énergie mécanique absorbée
 - Propriétés mécaniques spécifiques élevées

Empilements de sphères creuses

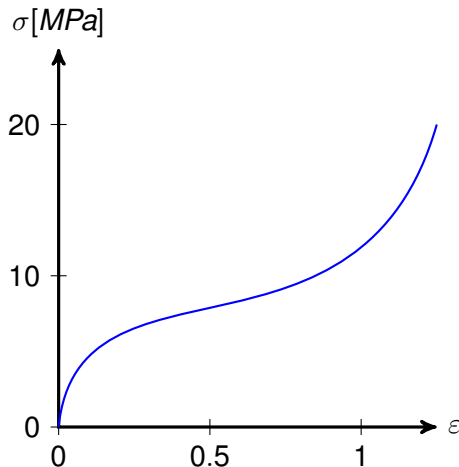


- 1 Matériau cellulaire
- 2 Elaboration par métallurgie des poudres
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Intégration dans des structures

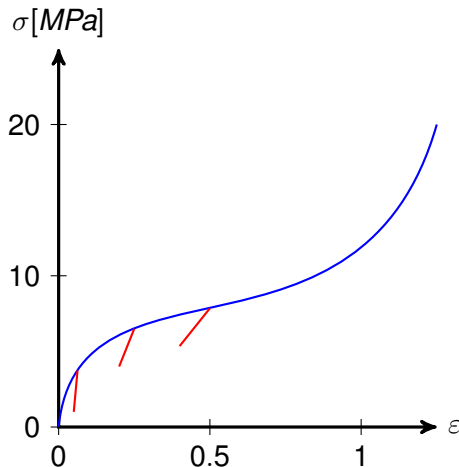
Propriétés



- Faible niveau de contraintes
- Endommagement du matériau
- Propriétés fortement influencées par la densité

Intégration dans des structures

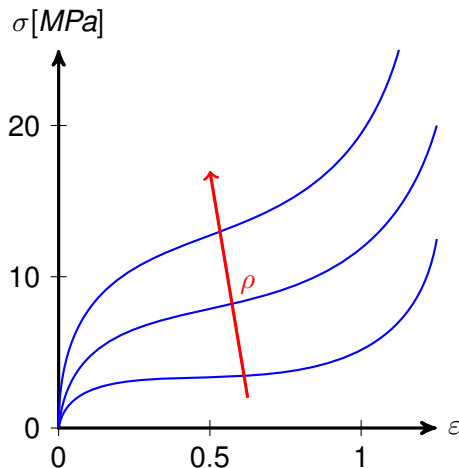
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Intégration dans des structures

Propriétés



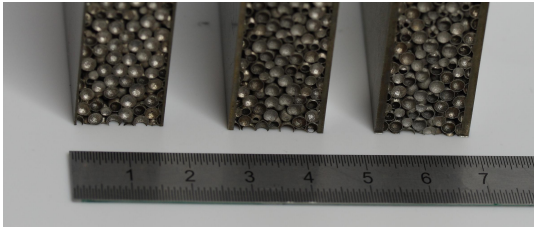
- Faible niveau de contraintes
- Endommagement du matériau
- Propriétés fortement influencées par la densité

Intégration dans des structures

Couplage de propriétés

➤ Association avec un matériau dense :

- Profilés
- Structures sandwich



Contexte de l'étude

Empilements ordonnés

S. GASSER
(ONERA, 2003)
Elastoplasticité et
acoustique



M.W. SANDERS
(MIT, 2002)
Elastoplasticité

Contexte de l'étude

Empilements ordonnés

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Matériaux POreux (Empilements aléatoires)

F. MAMOUD
(ONERA, 2007)
Elasticité et fluage

O. CATY
(INSA Lyon, 2008)
Fatigue

A. FALLET
(Grenoble INP, 2008)
Initiation plasticité et
endommagement



Contexte de l'étude

Empilements ordonnés

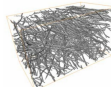
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Milieux enchevêtrés

C. BARBIER
(Grenoble INP,
2008)
Modélisation de
milieu enchevêtré



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J-P. MASSE
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Structures
sandwichs fines



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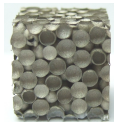


Matériaux P

F. MAMOUD
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Contexte de l'étude

Empilements ordonnés

Milieux enchevêtrés



Peu de données expérimentales sur le matériau



Pas de modèles pour les grandes déformations



Peu de connaissance sur l'endommagement

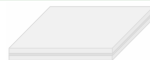


Pas de données expérimentales exploitables sur les structures

A. FALLET
(Grenoble INP, 2008)
Initiation plasticité et
endommagement



Structures
sandwichs fines



Stratégie

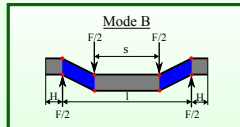


Stratégie

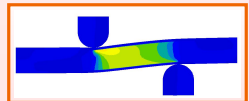
Expérimental



Analytique

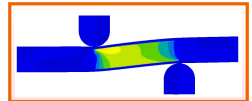
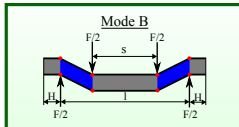


Numérique

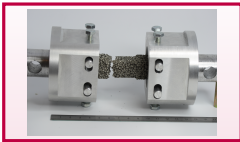


Stratégie

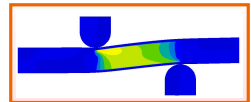
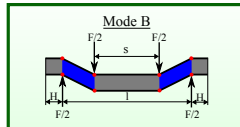
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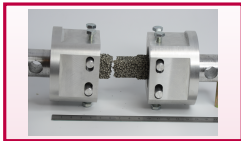
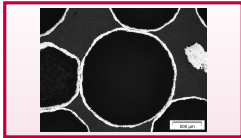
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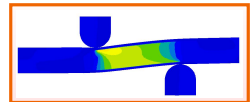
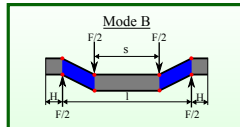
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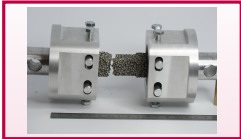
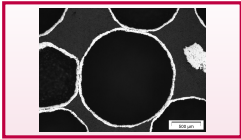
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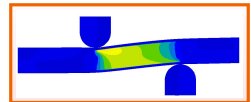
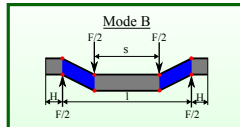
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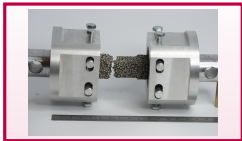
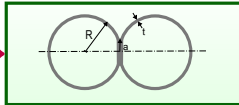
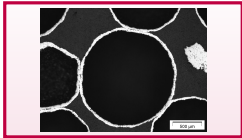
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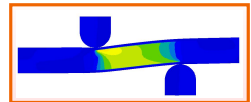
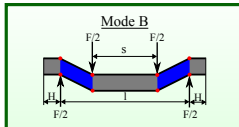
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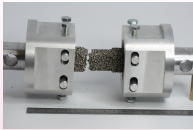
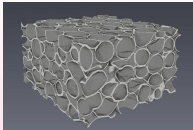
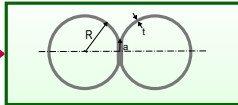
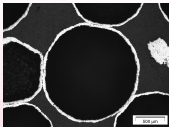
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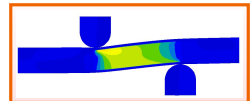
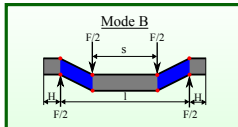
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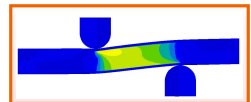
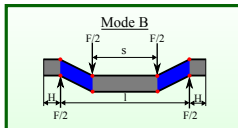
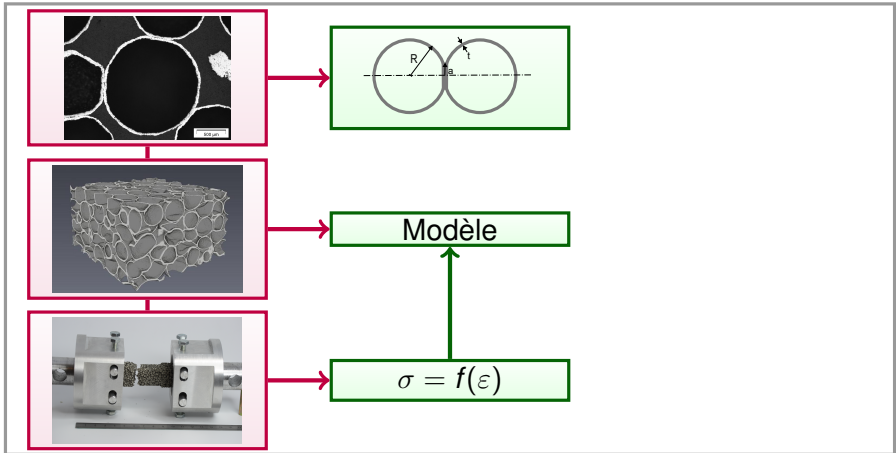
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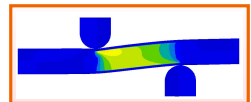
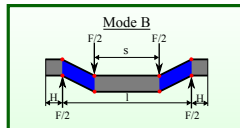
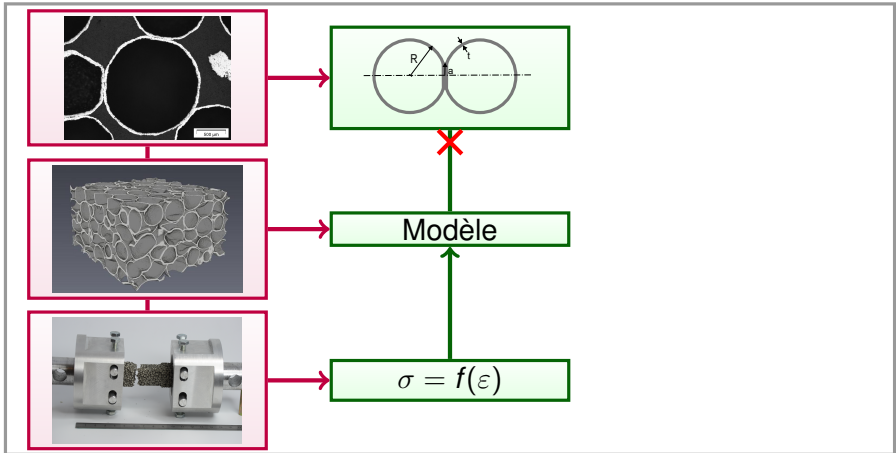
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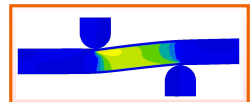
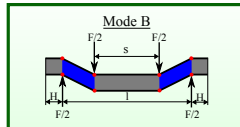
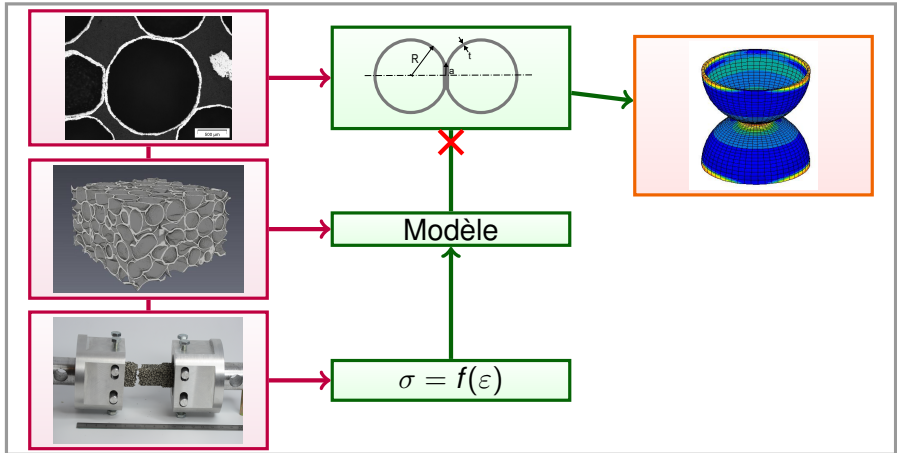
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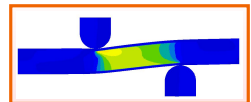
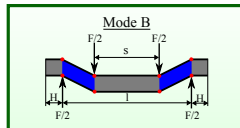
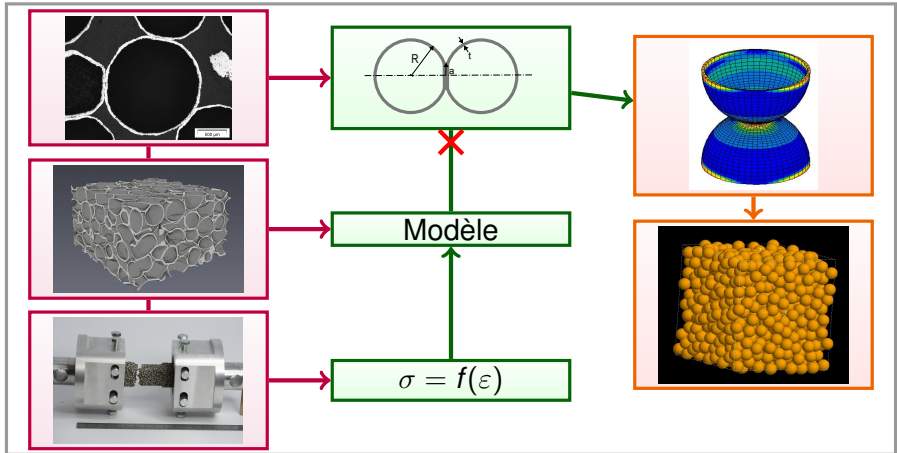
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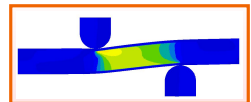
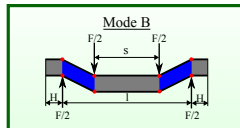
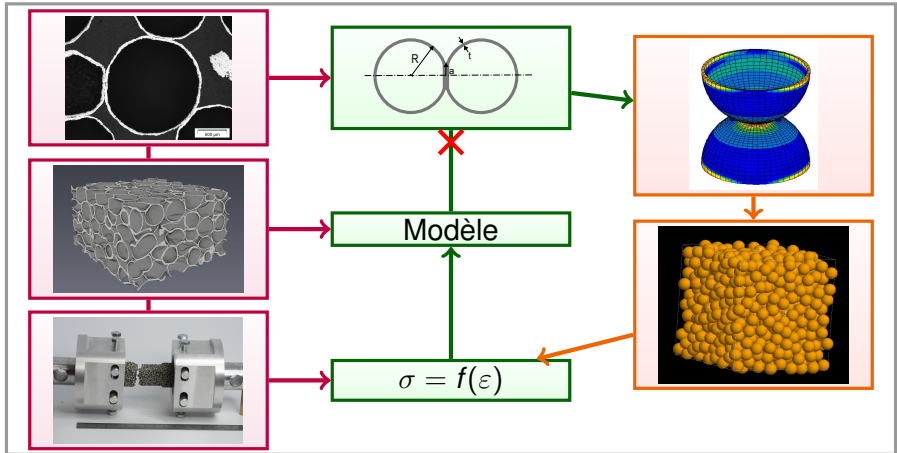
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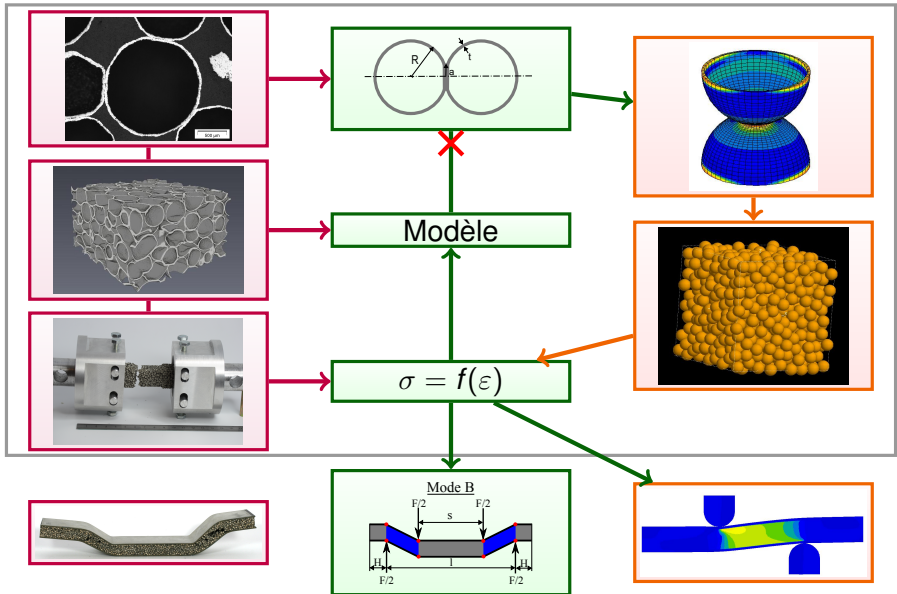
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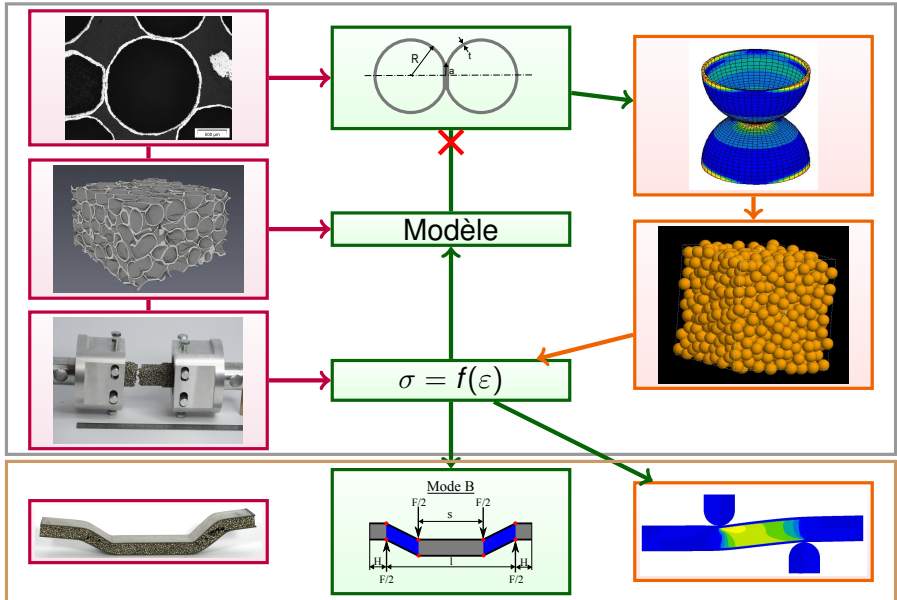
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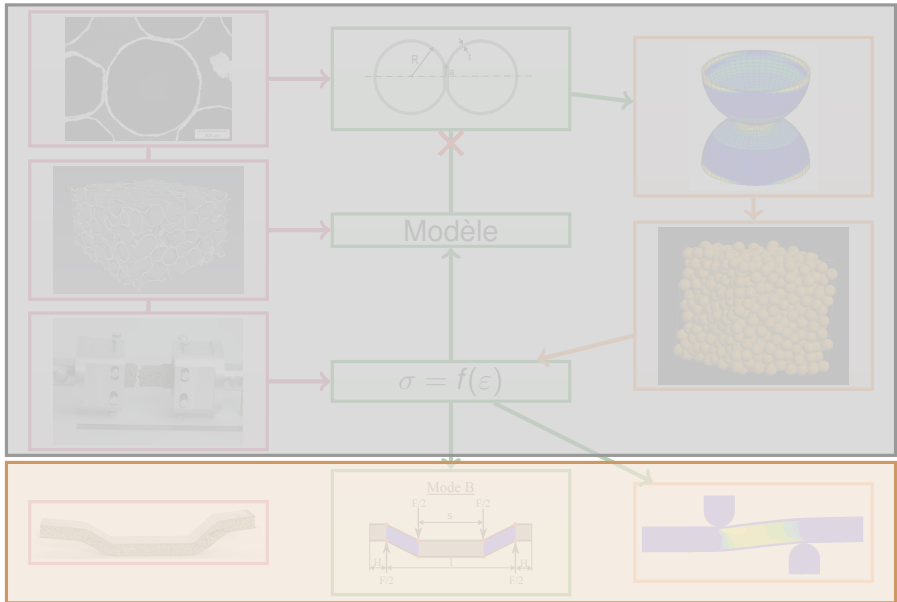
Stratégie



Stratégie



Stratégie



Stratégie

Empilements de sphère creuses

Structure et modélisation

Comportement sous chargement uni-axial

Comportement sous chargement multi-axial

$$u = f(\varepsilon)$$

Mode B



Stratégie

Empilements de sphère creuses

Structure et modélisation

Comportement sous chargement uni-axial

Comportement sous chargement multi-axial

Structures sandwich

Stratégie

Empilements de sphère creuses

Structure et modélisation

Comportement sous chargement uni-axial

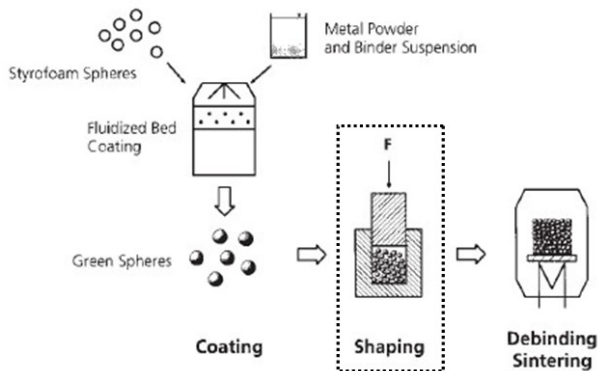
Comportement sous chargement multi-axial

Structures sandwich

Conclusions et perspectives

Procédé d'élaboration

IFAM



Echantillons étudiés

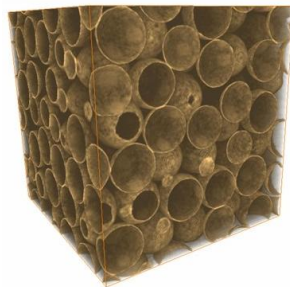
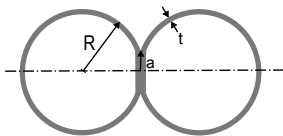
Fournis par PLANSEE.

Matériau constitutif : 314 (norme AISI).

Structure du matériau

Caractérisation par tomographie aux rayons X

	A	B	C
R (mm)	1.31	1.31	1.31
a (μm)	418	400	388
t (μm)	56	72	88
ρ^*/ρ_s	0.070	0.092	0.113
z	7.9	8.2	7.6

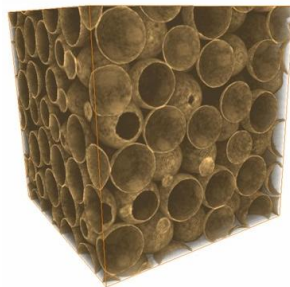
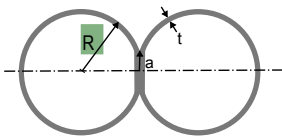


Paramètre structural : $t \rightarrow \rho$

Structure du matériau

Caractérisation par tomographie aux rayons X

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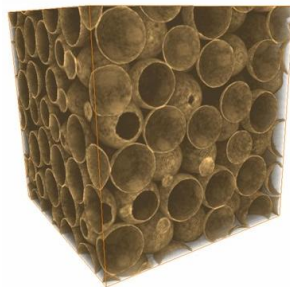
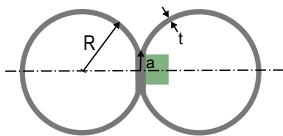


Paramètre structural : $t \rightarrow \rho$

Structure du matériau

Caractérisation par tomographie aux rayons X

	A	B	C
R (mm)	1.31	1.31	1.31
a (μm)	418	400	388
t (μm)	56	72	88
ρ^*/ρ_s	0.070	0.092	0.113
z	7.9	8.2	7.6

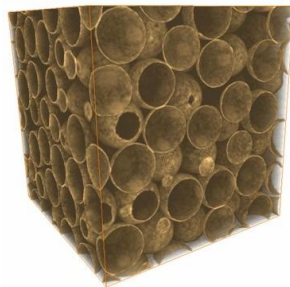
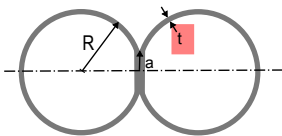


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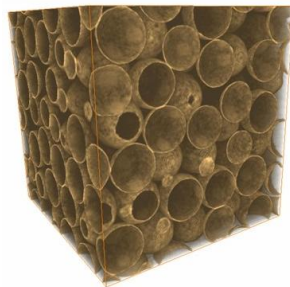
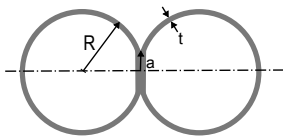


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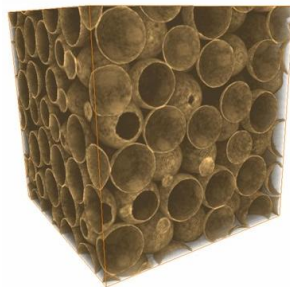
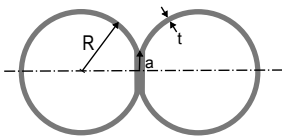


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Structure du matériau

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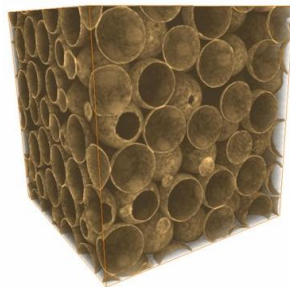
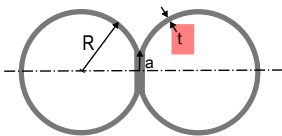


Paramètre structural : $t \rightarrow \rho$

Structure du matériau

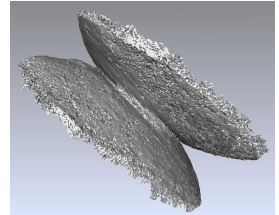
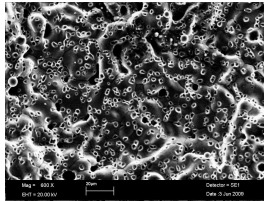
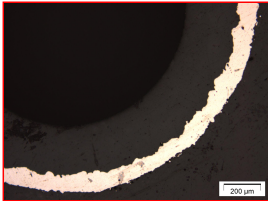
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Paramètre structural : $t \rightarrow \rho$

Structure du matériau

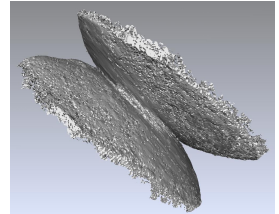
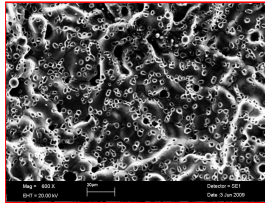
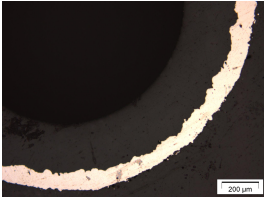


- Surface rugueuses ($\simeq 20\mu m$)
- Porosité des parois ($\simeq 4\%$)
- Surface de contact

surrestimée



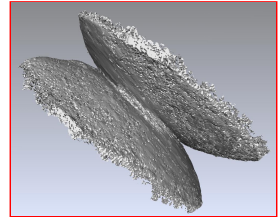
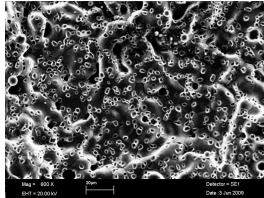
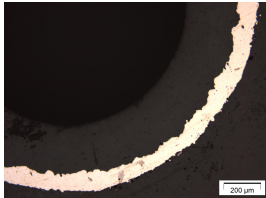
Structure du matériau



- Surface rugueuses ($\simeq 20\mu m$)
- Porosité des parois ($\simeq 4\%$)
- Surface de contact surrestimée



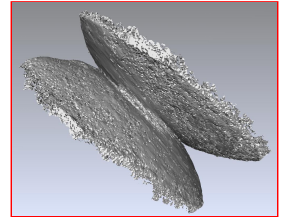
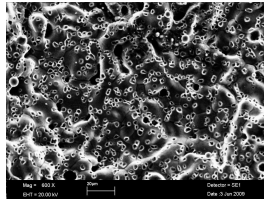
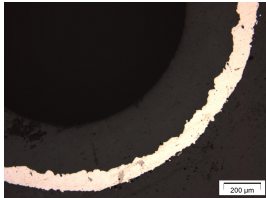
Structure du matériau



- Surface rugueuses ($\simeq 20\mu m$)
- Porosité des parois ($\simeq 4\%$)
- Surface de contact surrestimée

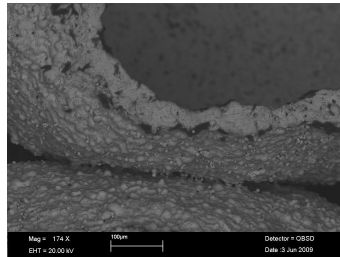


Structure du matériau

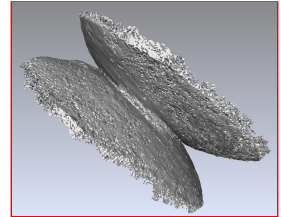
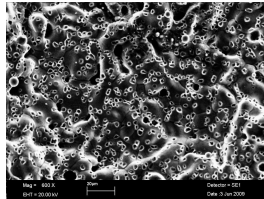
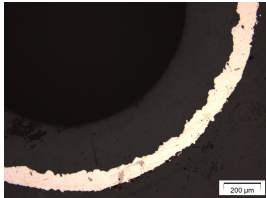


- Surface rugueuses ($\simeq 20\mu\text{m}$)
- Porosité des parois ($\simeq 4\%$)
- Surface de contact

surrestimée

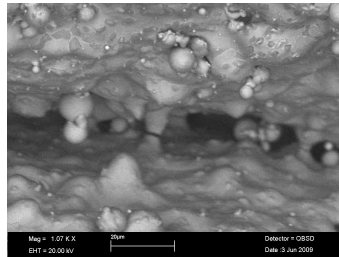


Structure du matériau

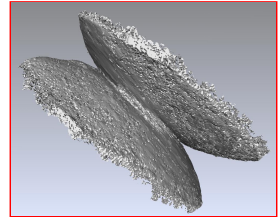
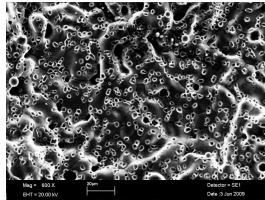
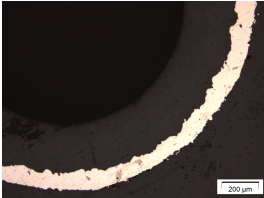


- Surface rugueuses ($\simeq 20\mu m$)
- Porosité des parois ($\simeq 4\%$)
- Surface de contact

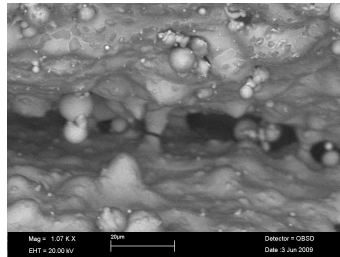
surrestimée



Structure du matériau

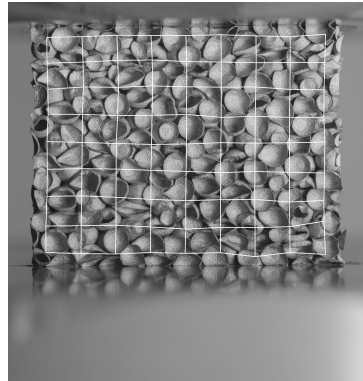
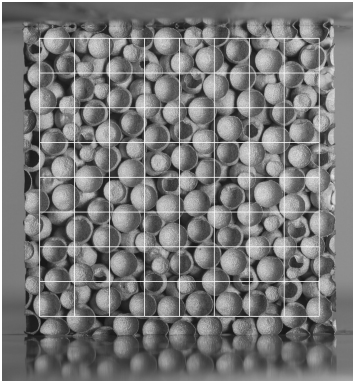


- Surface rugueuses ($\simeq 20\mu m$)
- Porosité des parois ($\simeq 4\%$)
- Surface de contact surrestimée ⚠



Essais mécaniques

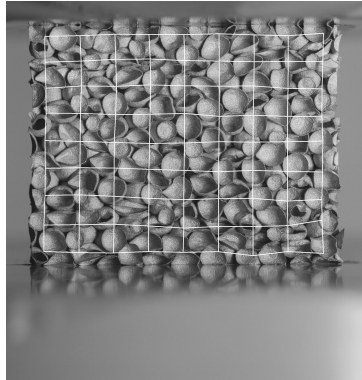
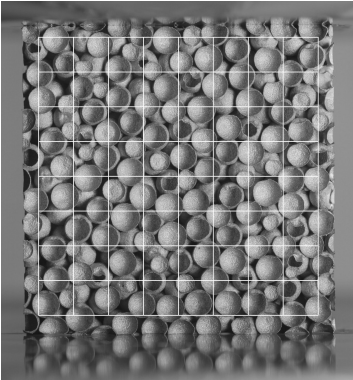
Compression uniaxiale



Déformation homogène

Essais mécaniques

Compression uniaxiale

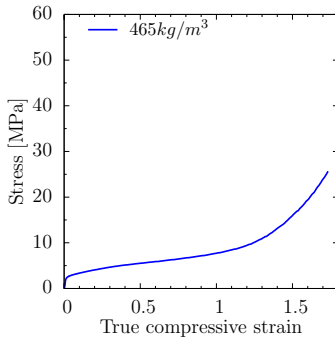


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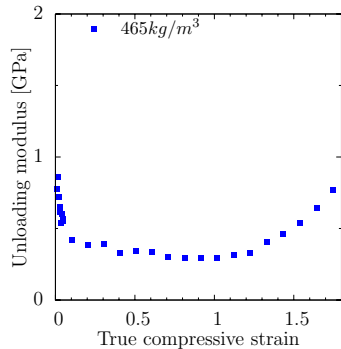
Essais mécaniques

Compression uniaxiale

Contrainte-déformation



Module de décharge

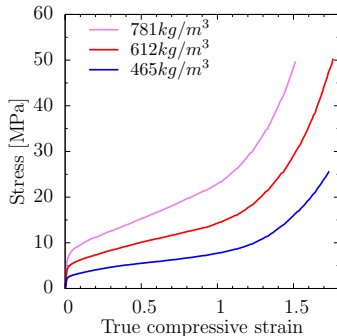


Lois puissance : $P = P_0 \rho^n$

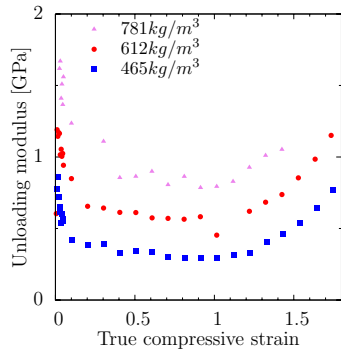
Essais mécaniques

Compression uniaxiale

Contrainte-déformation



Module de décharge

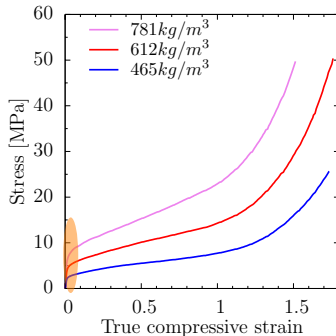


Lois puissance : $P = P_0 \rho^n$

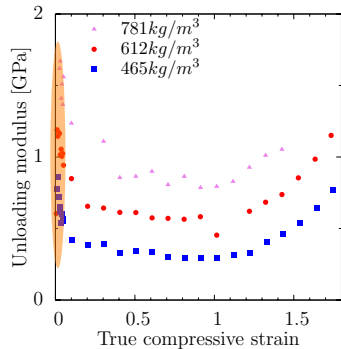
Essais mécaniques

Compression uniaxiale

Contrainte-déformation



Module de décharge

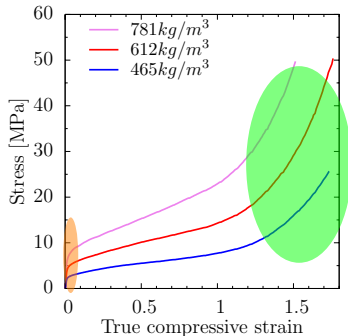


Lois puissance : $P = P_0 \rho^n$

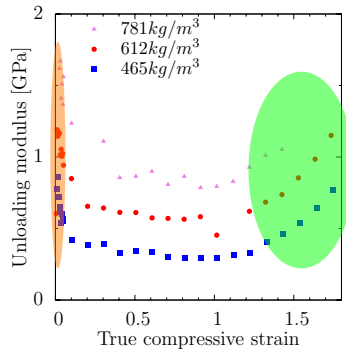
Essais mécaniques

Compression uniaxiale

Contrainte-déformation



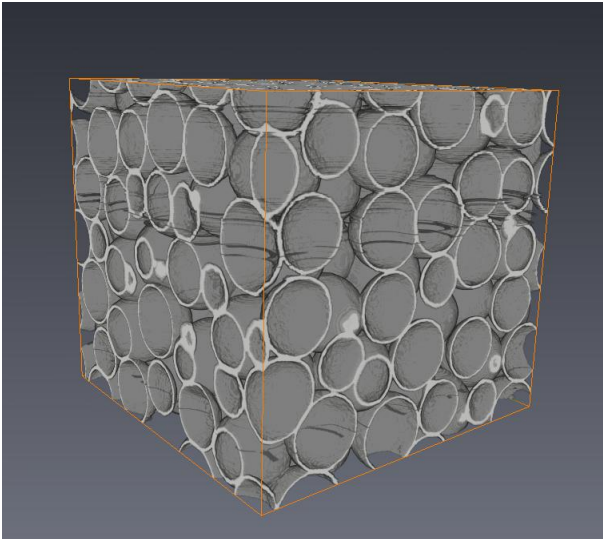
Module de décharge



Lois puissance : $P = P_0 \rho^n$

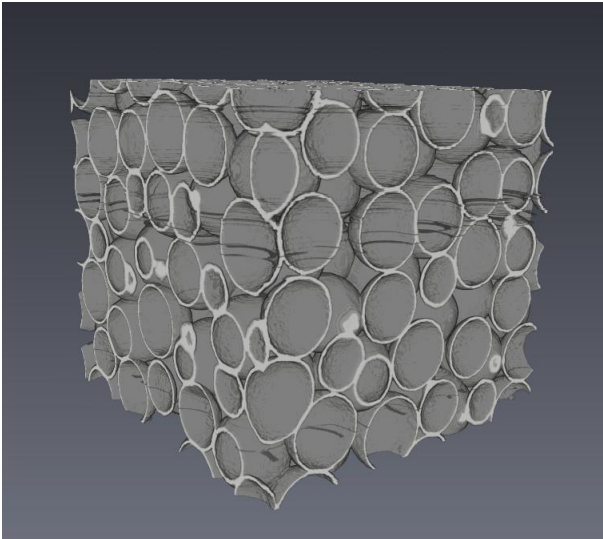
Mécanismes locaux

Densification



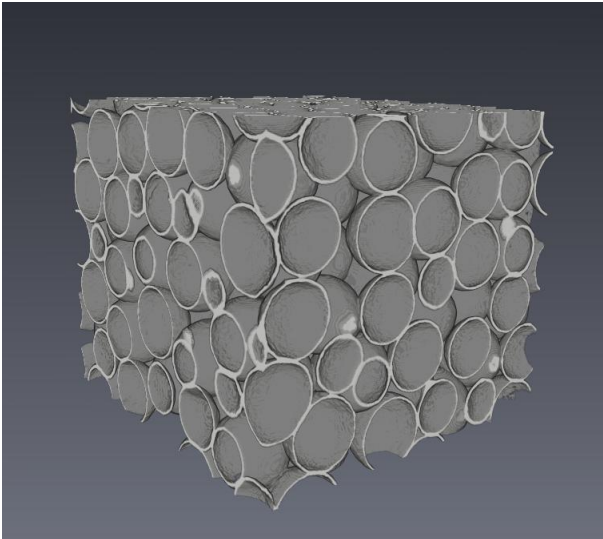
Mécanismes locaux

Densification



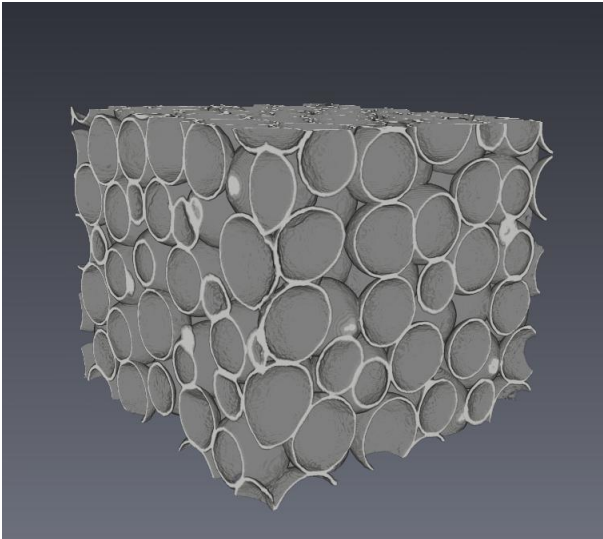
Mécanismes locaux

Densification



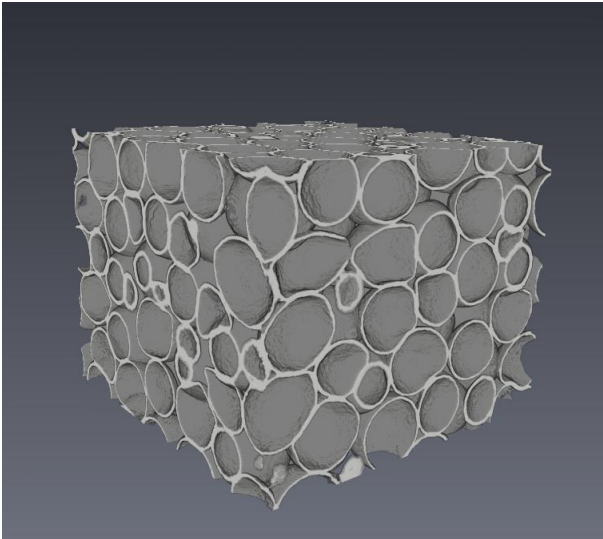
Mécanismes locaux

Densification



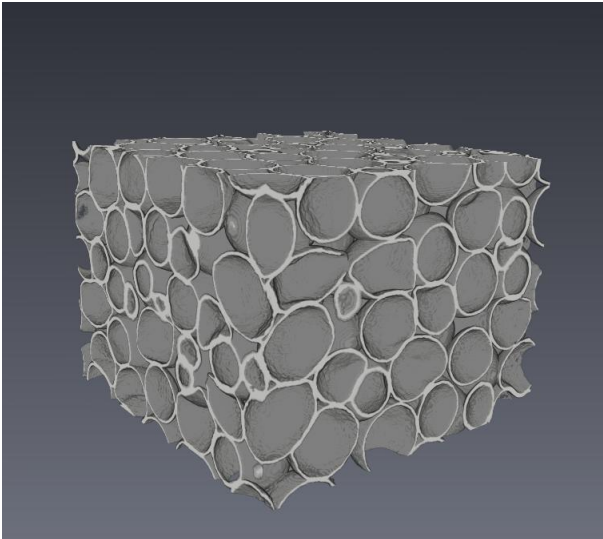
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Densification



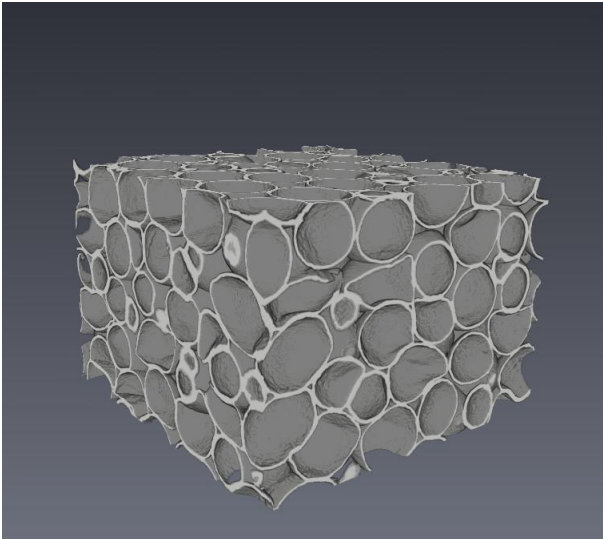
Mécanismes locaux

Densification



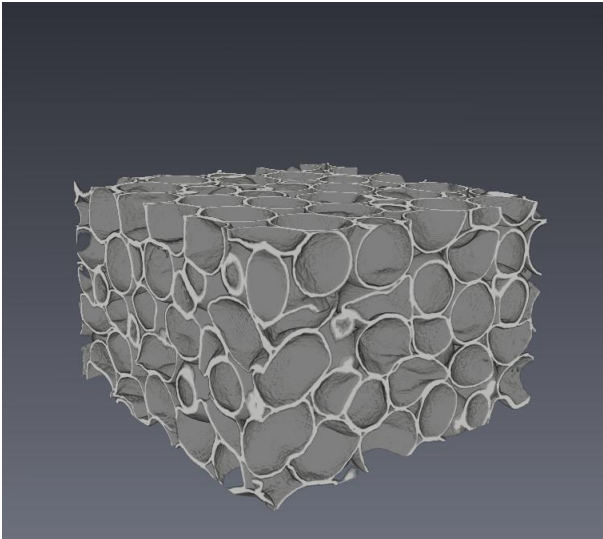
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Densification



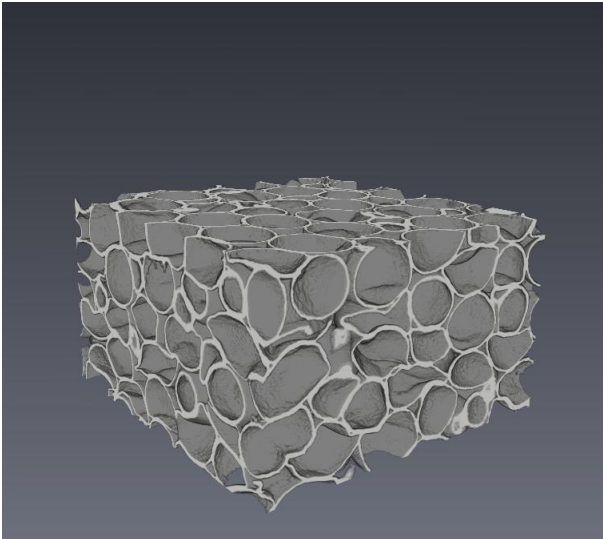
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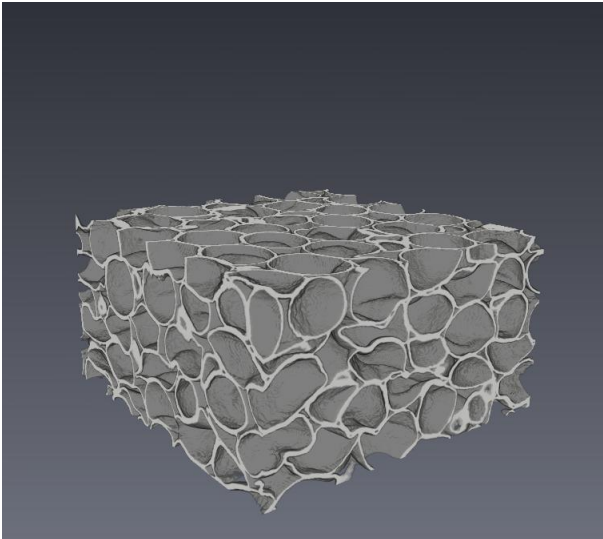
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Densification



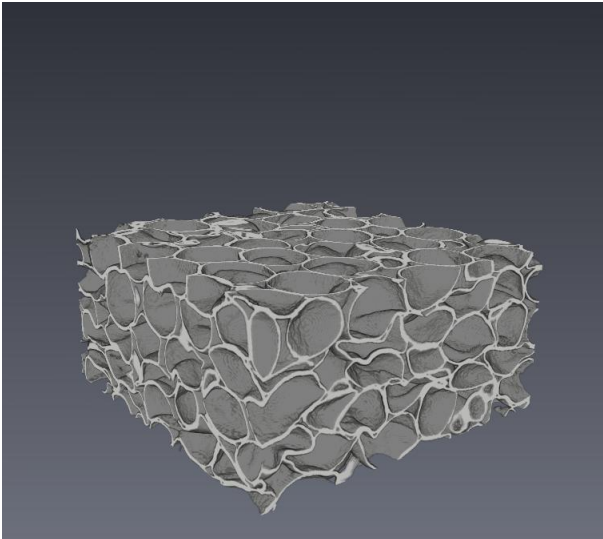
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Densification



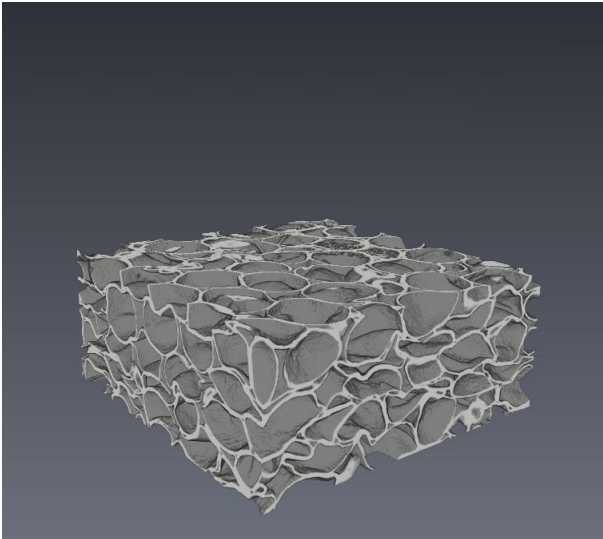
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Densification



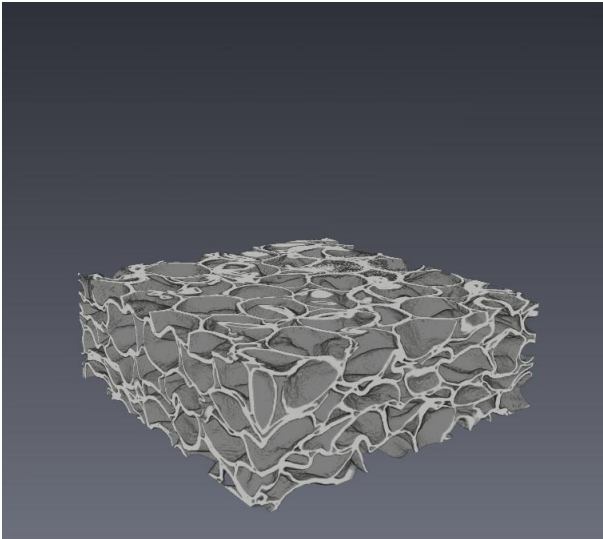
Mécanismes locaux

Densification



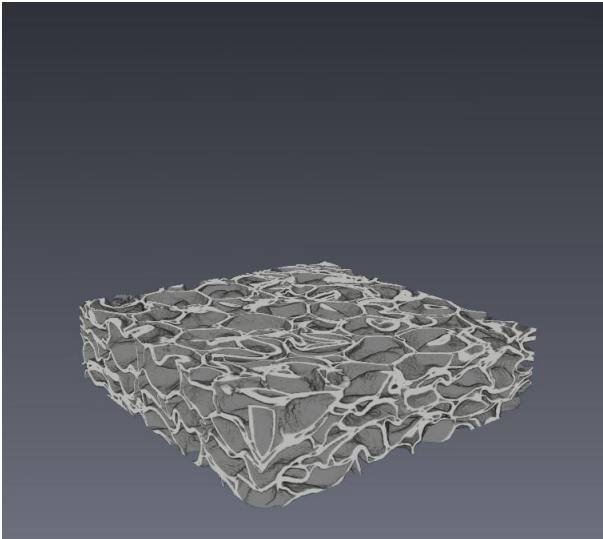
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Densification



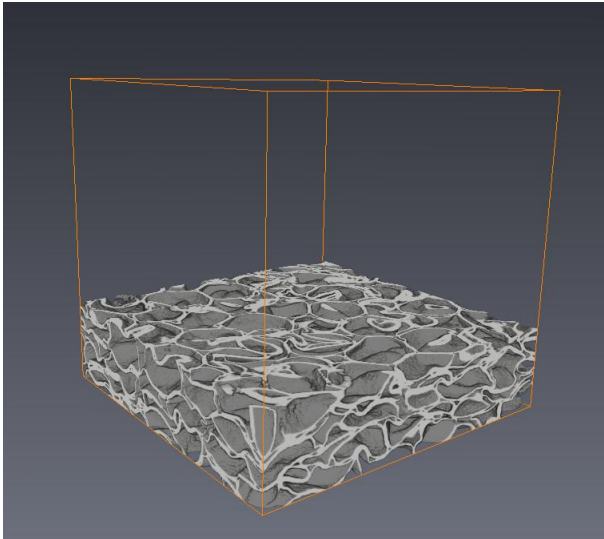
Mécanismes locaux

Densification



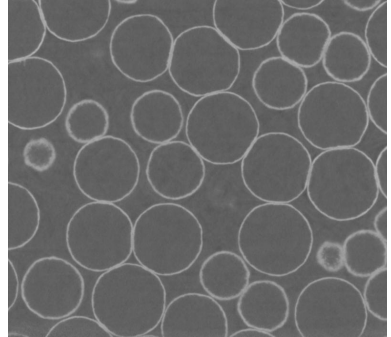
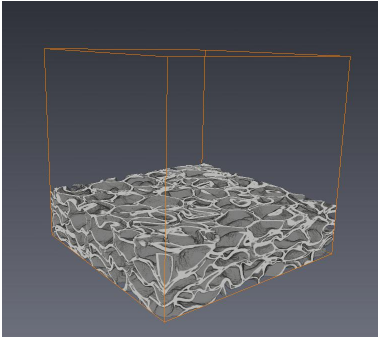
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Densification



Mécanismes locaux

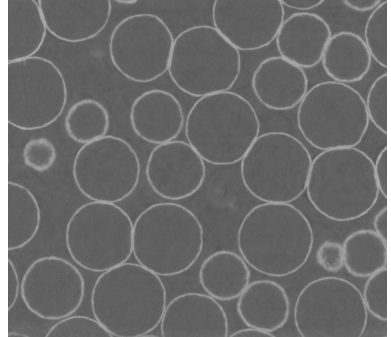
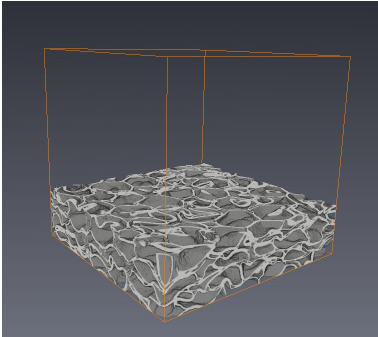
Densification



Plateau = Occlusion de la porosité ouverte
Densification = Occlusion de la porosité fermée

Mécanismes locaux

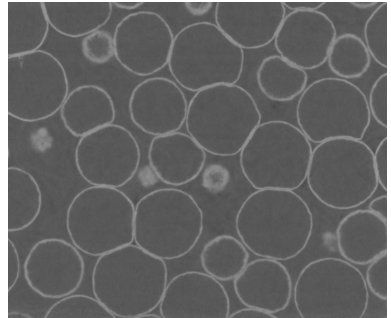
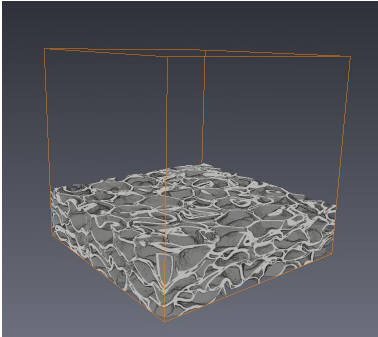
Densification



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Mécanismes locaux

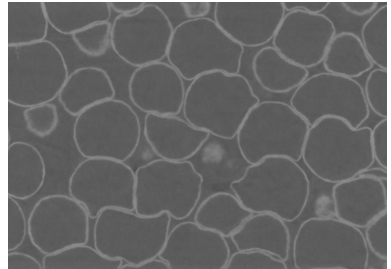
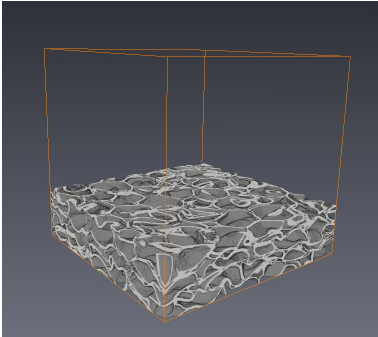
Densification



Plateau = Occlusion de la porosité ouverte
Densification = Occlusion de la porosité fermée

Mécanismes locaux

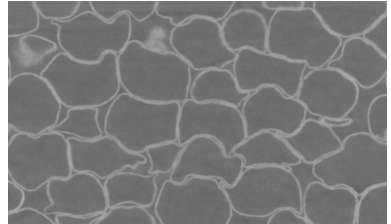
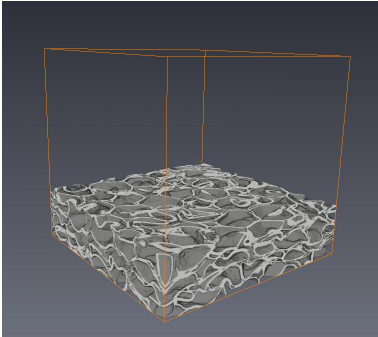
Densification



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Mécanismes locaux

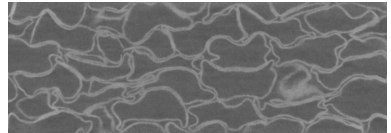
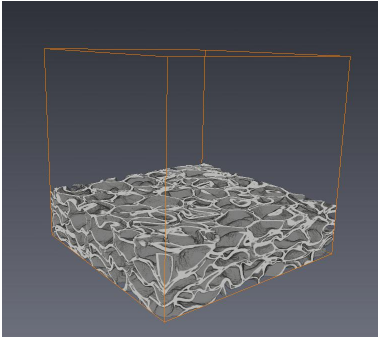
Densification



Plateau = Occlusion de la porosité ouverte
Densification = Occlusion de la porosité fermée

Mécanismes locaux

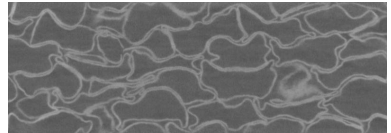
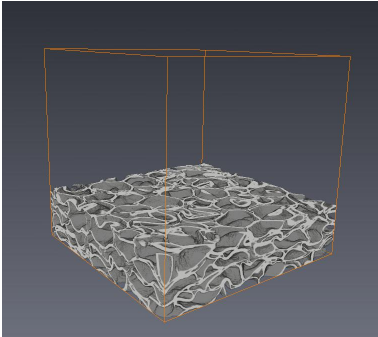
Densification



Plateau = Occlusion de la porosité ouverte
Densification = Occlusion de la porosité fermée

Mécanismes locaux

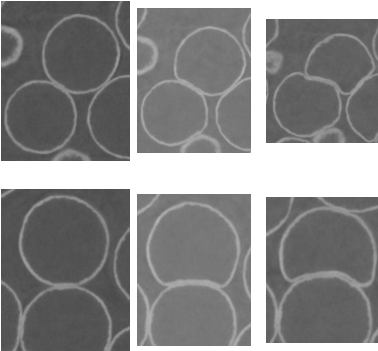
Densification



Plateau = Occlusion de la porosité ouverte
Densification = Occlusion de la porosité fermée

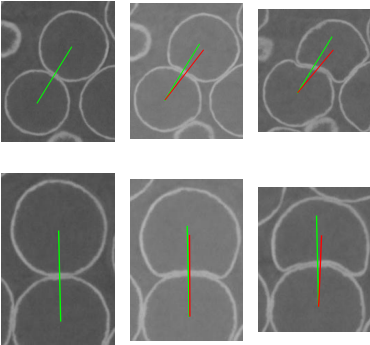
Mécanismes locaux

Endommagement



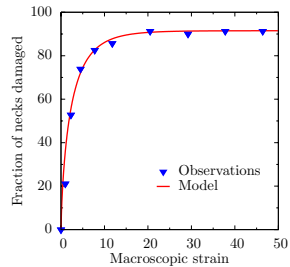
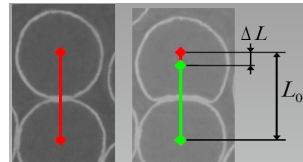
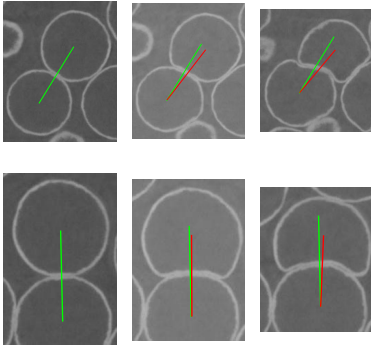
Mécanismes locaux

Endommagement



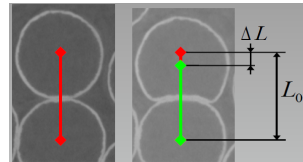
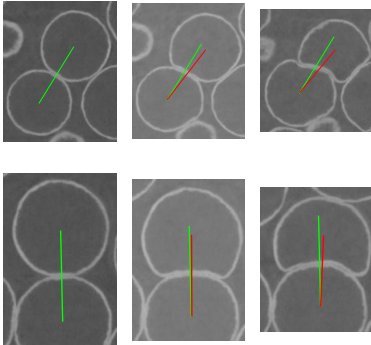
Mécanismes locaux

Endommagement



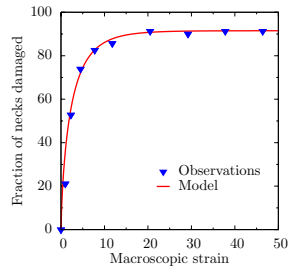
Mécanismes locaux

Endommagement



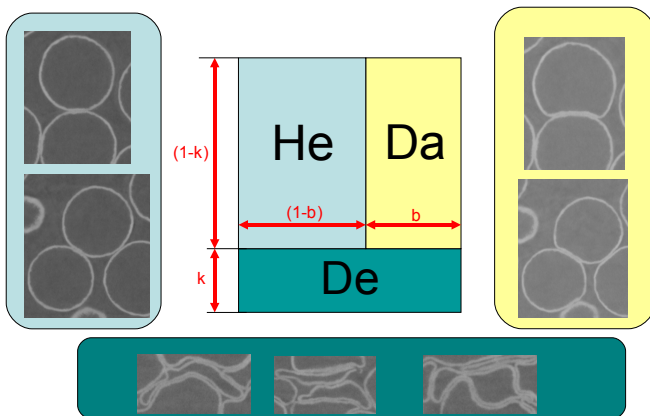
Fraction de cols endommagée :

$$P(\varepsilon) = 0.9 \left[1 - e^{\left(\frac{\varepsilon}{\varepsilon_u} \right)^{0.75}} \right]$$



Modèle phénoménologique

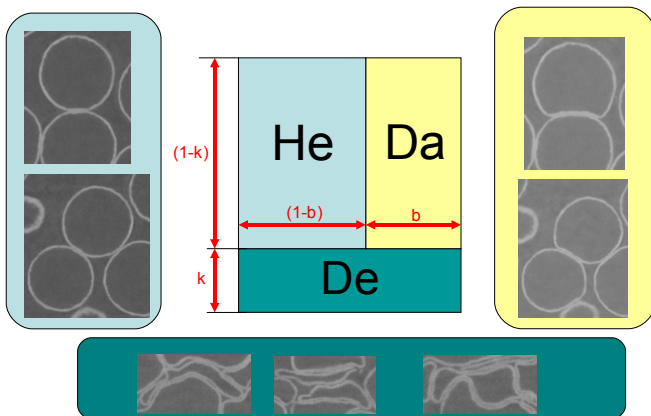
Présentation



Changement de phase : Weibul

Modèle phénoménologique

Présentation

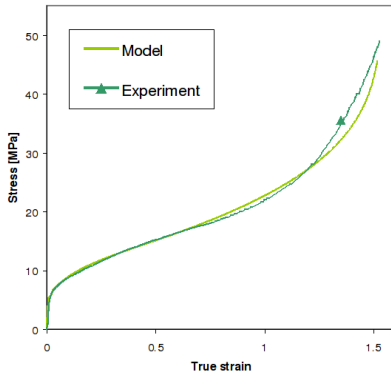


Changement de phase : Weibul

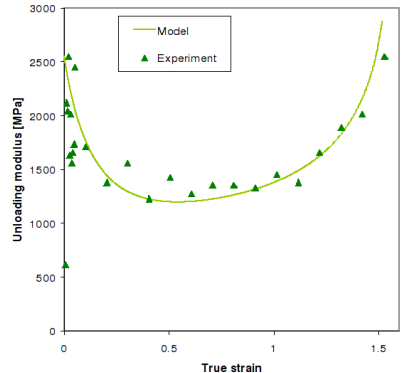
Modèle phénoménologique

Réponse

Contrainte-Déformation



Module de décharge

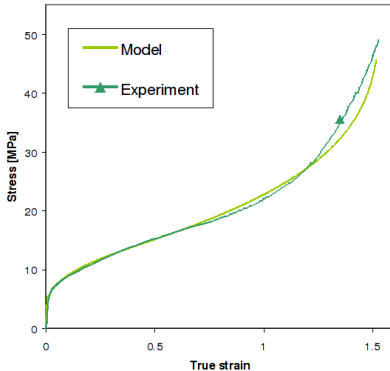


Changement de densité : lois puissance

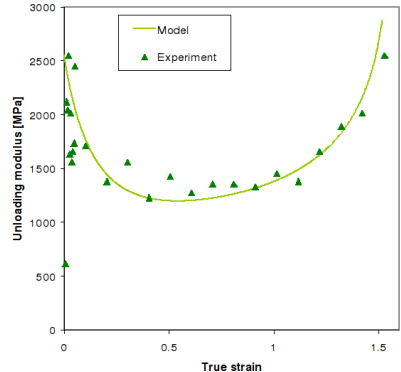
Modèle phénoménologique

Réponse

Contrainte-Déformation



Module de décharge

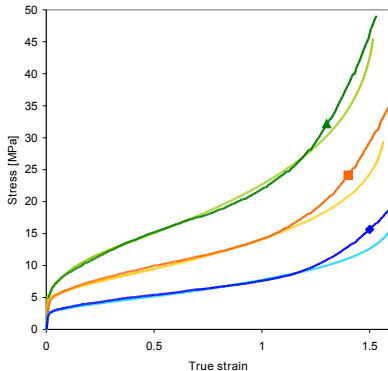


Changement de densité : lois puissance

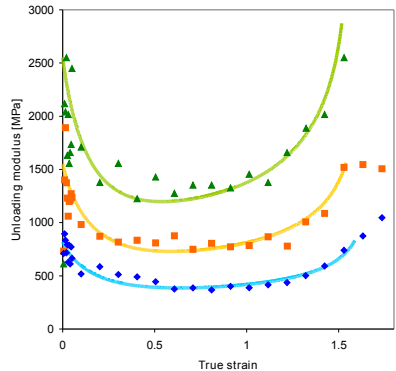
Modèle phénoménologique

Réponse

Contrainte-Déformation



Module de décharge

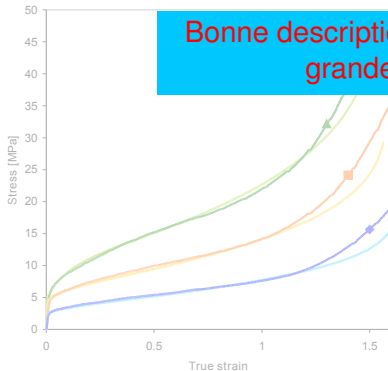


Changement de densité : lois puissance

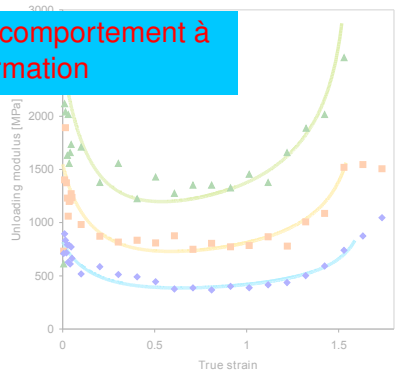
Modèle phénoménologique

Réponse

Contrainte-Déformation



Module de décharge

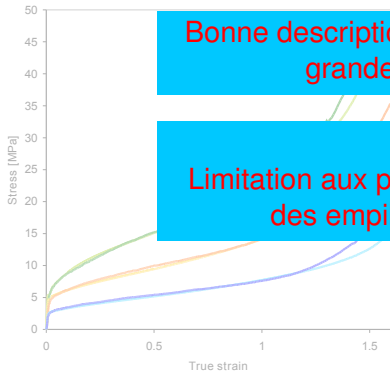


Changement de densité : lois puissance

Modèle phénoménologique

Réponse

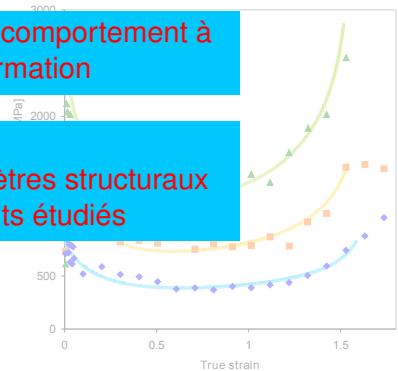
Contrainte-Déformation



Bonne description du comportement à grande déformation

MAIS
Limitation aux paramètres structuraux
des empilements étudiés

Module de décharge

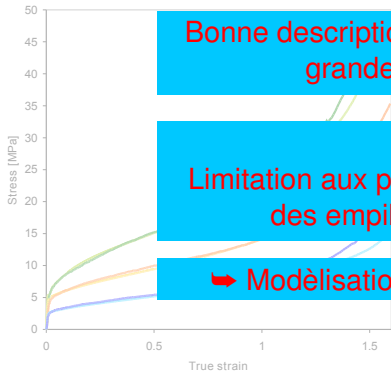


Changement de densité : lois puissance

Modèle phénoménologique

Réponse

Contrainte-Déformation



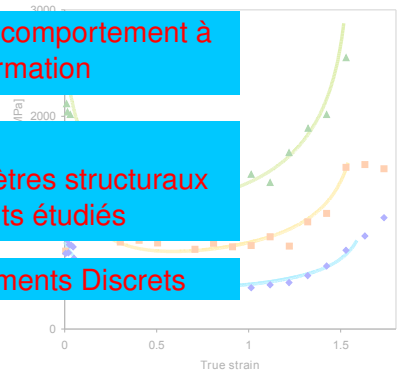
Bonne description du comportement à grande déformation

MAIS

Limitation aux paramètres structuraux des empilements étudiés

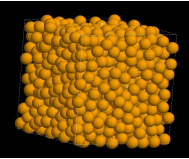
➔ Modélisation Eléments Discrets

Module de décharge



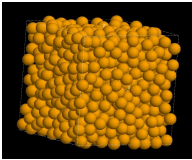
Changement de densité : lois puissance

Méthode des Éléments Discrets

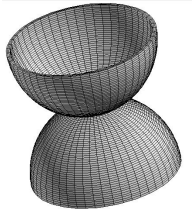


Empilement

Méthode des Éléments Discrets

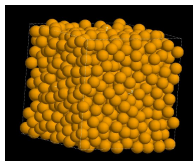


Empilement

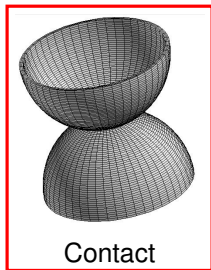
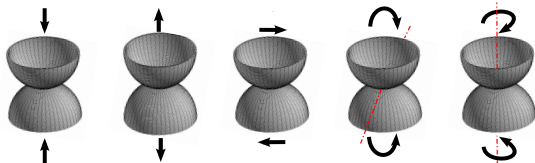


Contact

Méthode des Éléments Discrets



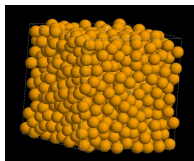
Empilement



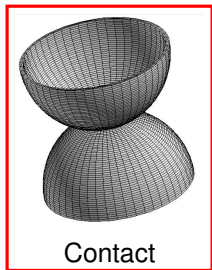
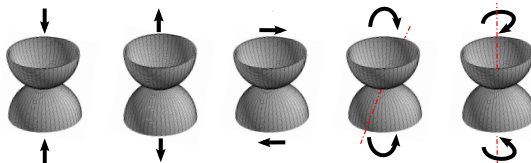
Contact

[Fallet, 2008]

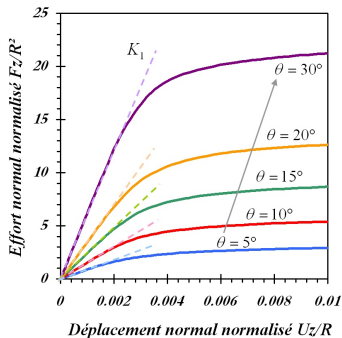
Méthode des Éléments Discrets



Empilement

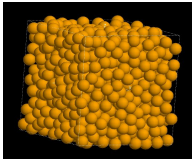


Contact

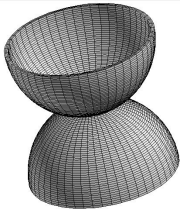


[Fallet, 2008]

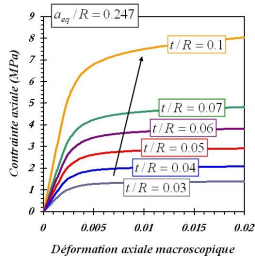
Méthode des Eléments Discrets



Empilement

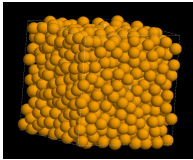


Contact

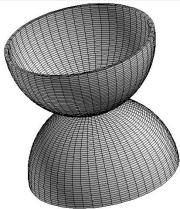


[Fallet, 2008]

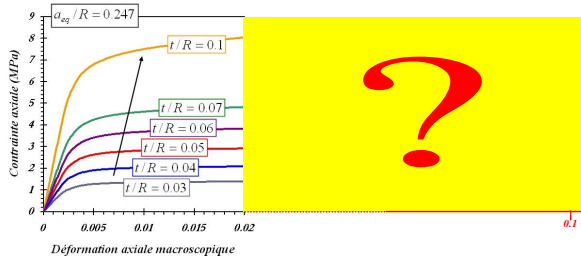
Méthode des Eléments Discrets



Empilement

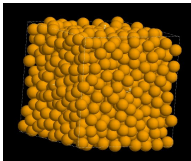


Contact

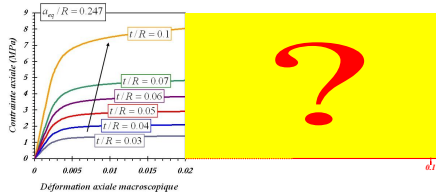


[Fallet, 2008]

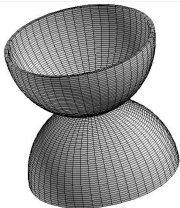
Méthode des Eléments Discrets



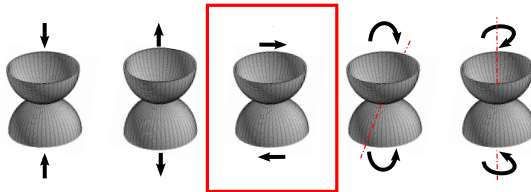
Empilement



Evolution du module de décharge ?



Contact



[Fallet, 2008]

Méthode des Éléments Discrets

Extension des lois

Evolution du module
de décharge

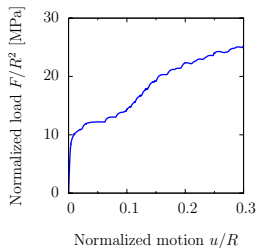
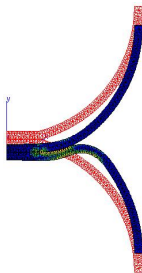
Influence des
conditions aux limites

Méthode des Éléments Discrets

Extension des lois

Evolution du module
de décharge

Influence des
conditions aux limites

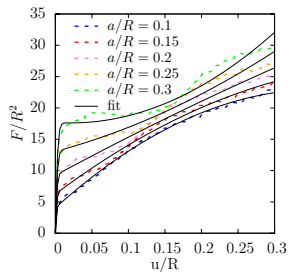
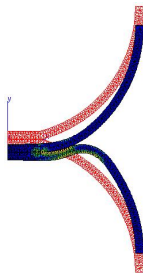


Méthode des Éléments Discrets

Extension des lois

Evolution du module
de décharge

Influence des
conditions aux limites

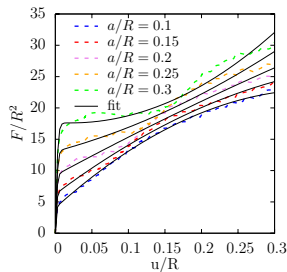
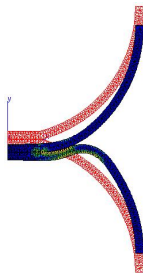


Méthode des Eléments Discrets

Extension des lois

Evolution du module
de décharge

Influence des
conditions aux limites



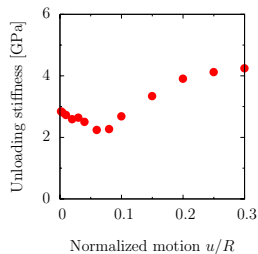
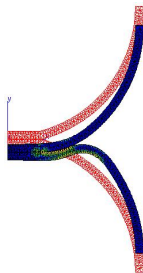
Simulations de sphères sans cols

Méthode des Éléments Discrets

Extension des lois

Evolution du module
de décharge

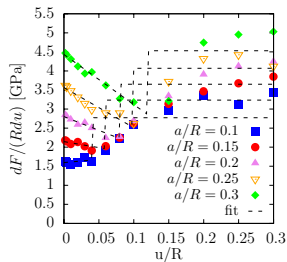
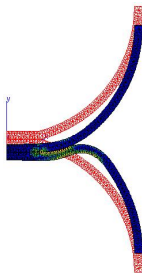
Influence des
conditions aux limites



Méthode des Eléments Discrets

Extension des lois

Evolution du module
de décharge



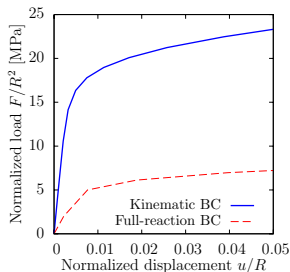
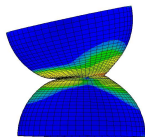
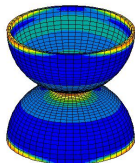
Influence des
conditions aux limites

Méthode des Éléments Discrets

Extension des lois

Evolution du module
de décharge

Influence des
conditions aux limites

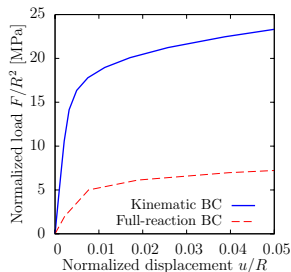
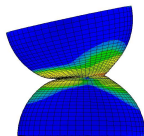
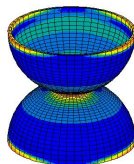


Méthode des Éléments Discrets

Extension des lois

Evolution du module
de décharge

Influence des
conditions aux limites

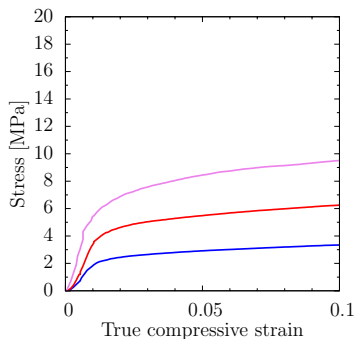


Loi de cisaillement

Méthode des Éléments Discrets

Confrontation modèles-experiences

Contrainte-déformation



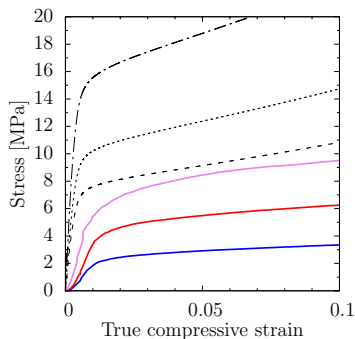
Correction taille des cols ($a \searrow 20\%$)

Correction loi de cisaillement (facteur 4)

Méthode des Éléments Discrets

Confrontation modèles-exériences

Contrainte-déformation



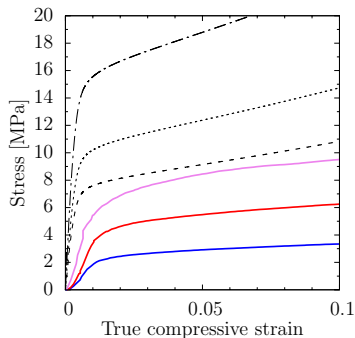
Correction taille des cols ($a \searrow 20\%$)

Correction loi de cisaillement (facteur 4)

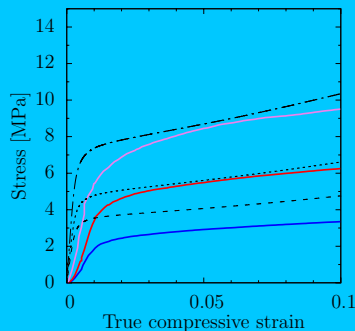
Méthode des Éléments Discrets

Confrontation modèles-expériences

Contrainte-déformation



Contrainte-déformation



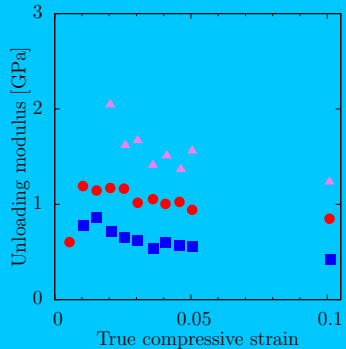
Correction taille des cols ($a \searrow 20\%$)

Correction loi de cisaillement (facteur 4)

Méthode des Éléments Discrets

Confrontation modèles-expériences

Module de décharge



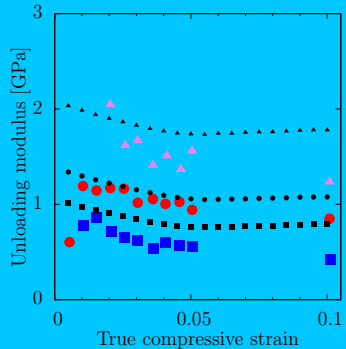
Correction taille des cols ($a \searrow 20\%$)

Correction loi de cisaillement (facteur 4)

Méthode des Éléments Discrets

Confrontation modèles-expériences

Module de décharge



Correction taille des cols ($a \searrow 20\%$)

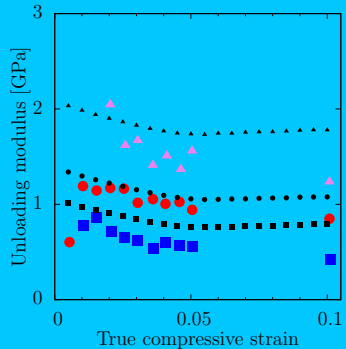
Correction loi de cisaillement (facteur 4)

Méthode des Éléments Discrets

Confrontation modèles-expériences

Baisse du module :

Module de décharge



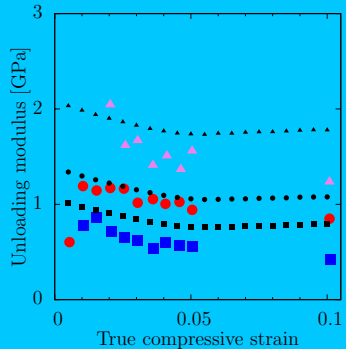
Correction taille des cols ($a \searrow 20\%$)
Correction loi de cisaillement (facteur 4)

Méthode des Éléments Discrets

Confrontation modèles-expériences

Baisse du module :
➔ Effet géométrique

Module de décharge



Correction taille des cols ($a \searrow 20\%$)
Correction loi de cisaillement (facteur 4)

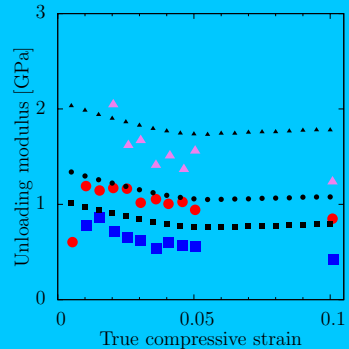
Méthode des Éléments Discrets

Confrontation modèles-expériences

Module de décharge

Baisse du module :

- ➡ Effet géométrique
- ➡ Matériau constitutif



Correction taille des cols ($a \searrow 20\%$)

Correction loi de cisaillement (facteur 4)

Sollicitation uniaxiale : Bilan



Données expérimentales



Modèle



Evolution



Endommagement

Sollicitation uniaxiale : Bilan



Données expérimentales

Compression
Traction



Modèle



Evolution



Endommagement

Sollicitation uniaxiale : Bilan



Données expérimentales

Compression

Traction



Modèle

Phénoménologique



Evolution



Endommagement

Sollicitation uniaxiale : Bilan



Données expérimentales

Compression

Traction



Modèle

Phénoménologique



Evolution

DEM + Corrections



Endommagement

Sollicitation uniaxiale : Bilan



Données expérimentales

Compression
Traction



Modèle

Phénoménologique



Evolution

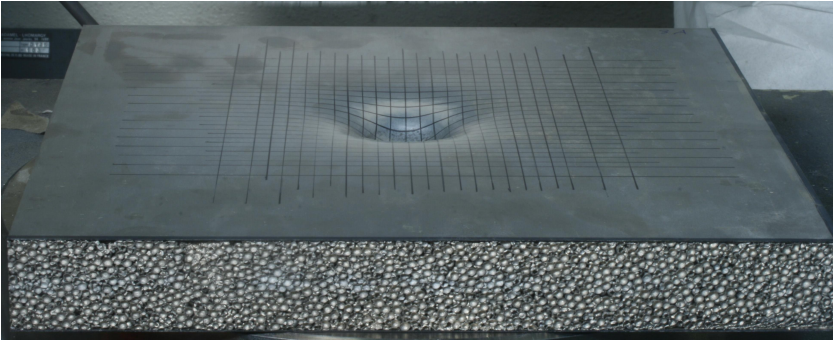
DEM + Corrections



Endommagement

Géométrie
Porosité parois

Objectif

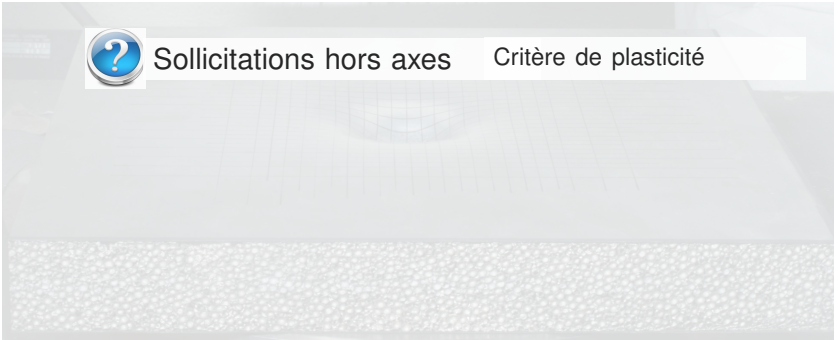


Objectif



Sollicitations hors axes

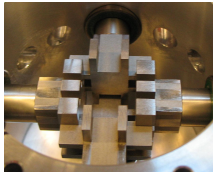
Critère de plasticité



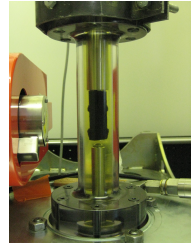
Essais mécaniques

Compression multiaxiale

3 axes - EPFL



Confinement - 3SR

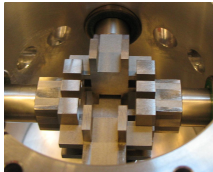


Taille d'échantillon limitée

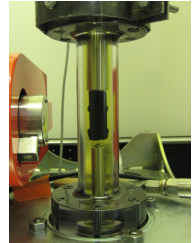
Essais mécaniques

Compression multiaxiale

3 axes - EPFL



Confinement - 3SR

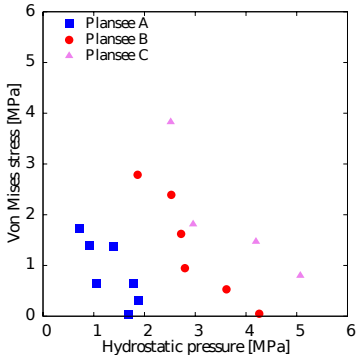


Taille d'échantillon limitée

Essais multiaxes

3 axes

Critère de plasticité

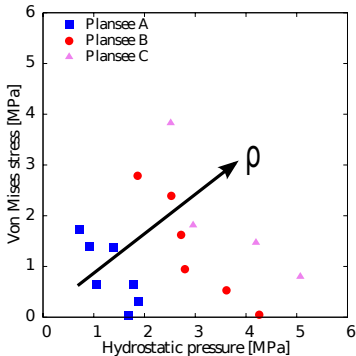


Quel est le critère ?

Essais multiaxes

3 axes

Critère de plasticité

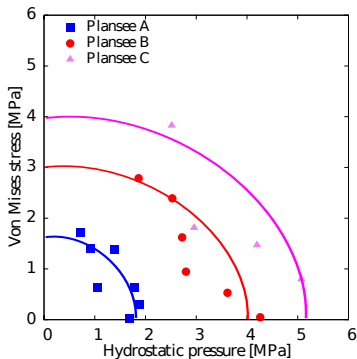


Quel est le critère ?

Essais multiaxes

3 axes

Critère de plasticité



Critère elliptique

$$f(\underline{\underline{\sigma}}) = \sqrt{Ap^2 + Bq^2} - \sigma_y$$

$$p = \frac{1}{3} \text{Trace}(\underline{\underline{\sigma}})$$

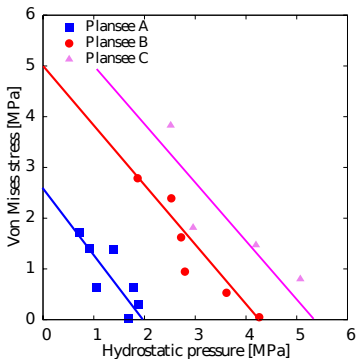
$$q = \sqrt{\frac{3}{2} \underline{\underline{s}} : \underline{\underline{s}}}$$

Quel est le critère ?

Essais multiaxes

3 axes

Critère de plasticité



Drucker-Prager

$$f(\underline{\underline{\sigma}}) = q - \frac{\sigma_y - 3\alpha p}{1 - \alpha}$$

$$p = \frac{1}{3} \text{Trace}(\underline{\underline{\sigma}})$$

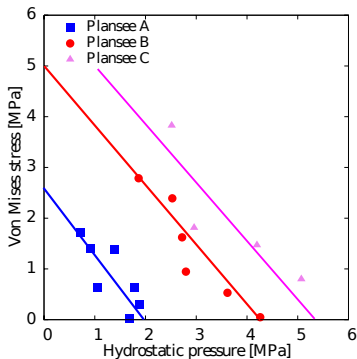
$$q = \sqrt{\frac{3}{2} \underline{\underline{s}} : \underline{\underline{s}}}$$

Quel est le critère ?

Essais multiaxes

3 axes

Critère de plasticité

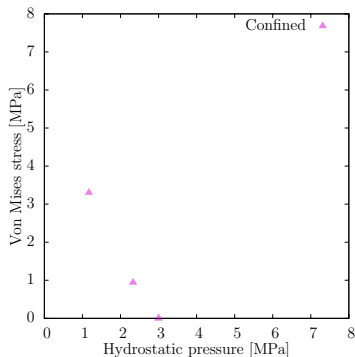


Quel est le critère ?

Essais multiaxes

Comparaison à la DEM

Critère de plasticité

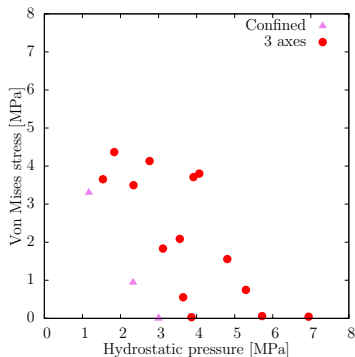


Description possible de la surface par la DEM.
MAIS sensibilité aux lois de contact

Essais multiaxes

Comparaison à la DEM

Critère de plasticité

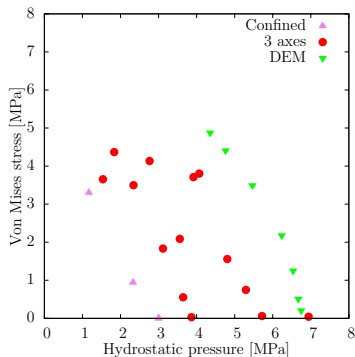


Description possible de la surface par la DEM.
MAIS sensibilité aux lois de contact
➡ Critère elliptique ?

Essais multiaxes

Comparaison à la DEM

Critère de plasticité

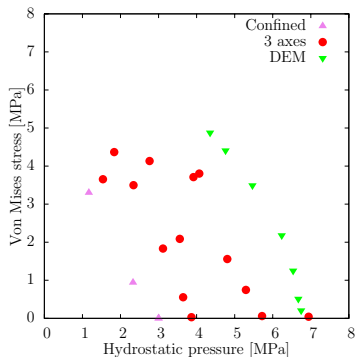


Description possible de la surface par la DEM.
MAIS sensibilité aux lois de contact
➡ Critère elliptique ?

Essais multiaxes

Comparaison à la DEM

Critère de plasticité



Description possible de la surface par la DEM.
MAIS sensibilité aux lois de contact
➡ Critère elliptique ?

Contexte de l'étude

Empilements ordonnés

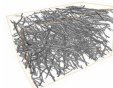
S. GASSER
(ONERA, 2003)
Elastoplasticité et
acoustique



M.W. SANDERS
(MIT, 2002)
Elastoplasticité

Milieux enchevêtrés

C. BARBIER
(Grenoble INP,
2008)
Modélisation de
milieu enchevêtré



Matériaux POREux (Empilements aléatoires)

F. MAMOUD
(ONERA, 2007)
Elasticité et fluage

O. CATY
(INSA Lyon, 2008)
Fatigue

A. FALLET
(Grenoble INP, 2008)
Initiation plasticité et
endommagement



J-P. MASSE
(Grenoble INP,
2008)
Structures
sandwichs fines



Contexte de l'étude

Empilements ordonnés

Milieux enchevêtrés



Peu de données expérimentales sur le matériau



Pas de modèles pour les grandes déformations



Peu de connaissance sur l'endommagement

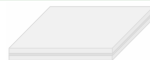


Pas de données expérimentales exploitables sur les structures

A. FALLET
(Grenoble INP, 2008)
Initiation plasticité et
endommagement



Structures
sandwichs fines



Contexte de l'étude

Empilements ordonnés

Milieux enchevêtrés



Données expérimentales sur le matériau



Pas de modèles pour les grandes déformations



Peu de connaissance sur l'endommagement

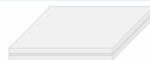


Pas de données expérimentales exploitables sur les structures

A. FALLET
(Grenoble INP, 2008)
Initiation plasticité et
endommagement



Structures
sandwichs fines



Contexte de l'étude

Empilements ordonnés

Milieux enchevêtrés



Données expérimentales sur le matériau



Modèle pour les grandes déformations



Peu de connaissance sur l'endommagement

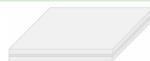


Pas de données expérimentales exploitables sur les structures

A. FALLET
(Grenoble INP, 2008)
Initiation plasticité et
endommagement



Structures
sandwichs fines



Contexte de l'étude

Empilements ordonnés

Milieux enchevêtrés



Données expérimentales sur le matériau



Modèle pour les grandes déformations



Connaissance sur l'endommagement

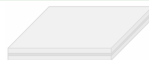


Pas de données expérimentales exploitables sur les structures

A. FALLET
(Grenoble INP, 2008)
Initiation plasticité et
endommagement



Structures
sandwichs fines



Contexte de l'étude

Empilements ordonnés

Milieux enchevêtrés



Données expérimentales sur le matériau



Modèle pour les grandes déformations



Connaissance sur l'endommagement



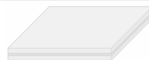
Expérimentation sur les structures

A. FALLET
(Grenoble INP, 2008)
Initiation plasticité et
endommagement

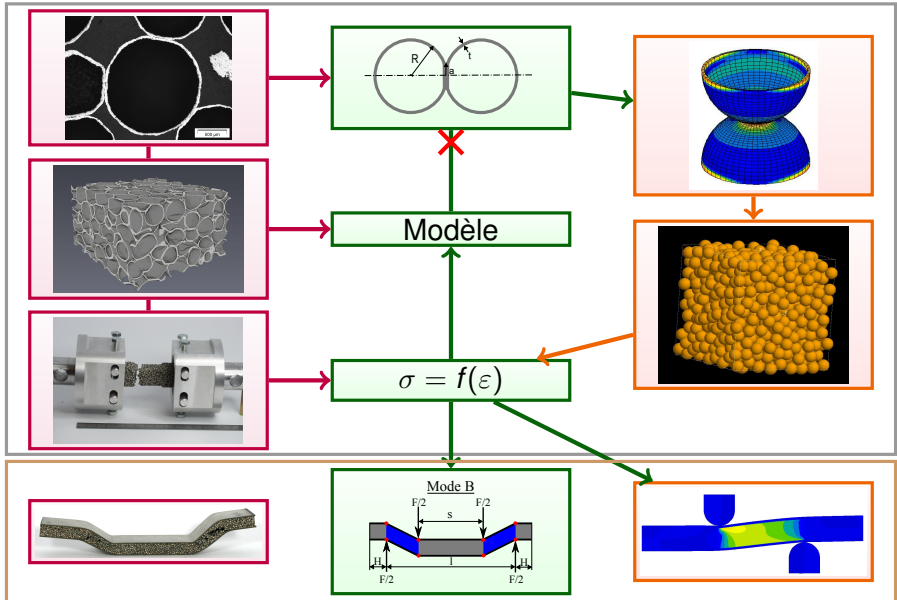


C. BARBIER
(Grenoble INP,
2008)
Modélisation de
milieu enchevêtré

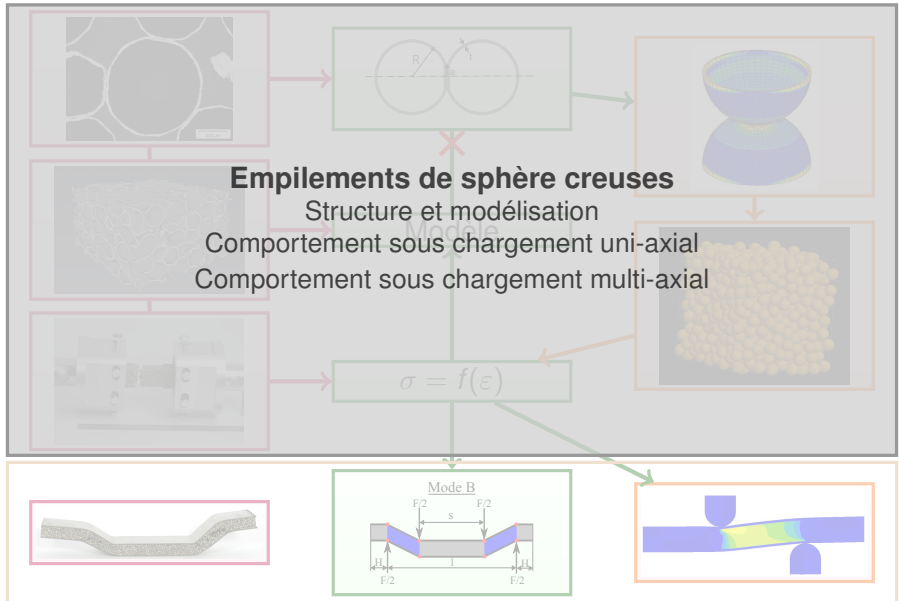
J-P. MASSE
(Grenoble INP,
2008)
Structures
sandwichs fines



Intégration dans des structures



Intégration dans des structures



Intégration dans des structures

Empilements de sphère creuses

Structure et modélisation

Comportement sous chargement uni-axial

Comportement sous chargement multi-axial

Structures sandwich

Caractérisation des structures

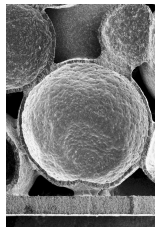
Indentation de plaques

Flexion 4-points de poutres

Structures sandwich

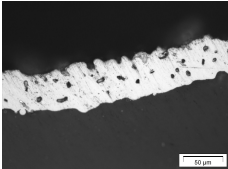
Echantillons

- Matériaux :
 - Coeur : $\rho = 600\text{kg}/\text{m}^3$
 - Peaux : 314 (norm AISI)
- Dimensions :
 - 3 épaisseurs de peau (t) : 0.4, 1.0 and 1.5mm
 - 4 épaisseurs de coeur (c) : 14, 18, 24 and 28 mm

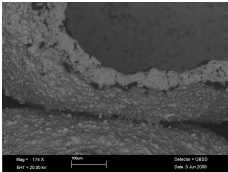


Structure du matériau

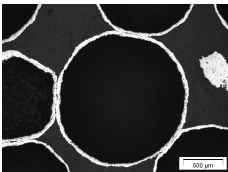
Avant intégration



Porosité des parois



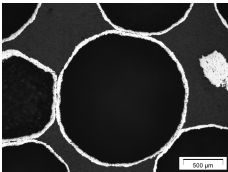
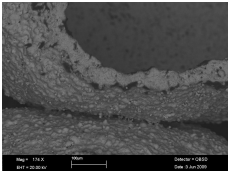
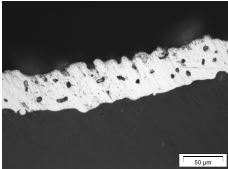
Surface de contact faible



Structure saine

Structure du matériau

Avant intégration

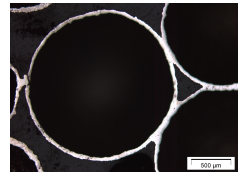
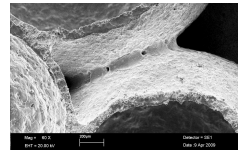
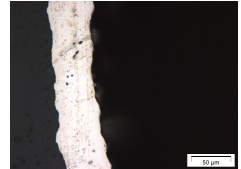


Porosité des parois

Surface de contact faible

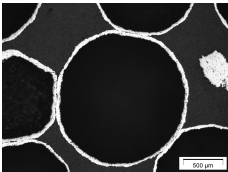
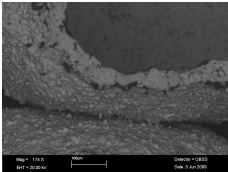
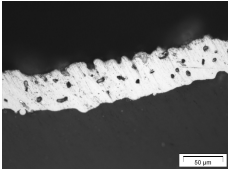
Structure saine

Après intégration



Structure du matériau

Avant intégration

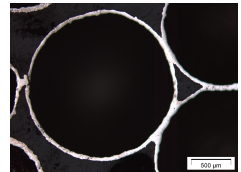
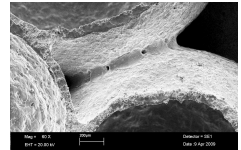
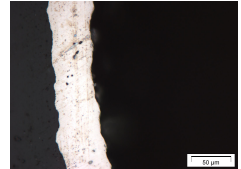


~~Porosité des parois~~
Parois denses

Surface de contact faible

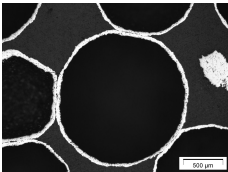
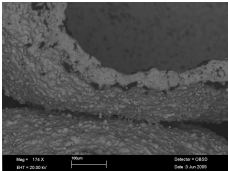
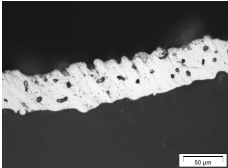
Structure saine

Après intégration



Structure du matériau

Avant intégration



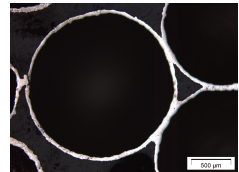
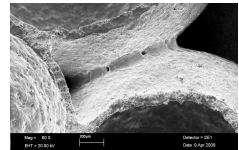
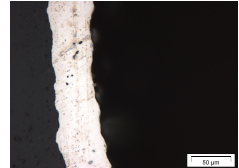
~~Porosité des parois~~
Parois denses

~~Surface de contact~~
faible

Surface de contact
importante

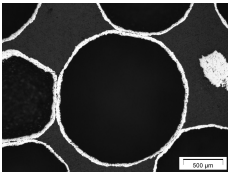
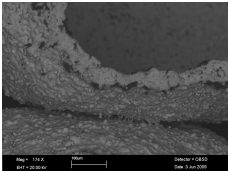
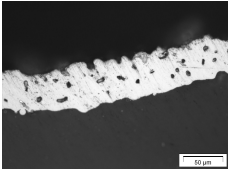
Structure saine

Après intégration



Structure du matériau

Avant intégration



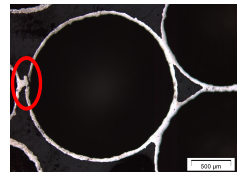
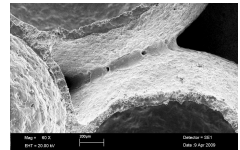
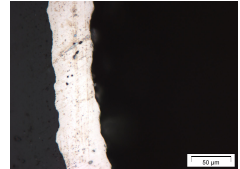
~~Porosité des parois~~
Parois denses

~~Surface de contact~~
faible

Surface de contact
importante

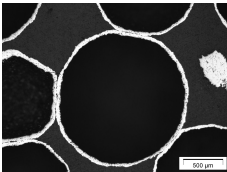
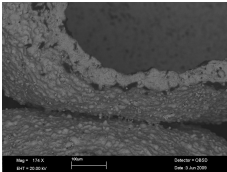
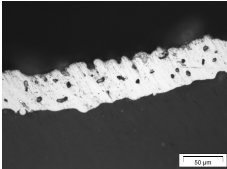
~~Structure saine~~
Structure endommagée

Après intégration



Structure du matériau

Avant intégration

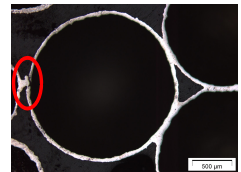
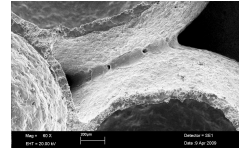
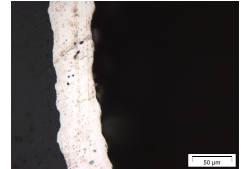


~~Porosité des parois~~
Parois denses

~~Surface de contact faible~~
Surface de contact importante

~~Structure saine~~
Structure endommagée

Après intégration



Forte modification du matériau lors de l'intégration dans les structures

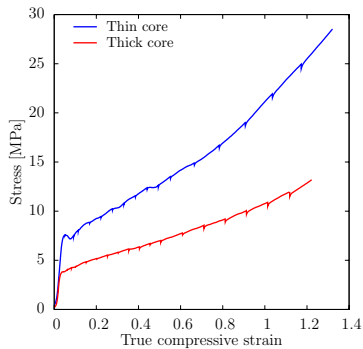
Matériau coeur

Épaisseur de coeur
↑



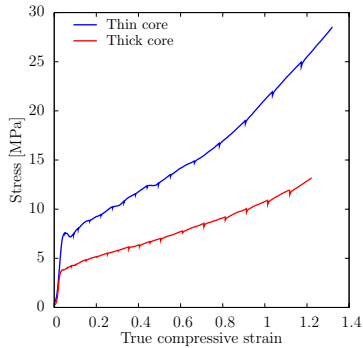
Matériau coeur

↑
Epaisseur de coeur



Matériau coeur

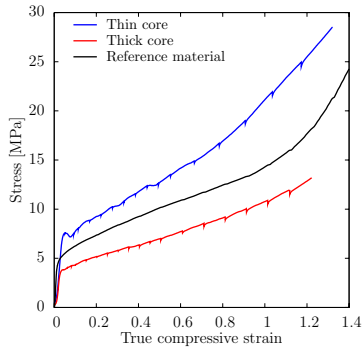
↑
Épaisseur de coeur



Influence de l'épaisseur du coeur

Matériau coeur

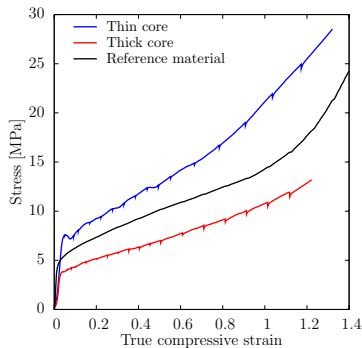
↑
Épaisseur de coeur



Influence de l'épaisseur du coeur

Matériau coeur

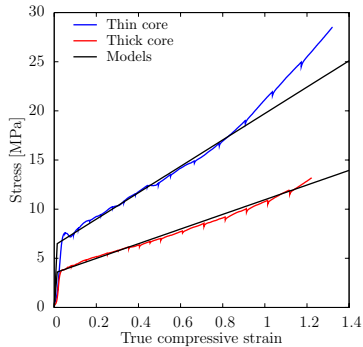
Épaisseur de coeur ↑



Influence de l'épaisseur du coeur
Propriétés du coeur : modèles

Matériau coeur

↑
Épaisseur de coeur



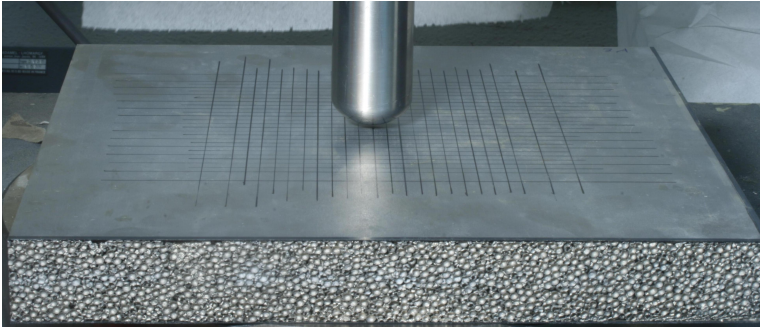
Influence de l'épaisseur du coeur

Propriétés du coeur : modèles

➡ expériences

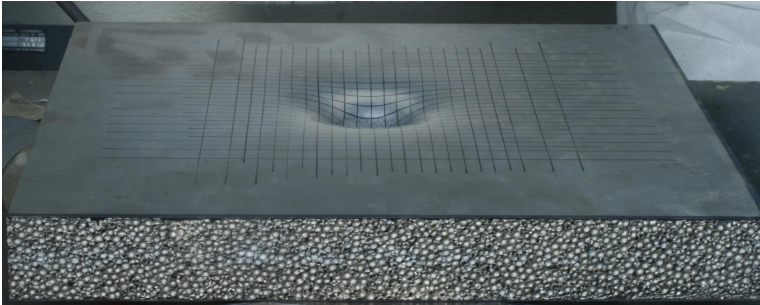
Indentation

Expériences



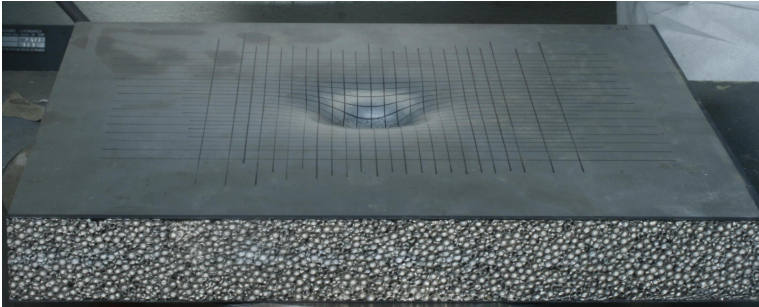
Indentation

Expériences



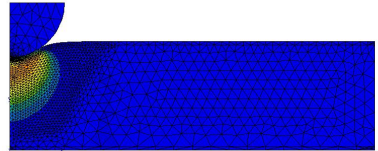
Indentation

Expériences



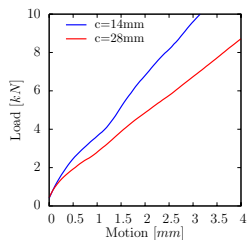
Simulations Eléments Finis

Modélisation axisymétrique
Peau élasto-plastique, Hollomon, Mises.
Coeur élasto-plastique, bi-linéaire, elliptique.



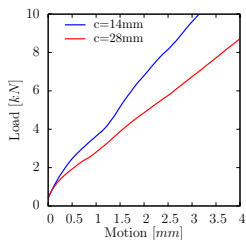
Indentation

Influence de l'épaisseur de coeur



Indentation

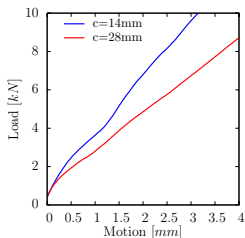
Influence de l'épaisseur de coeur



- Influence de l'épaisseur du coeur
- Influence des propriétés du coeur

Indentation

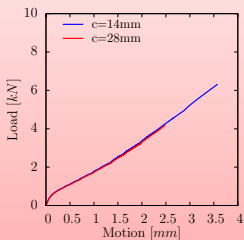
Influence de l'épaisseur de coeur



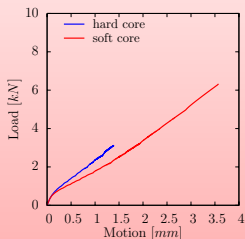
- Influence de l'épaisseur du coeur
- Influence des propriétés du coeur

Éléments finis

Epaisseur variable

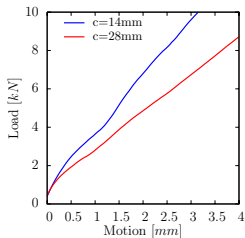


Coeur variable



Indentation

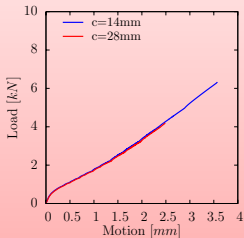
Influence de l'épaisseur de coeur



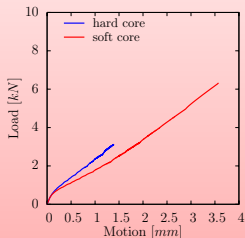
- Influence de l'épaisseur du coeur
- Influence des propriétés du coeur

Éléments finis

Epaisseur variable



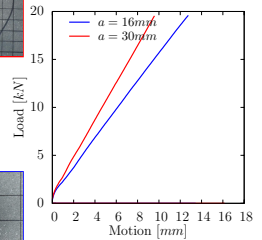
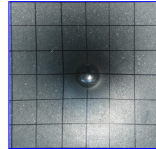
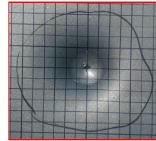
Coeur variable



Indentation

Influence de l'indenteur

Rayon d'indent

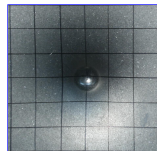
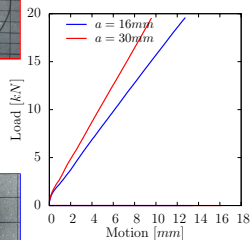
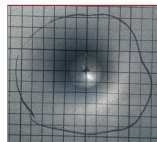
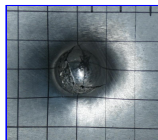
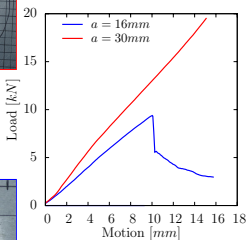
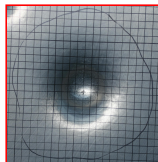


Epaisseur de peau

Indentation

Influence de l'indenteur

Rayon d'indent

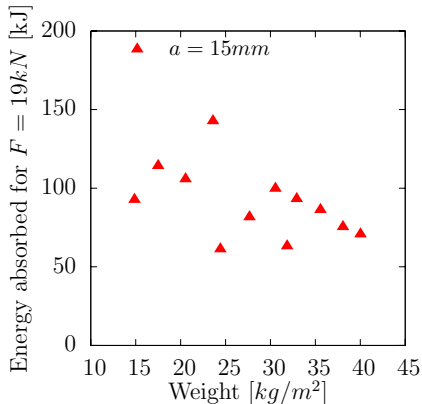


Epaisseur de peau

Indentation

Influence des dimensions

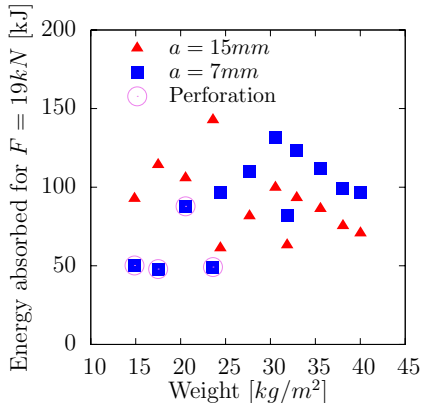
Energie absorbée à réaction seuil



Indentation

Influence des dimensions

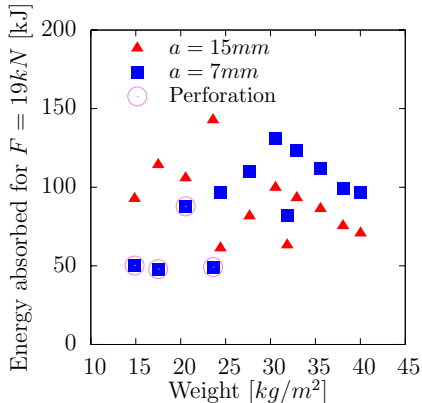
Energie absorbée à réaction seuil



Indentation

Influence des dimensions

Energie absorbée à réaction seuil



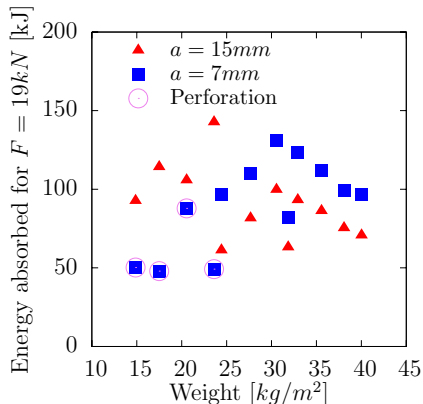
Sélection

Épaisseur de peau minimale
à indenteur donné

Indentation

Influence des dimensions

Energie absorbée à réaction seuil



Sélection

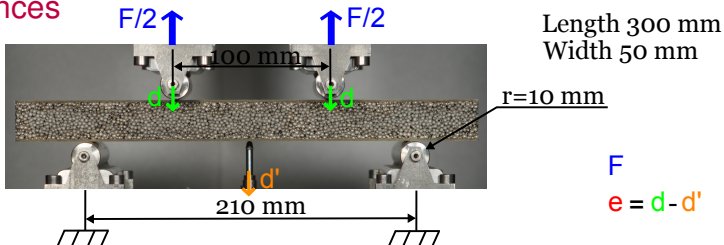
Epaisseur de peau minimale
à indenteur donné



Sollicitations combinées
→ Flexion 4-points

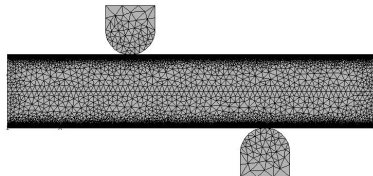
Flexion 4-points

Expériences



Simulations Eléments Finis

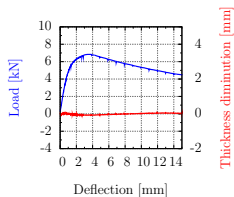
Modélisation déformations planes
 Peau élasto-plastique, Hollomon, Mises.
 Coeur élasto-plastique, bi-linéaire, elliptique.



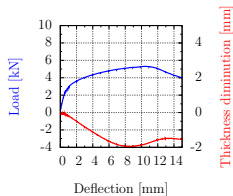
Essais de flexion 4-points

Modes d'endommagement

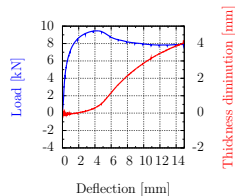
Cisaillement du coeur



Plastification des peaux



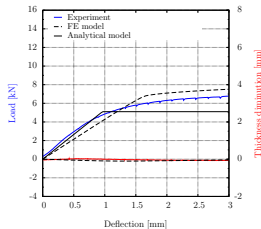
Indentation



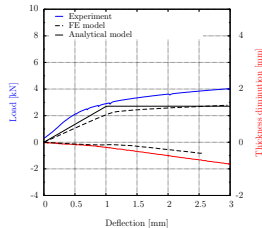
Essais de flexion 4-points

Modes d'endommagement

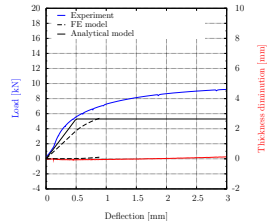
Cisaillement du coeur



Plastification des peaux

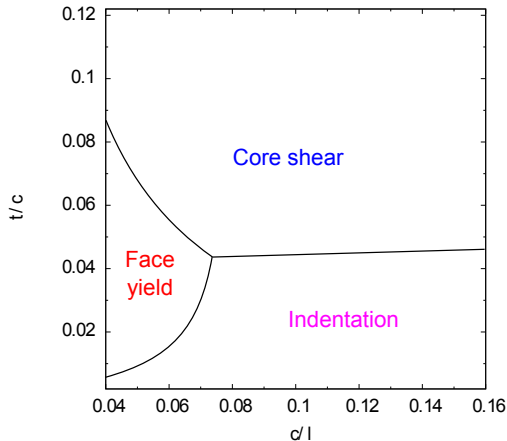


Indentation



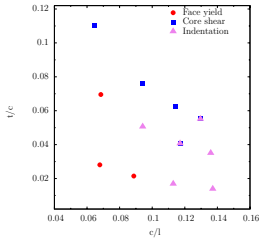
Carte d'endommagement

Modèle

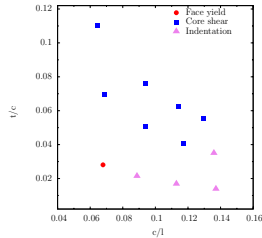


Cartes d'endommagement

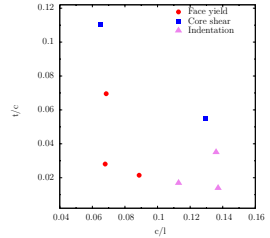
Expériences



Modèles analytiques



Modèles EF

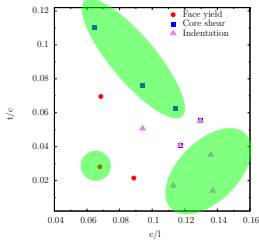


Limitation des modèles aux transitions

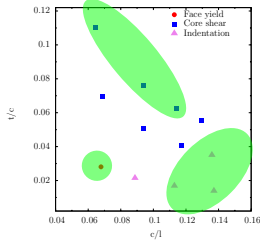
Bonne description par EF

Cartes d'endommagement

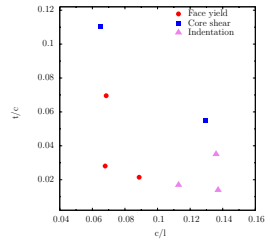
Expériences



Modèles analytiques



Modèles EF

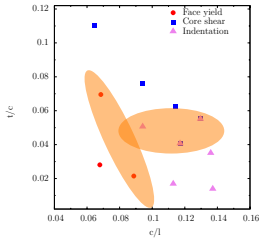


Limitation des modèles aux transitions

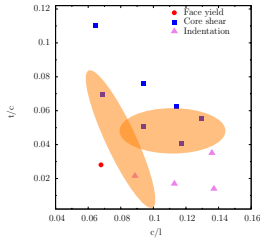
Bonne description par EF

Cartes d'endommagement

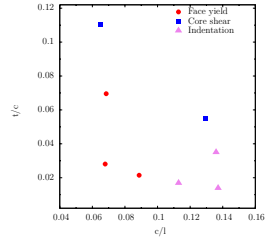
Expériences



Modèles analytiques



Modèles EF

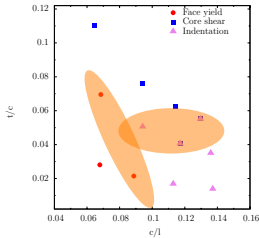


Limitation des modèles aux transitions

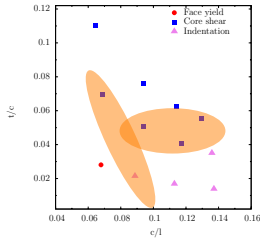
Bonne description par EF

Cartes d'endommagement

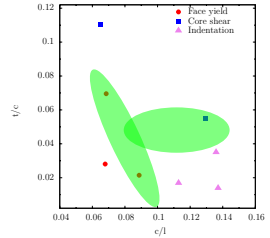
Expériences



Modèles analytiques



Modèles EF

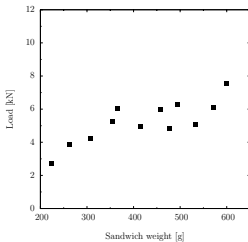


Limitation des modèles aux transitions

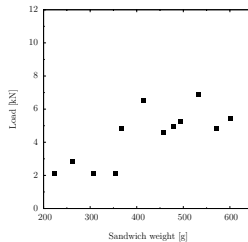
Bonne description par EF

Forces critiques

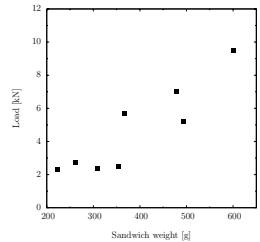
Expériences



Modèles analytiques



Modèles EF

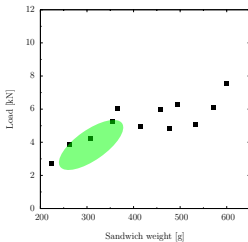


Niveau de contrainte

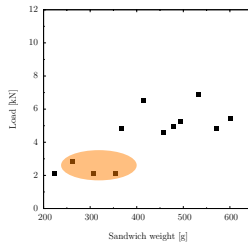
Propriétés de la peau ?

Forces critiques

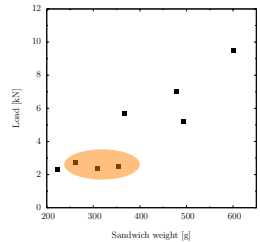
Expériences



Modèles analytiques



Modèles EF

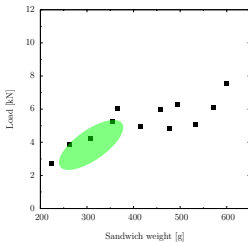


Niveau de contrainte

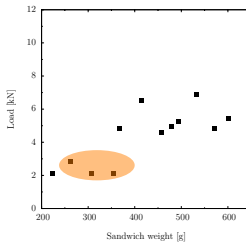
Propriétés de la peau ?

Forces critiques

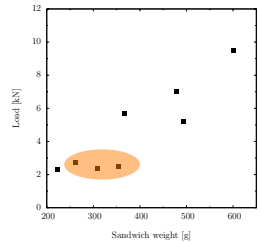
Expériences



Modèles analytiques



Modèles EF

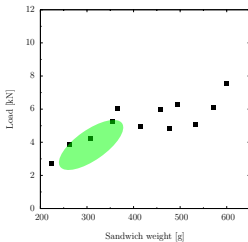


Niveau de contrainte

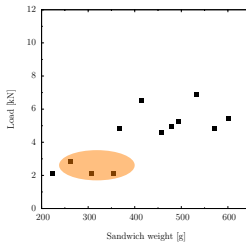
Propriétés de la peau ?

Forces critiques

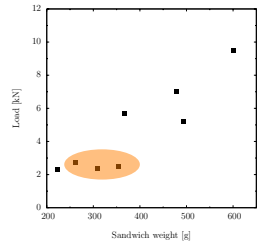
Expériences



Modèles analytiques



Modèles EF



Niveau de contrainte

Propriétés de la peau ?

Contexte de l'étude

Empilements ordonnés

Milieux enchevêtrés



Données expérimentales sur le matériau



Modèle pour les grandes déformations



Connaissance sur l'endommagement

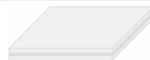


Pas de données expérimentales exploitables sur les structures

A. FALLET
(Grenoble INP, 2008)
Initiation plasticité et
endommagement



Structures
sandwichs fines



Contexte de l'étude

Empilements ordonnés

Milieux enchevêtrés



Données expérimentales sur le matériau



Modèle pour les grandes déformations



Connaissance sur l'endommagement

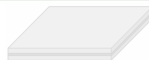


Données expérimentales paramétriques sur les structures

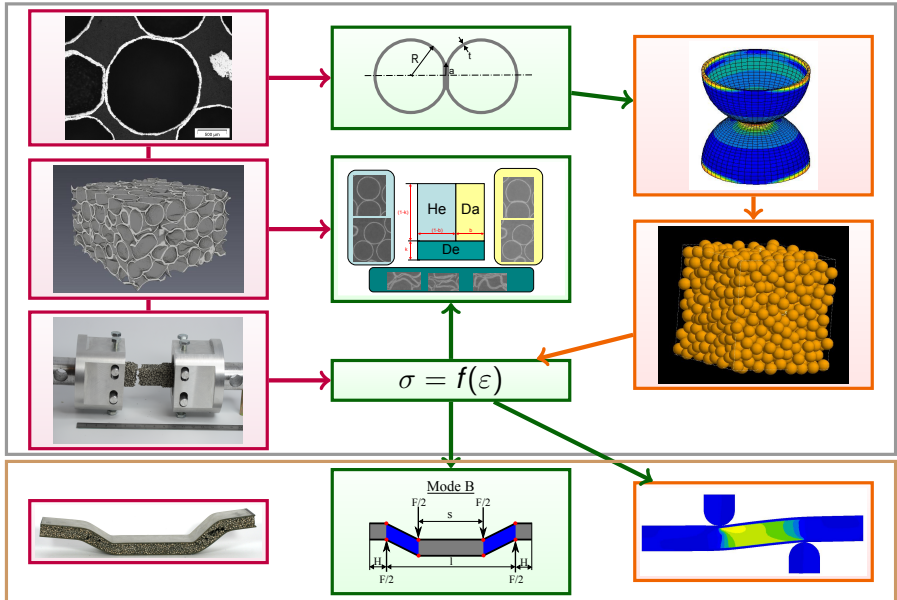
A. FALLET
(Grenoble INP, 2008)
Initiation plasticité et
endommagement



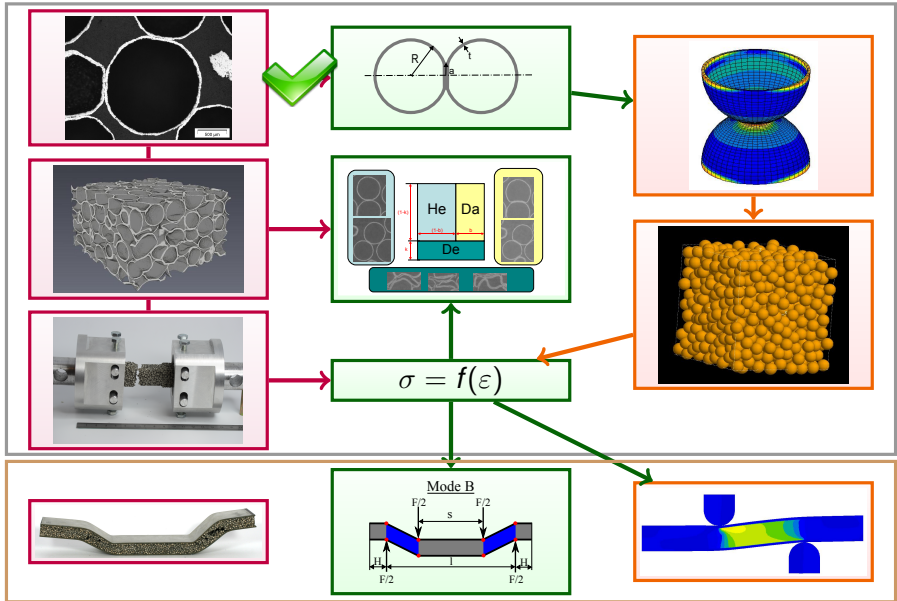
Structures
sandwichs fines



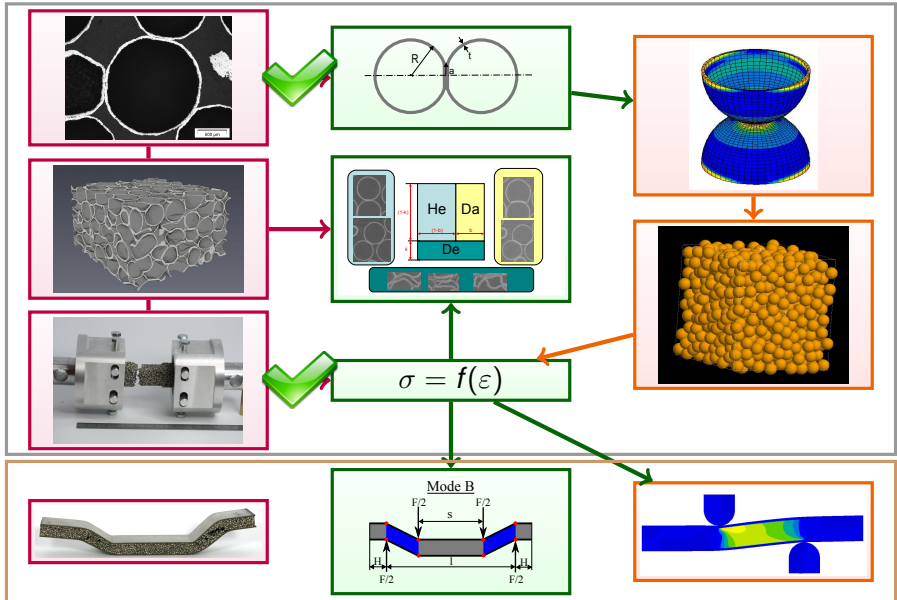
Bilan



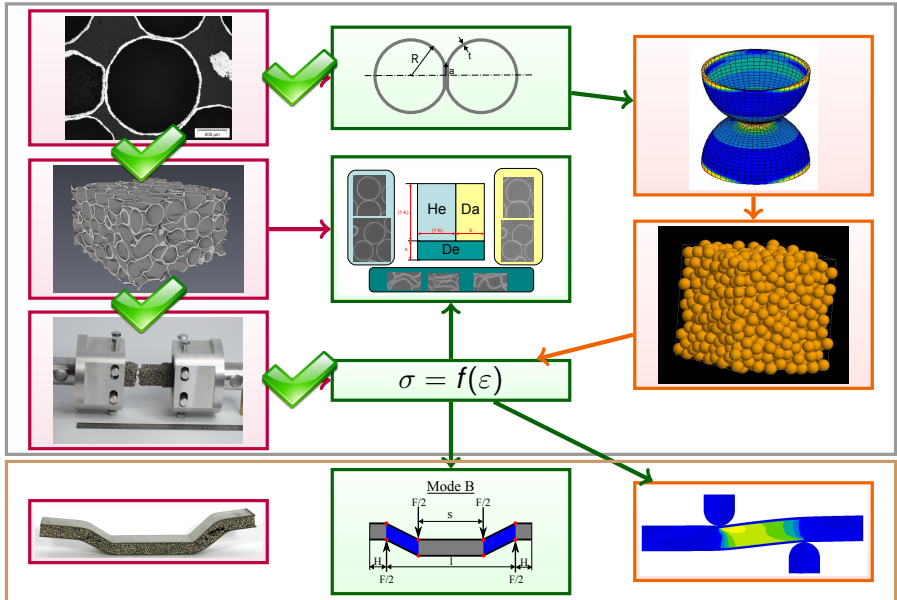
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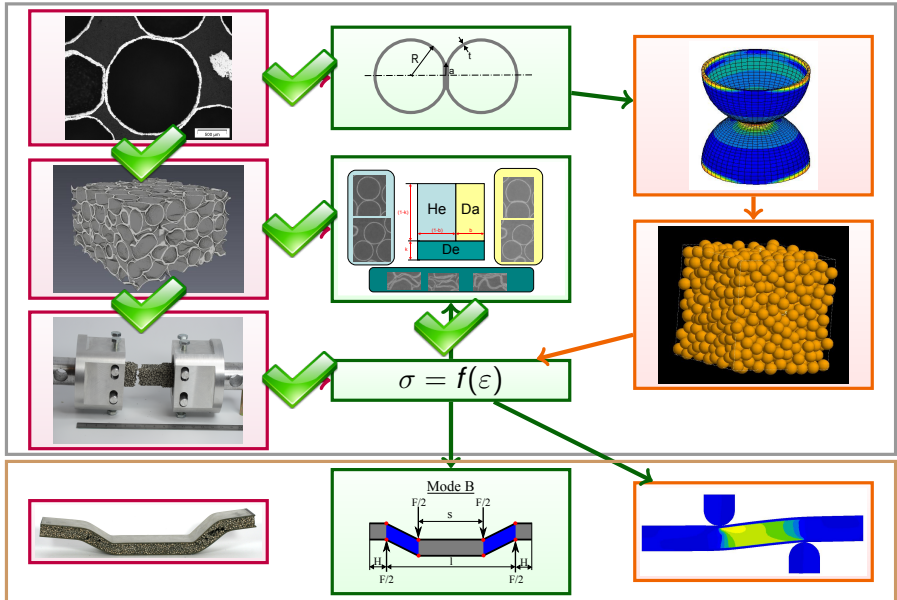
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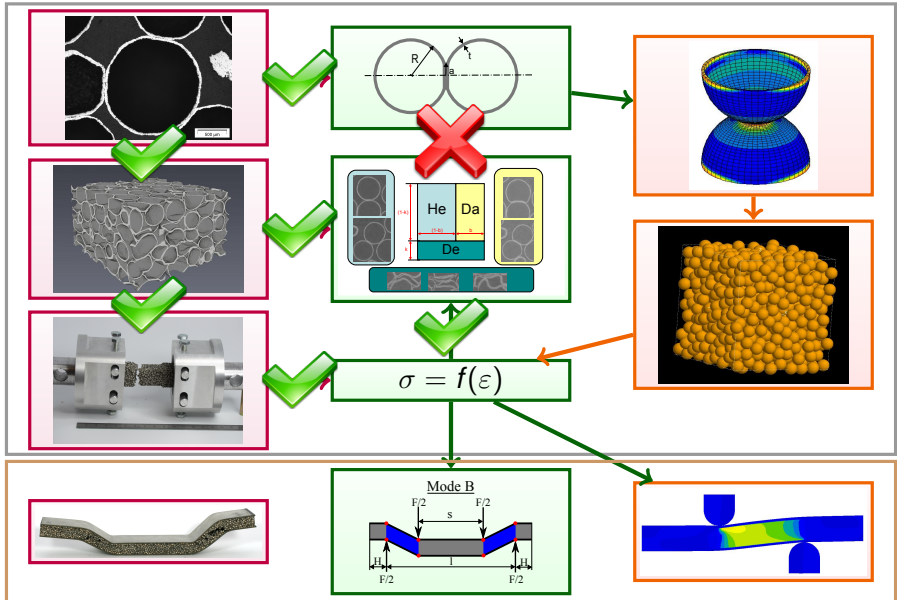
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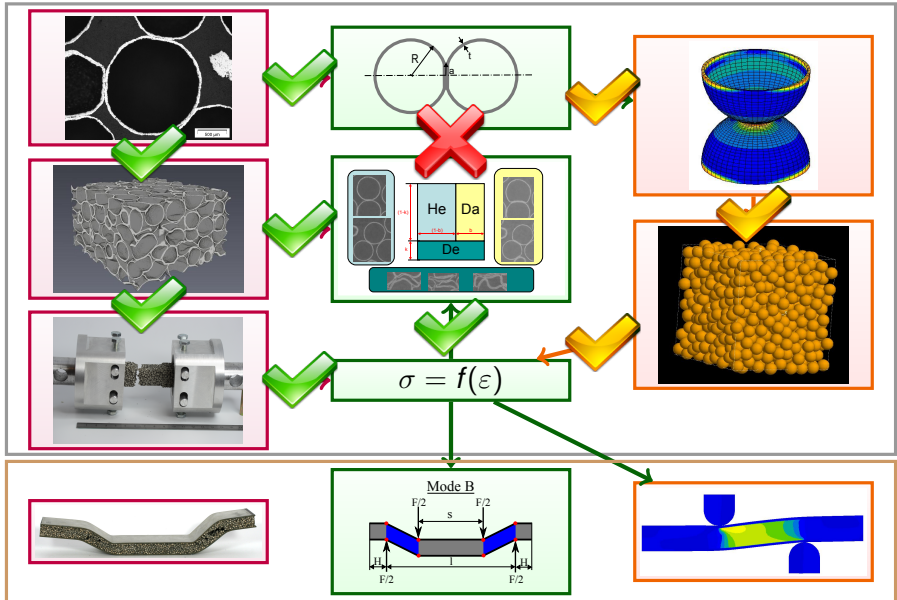
Bilan



Bilan



Bilan



Perspectives

Amélioration de la DEM

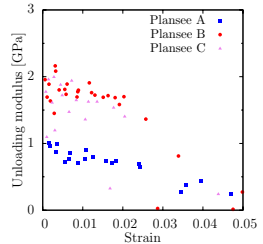
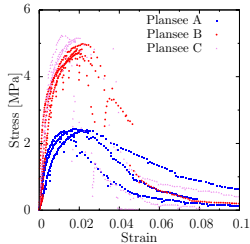
Épaisseur de coque t



Perspectives

Amélioration de la DEM

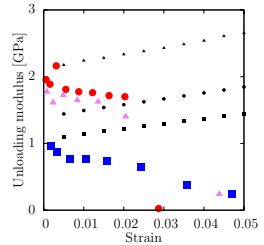
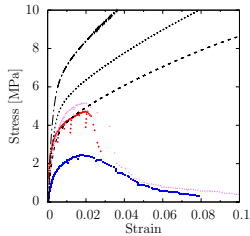
Épaisseur de coque t



Perspectives

Amélioration de la DEM

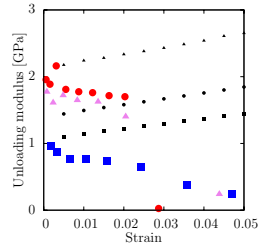
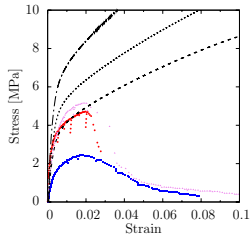
Épaisseur de coque t



Perspectives

Amélioration de la DEM

Épaisseur de coque t

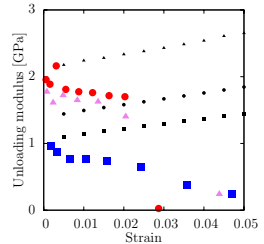
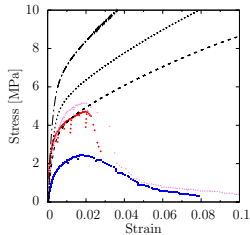



Critère de rupture

Perspectives

Amélioration de la DEM

Épaisseur de coque t

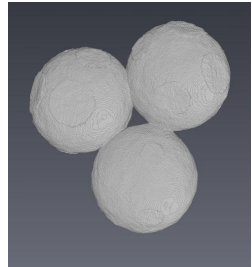
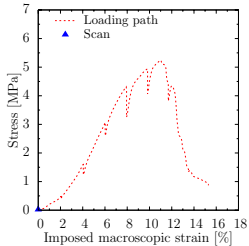



Critère de rupture
Endommagement

Perspectives

Amélioration de la DEM

Epaisseur de coque t

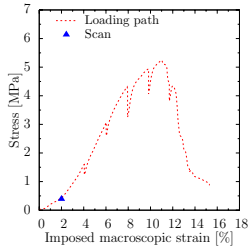


Critère de rupture
Endommagement

Perspectives

Amélioration de la DEM

Epaisseur de coque t

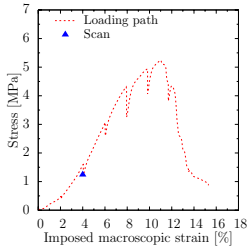


Critère de rupture
Endommagement

Perspectives

Amélioration de la DEM

Epaisseur de coque t

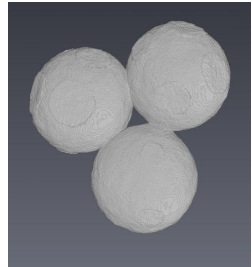
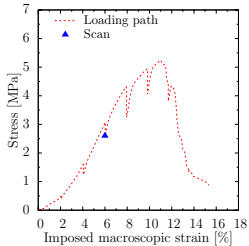


Critère de rupture
Endommagement

Perspectives

Amélioration de la DEM

Épaisseur de coque t

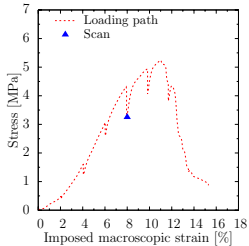


Critère de rupture
Endommagement

Perspectives

Amélioration de la DEM

Epaisseur de coque t

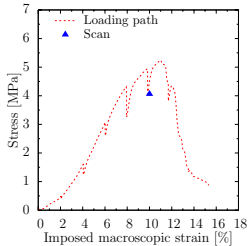


Critère de rupture
Endommagement

Perspectives

Amélioration de la DEM

Epaisseur de coque t

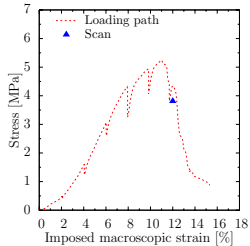


Critère de rupture
Endommagement

Perspectives

Amélioration de la DEM

Epaisseur de coque t

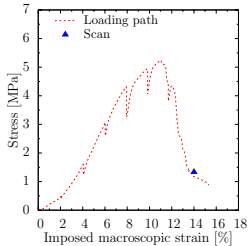


Critère de rupture
Endommagement

Perspectives

Amélioration de la DEM

Epaisseur de coque t

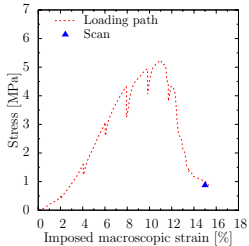


Critère de rupture
Endommagement

Perspectives

Amélioration de la DEM

Epaisseur de coque t

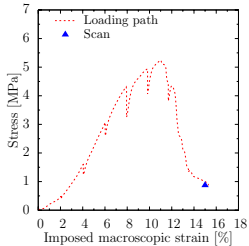


Critère de rupture
Endommagement

Perspectives

Amélioration de la DEM

Epaisseur de coque t

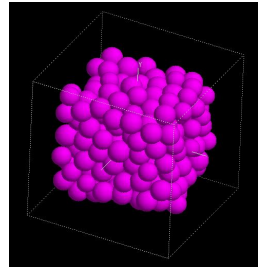
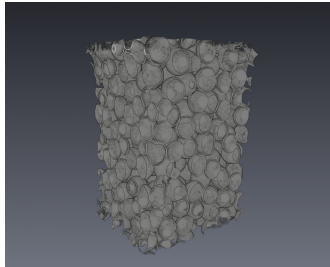


Critère de rupture
Endommagement
➡ matériau constitutif

Perspectives

Amélioration de la DEM

Epaisseur de coque t



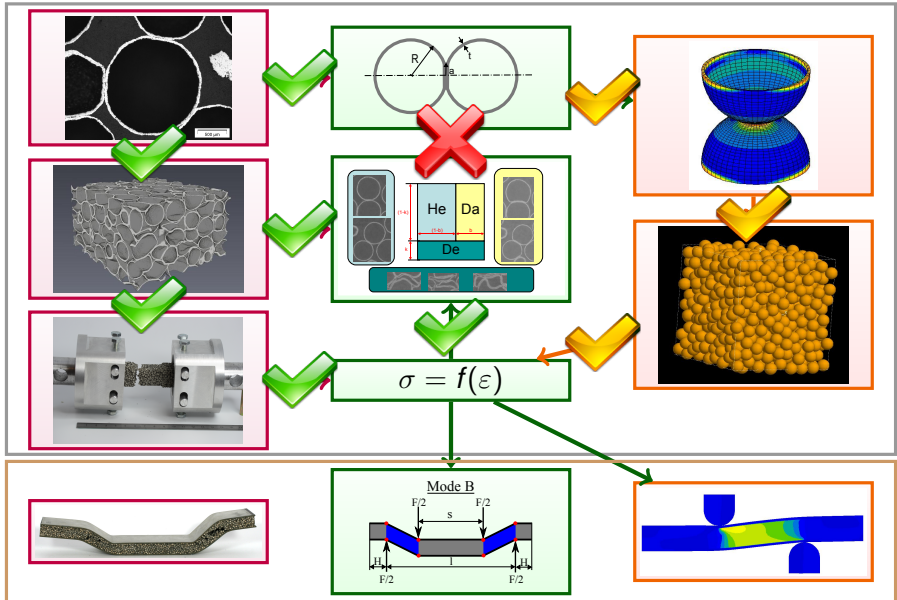
Critère de rupture

Endommagement

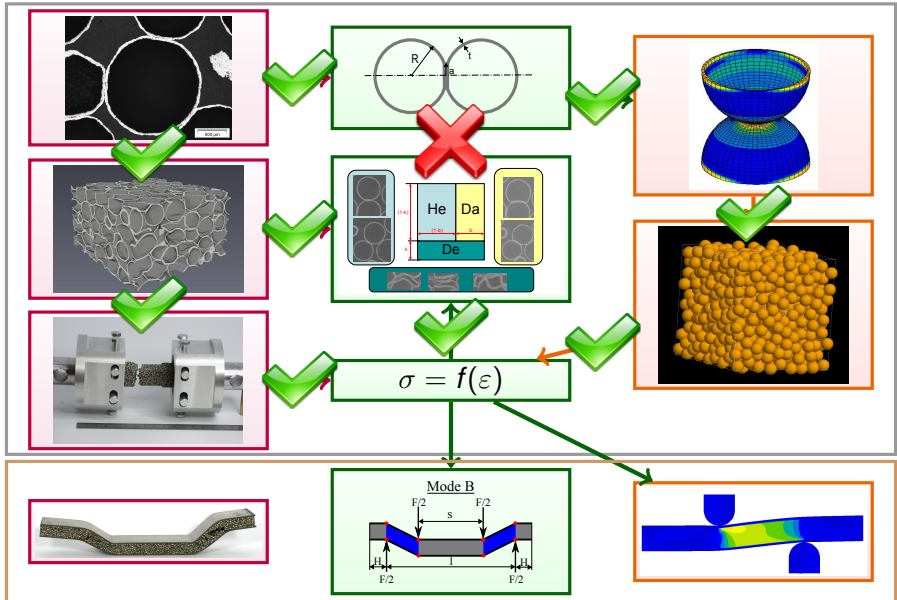
➔ matériau constitutif

➔ Méthode inverse DEM-tomographie

Bilan

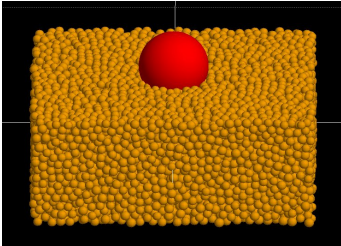


Bilan

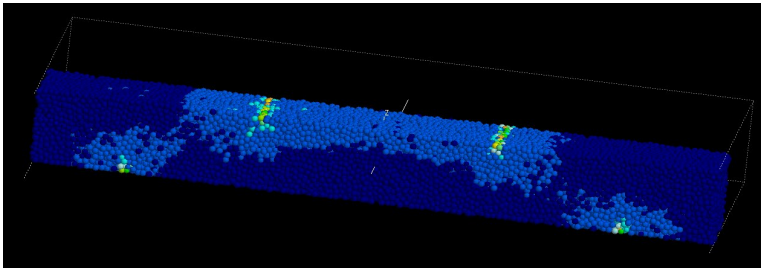


Perspectives

Application de la DEM aux structures

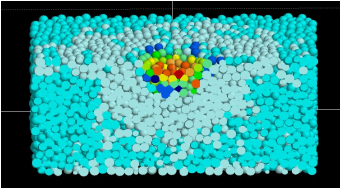


Longueur interne => Effets de tailles
Structures à gradients (tailles de
cols...)

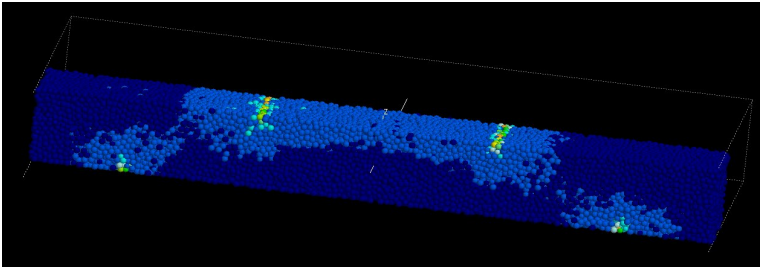


Perspectives

Application de la DEM aux structures

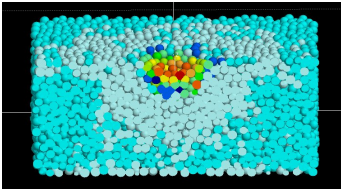


Longueur interne => Effets de tailles
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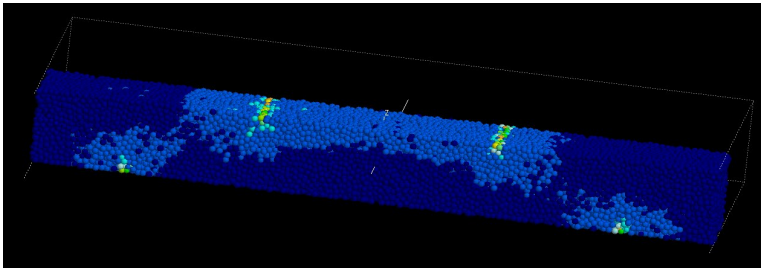


Perspectives

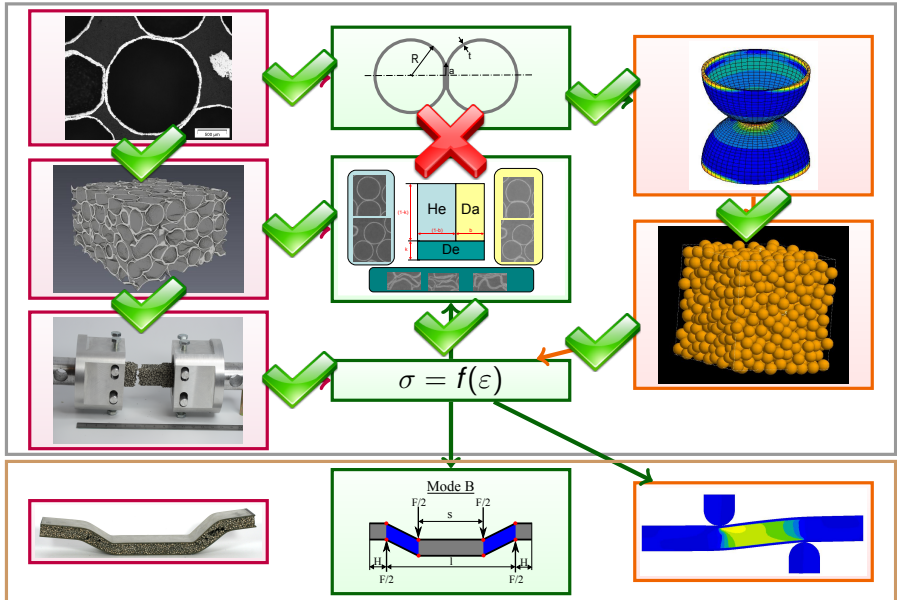
Application de la DEM aux structures



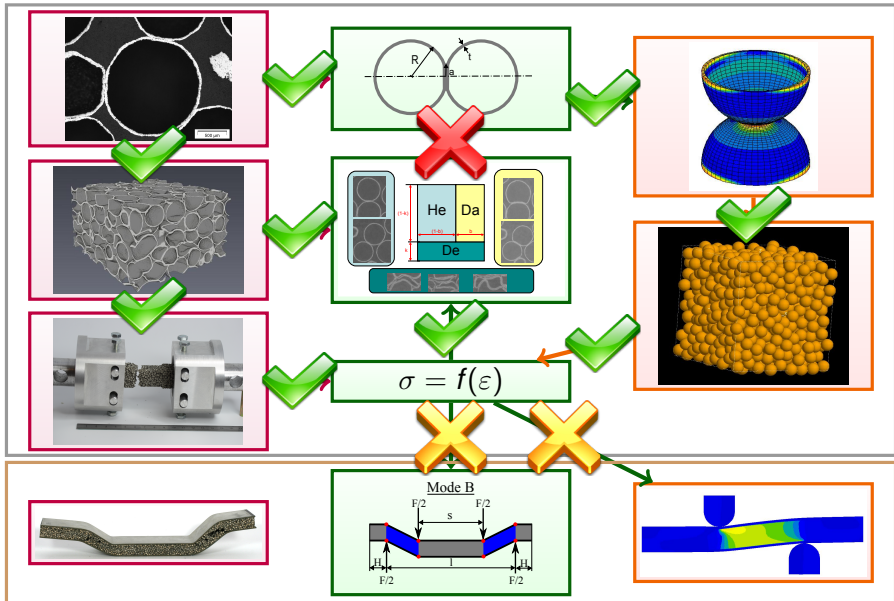
Longueur interne => Effets de tailles
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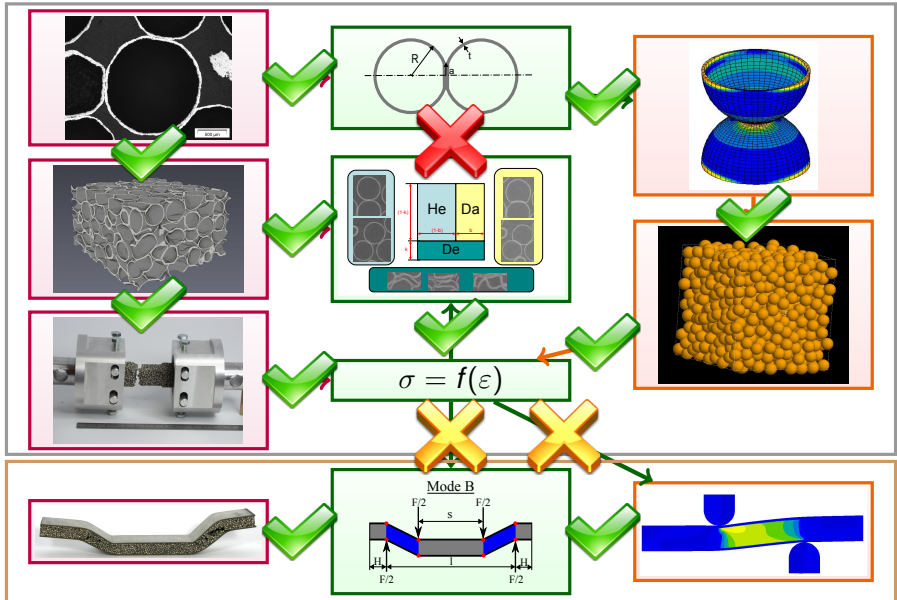
Bilan



Bilan



Bilan



Perspectives

Structures sandwich

Process d'intégration dans les structures

➡ Peu de modification du coeur

Qualification du matériau après intégration

➡ DEM

➡ Expérimental (VER)

Perspectives

Structures sandwich

Process d'intégration dans les structures

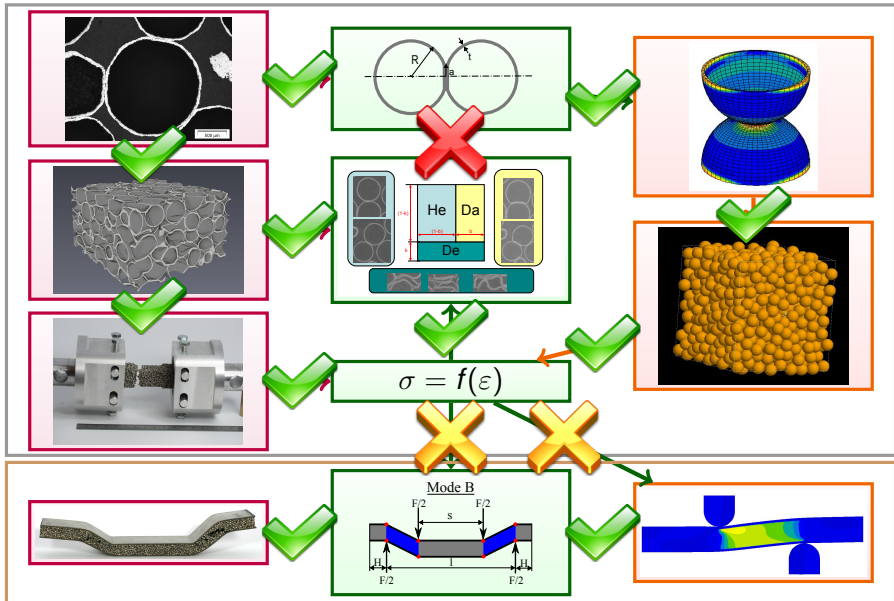
➡ Peu de modification du coeur

Qualification du matériau après intégration

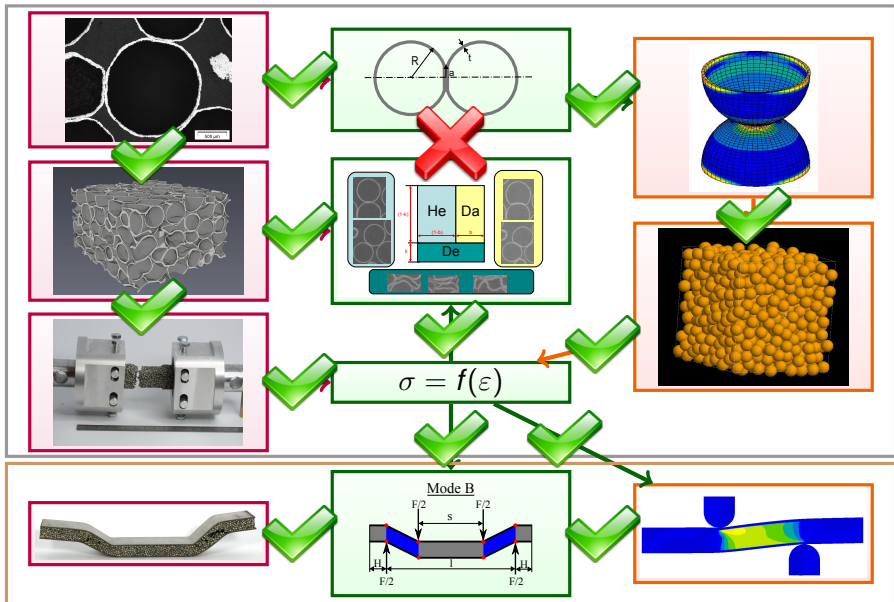
➡ DEM

➡ Expérimental (VER)

Bilan



Bilan



Applications

Optimisation de structures

Analyse multi-échelles
Liens entre les échelles

Applications

Optimisation de structures

Analyse multi-échelles
Liens entre les échelles



Optimisation de
structures

Merci



au jury

Merci



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Luc, Yves

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et l'ensemble du GPM2



Merci



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et l'ensemble du GPM2



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Merci



Alex et Jean-Phi
et l'ensemble des thésards et
ex-thésards

Merci



Alex et Jean-Phi
et l'ensemble des thésards et
ex-thésards

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