3D printed Bone-Inspired Composites

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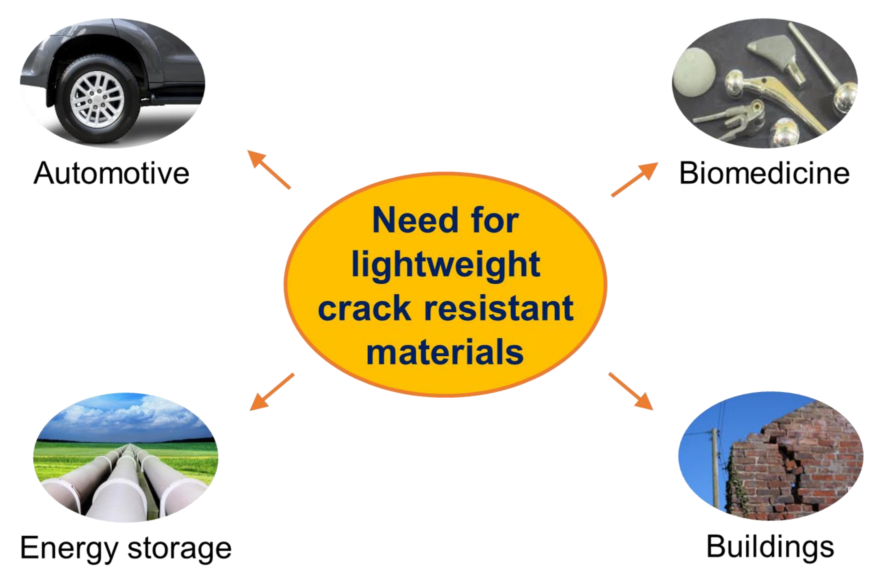
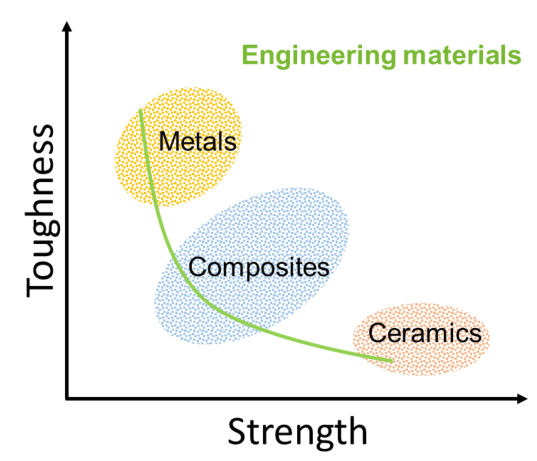
Rationale

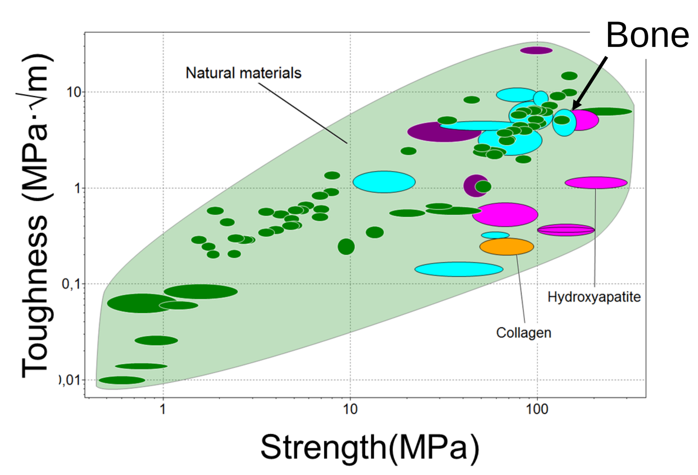


Material design issue:
Toughness and stiffness are often mutually exclusive in engineering materials



Bone:

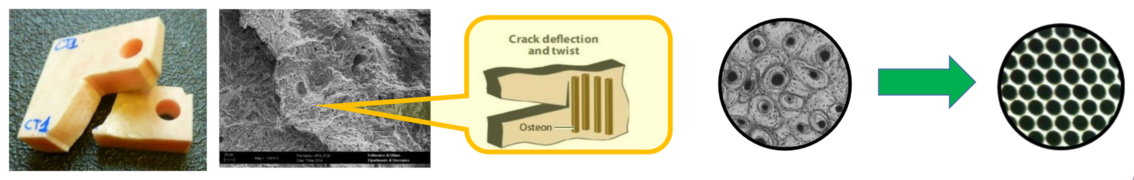
- Lightweight
- Large amplification in toughness with respect to its building blocks (3-5 orders of magnitude) [1]
- Unique combination of mechanical properties [2-4]



Objectives

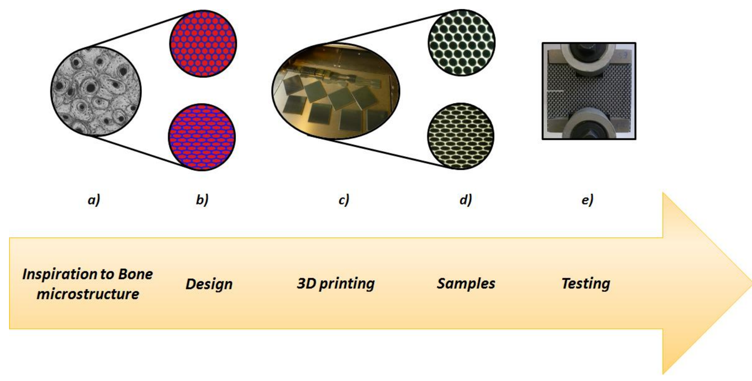
Goals:

- New composites with tailored properties by using a biomimetic design
- Implement the main microscale toughening mechanisms in *de novo* composites, by replicating the microstructural features involved in the process
- Obtain an increase in toughness
- Achieve an optimal strength-toughness balance



Methods

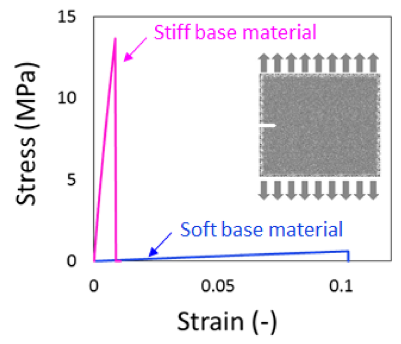
- Biomimetic approach adopted: materials design, manufacturing and testing



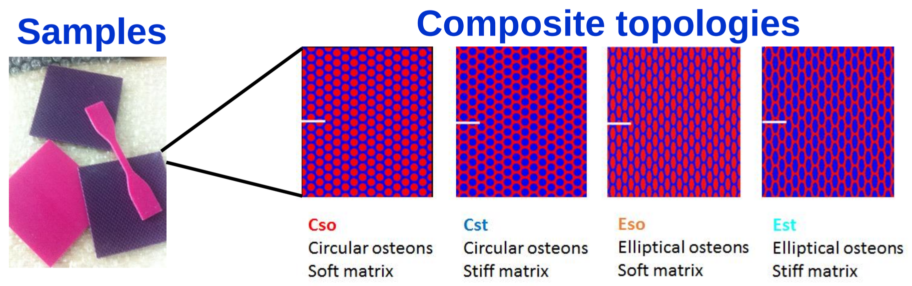
- Material selection: materials with markedly contrasting properties
- Testing of base materials

Materials	Maximum stress [MPa]	Elongation at breakage [%]	Stiffness [MPa]	Toughness modulus [MJ/m³]	Maximum force [N]
Stiff	13.3 ± 1.0	0.8 ± 0.1	1827 ± 102	0.062 ± 0.008	2684 ± 190
Soft	0.120 ± 0.006	35.6 ± 1.8	0.60 ± 0.01	0.027 ± 0.002	21.3 ± 0.9

Results of the fracture toughness tests on the base materials



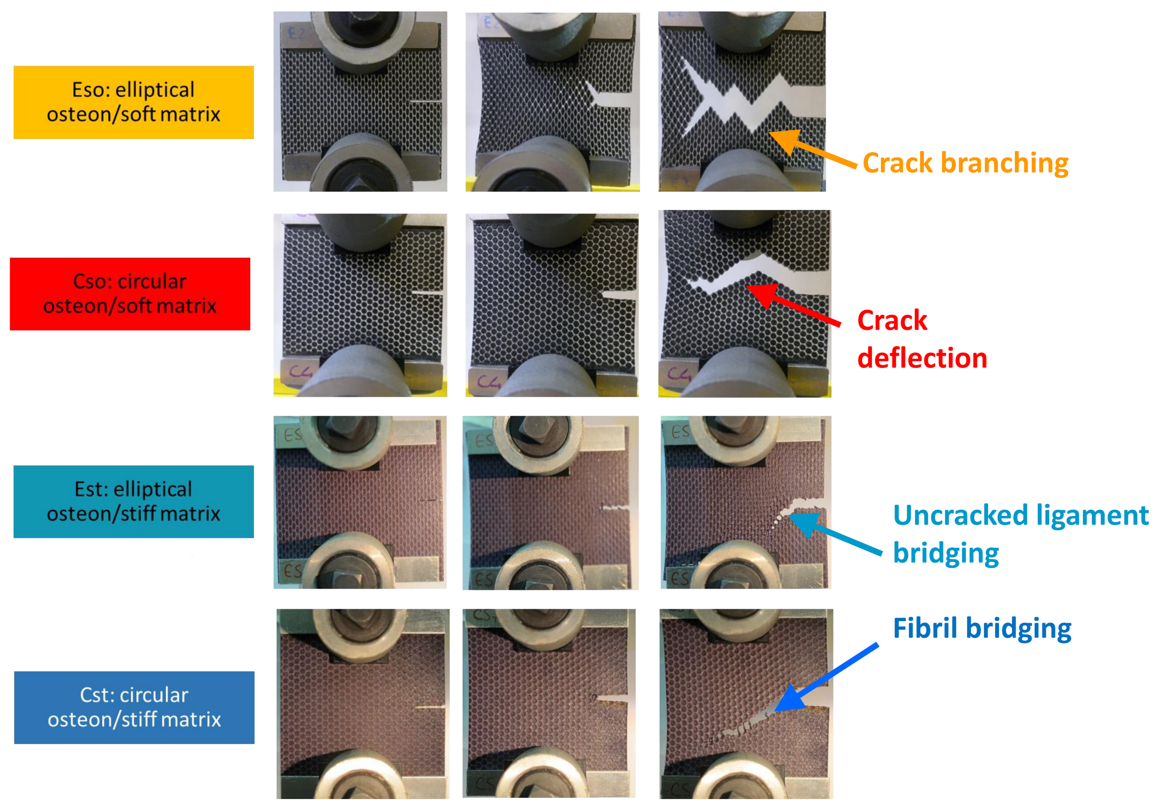
- Osteons mimicked as circular-to-elliptical inclusions
- Osteon vol. fraction (i.e. 60 %) equal to that of cortical bone [5]



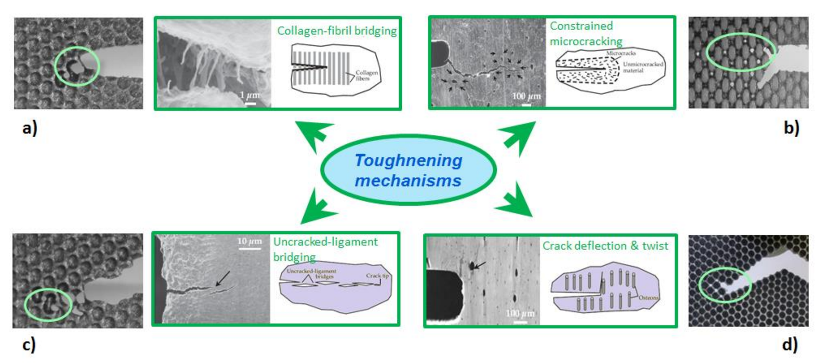
Results

Failure modes

- Failure modes for all the composite topologies



- Failure mechanisms similar to those occurring in cortical bone at microscale

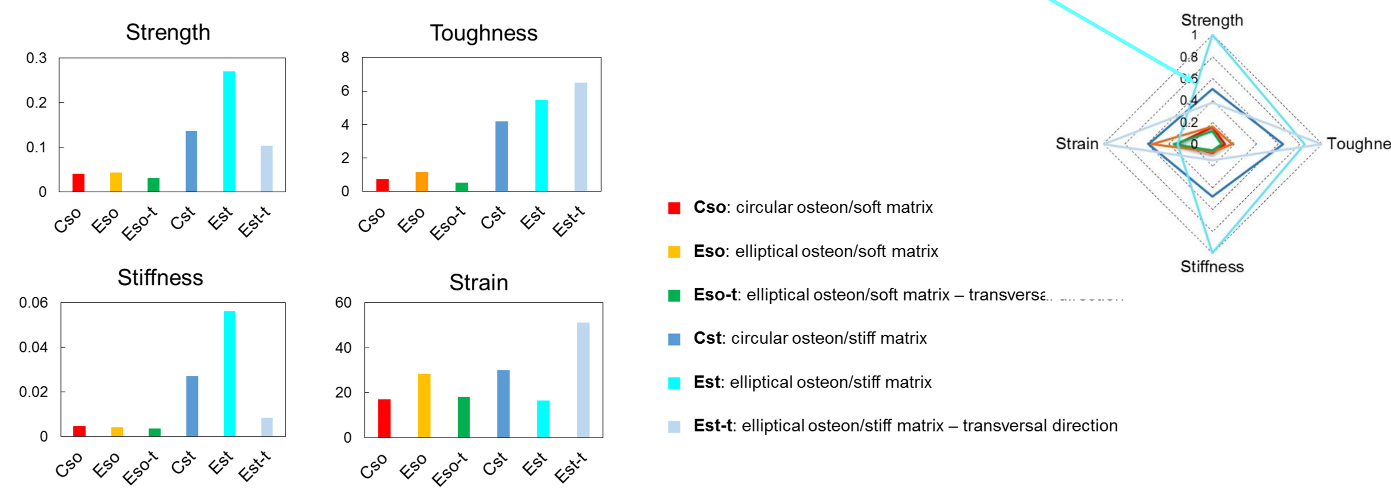


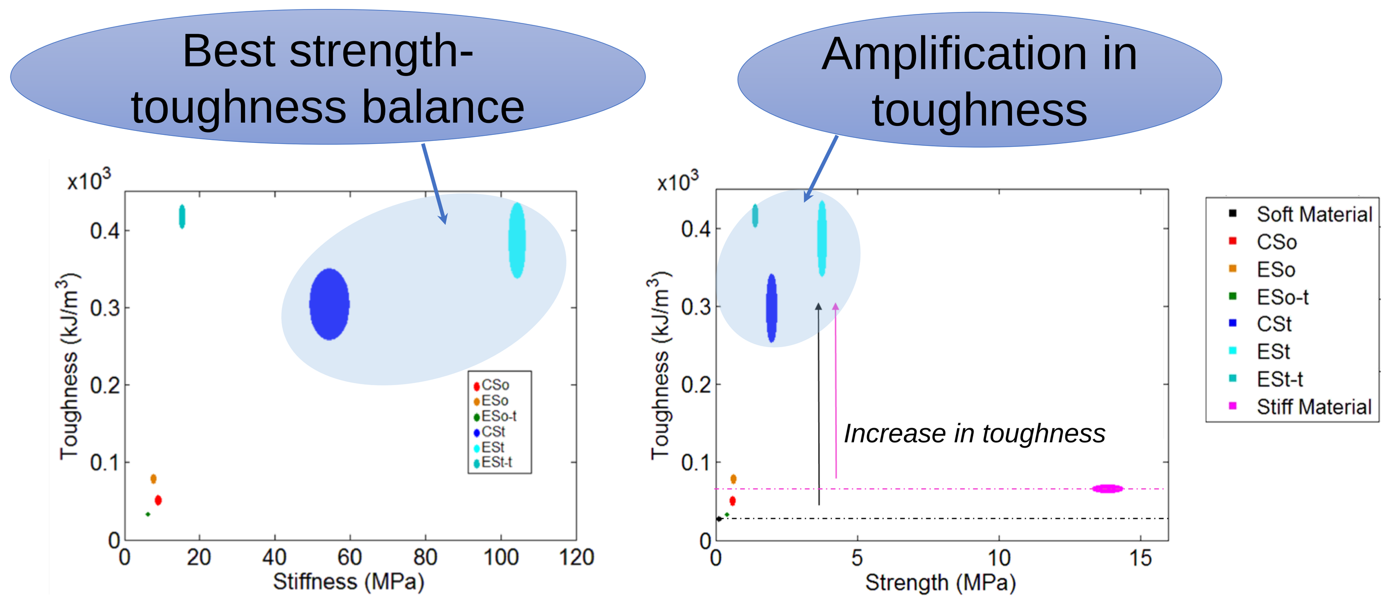
*adapted from Ritchie, R.O., et al., *Physics Today*, 2009.

Small scale mechanisms	Large scale mechanisms
Microvoids in the resin Fibril bridging Uncracked-ligament bridging	Crack blunting Crack deflection Crack branching

Mechanical properties

- Optimal combination of mechanical properties: increase in toughness and strain; good strength and stiffness performance
- The best performance is given by the Est composite type (elliptical inclusion-stiff matrix)

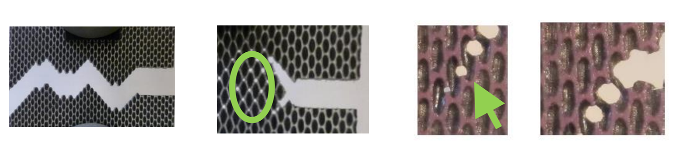




- Toughness: **15 times higher than the soft material** and **7 times higher than the stiff one**
- Composites with stiff matrix show the largest amplification in toughness (these cases are similar to the bone one, where the matrix is stiffer due to a higher degree of mineralization)

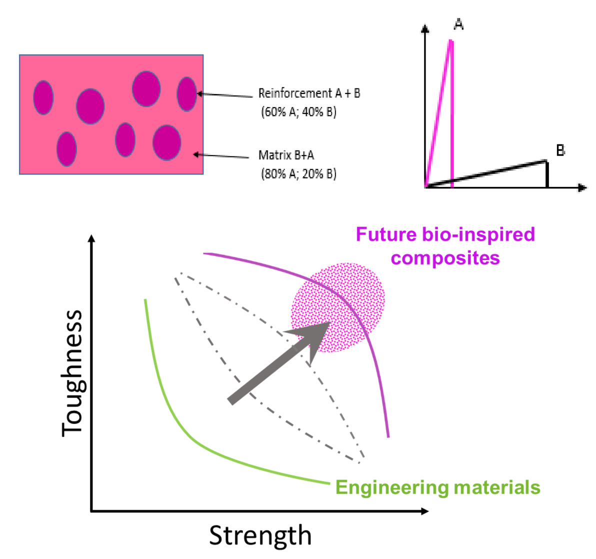
Remarks

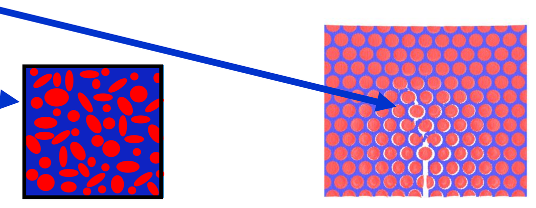
- Role of the osteon-like reinforcement:
  - Reduce the stress concentration at crack tip
  - Promote a nonlinear crack path
  - Cause the formation of stress-induced microvoids
- Successful design:
  - Mimic bone microscale toughening mechanisms
  - Increase in toughness with respect to the base materials (7-15 times)



Future work

- Use dual jet material technology to print composites, whose reinforcement and matrix are a mixture of the two base materials
- Find the optimal combination of the base materials and the optimal reinforcement/matrix stiffness ratio to get the largest amplification in toughness and the best toughness-strength balance
- Build numerical models, able to predict the behavior, to be used for future design
- Print composites with random osteon distribution
- Challenge: scale-up successfully laboratory examples





References

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