Probing the effect of bone microstructure via 3D-printing

Flavia Libonati[1, 2], Grace Gu[2], Leon Dimas[2], Zhao Qin[2], Laura Vergani[1], Markus Buehler[2]

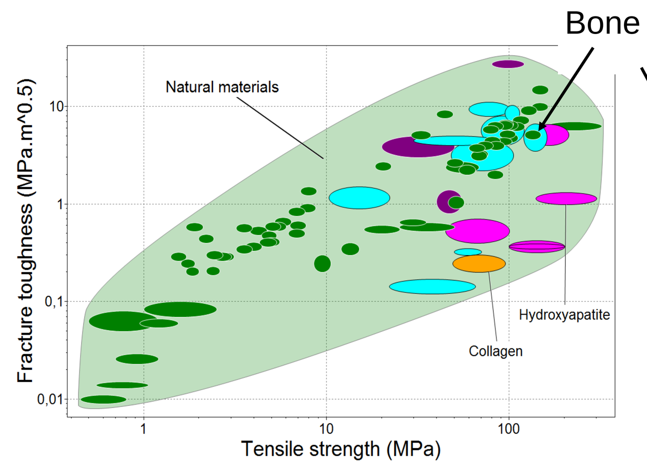
[1] Department of Mechanical Engineering, Politecnico di Milano, Italy

[2] Department of Civil & Environmental Engineering, MIT

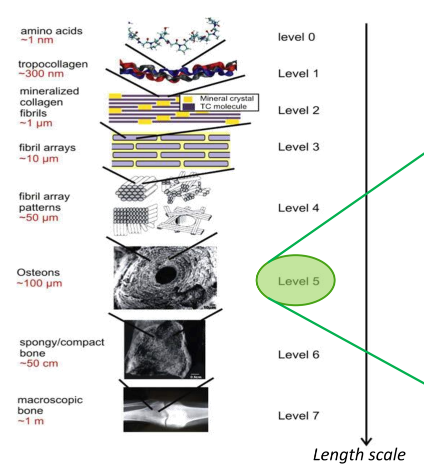
flavia.libonati@polimi.it

Motivation

Bone shows a large amplification in toughness with respect to its building blocks (3-5 orders of magnitude) [1]



The hierarchical structure leads to a unique combination of mechanical properties (e.g. stiffness, strength and toughness) [2-4]



*Weiner, S. et al., *Annu Rev Mater Sci*, 1998.

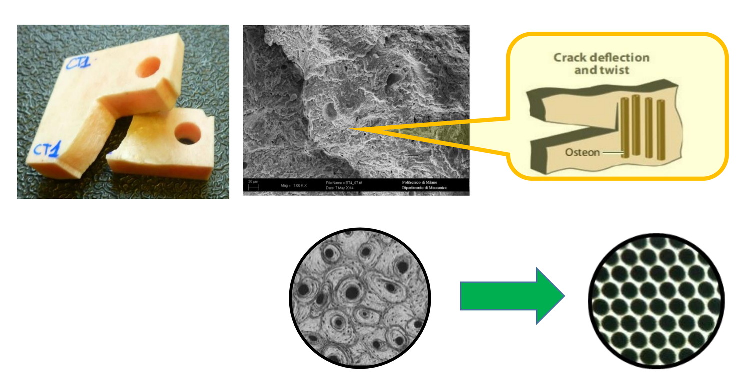
*Ritchie, R.O., et al., *Physics Today*, 2009.

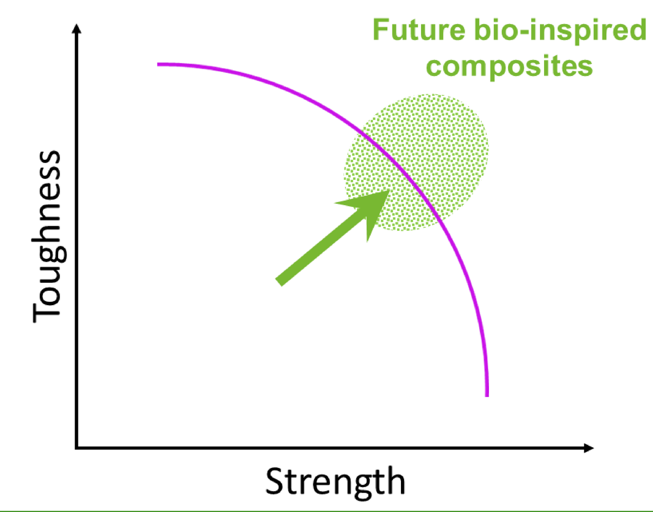
Focus on microscale toughening mechanisms

Objectives

- Obtain an increase in toughness
- Achieve an optimal strength-toughness balance

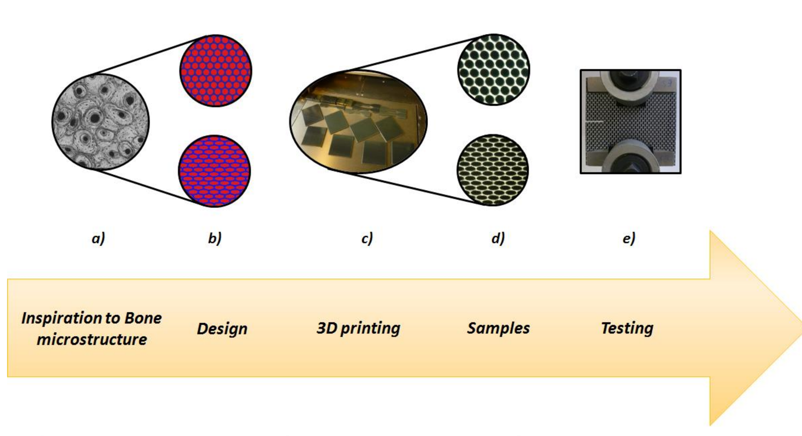
- Implement the main microscale toughening mechanism in *de novo* composites, by replicating the microstructural feature involved in the process





Methods

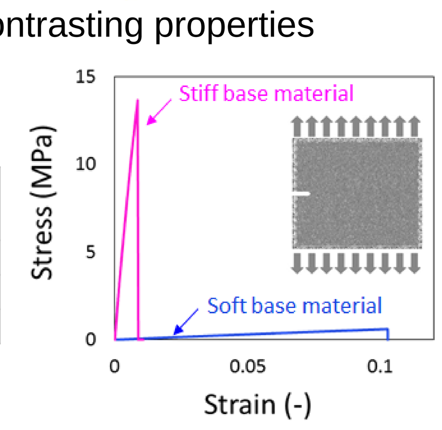
- Biomimetic approach adopted: materials design, manufacturing and testing



- 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

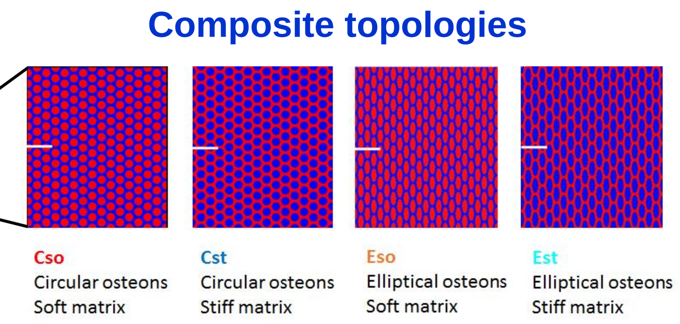
Results of the fracture toughness tests on the base materials



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

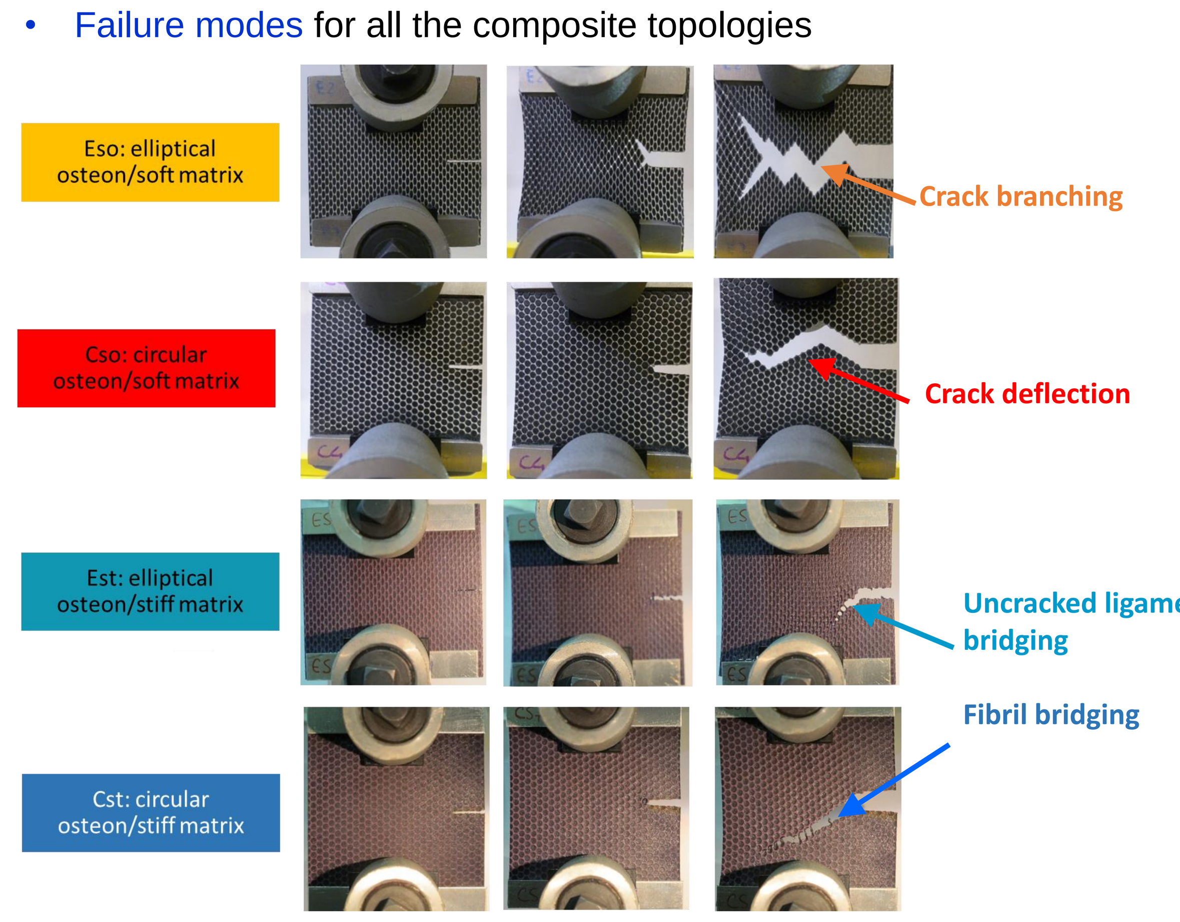
Samples

Composite topologies

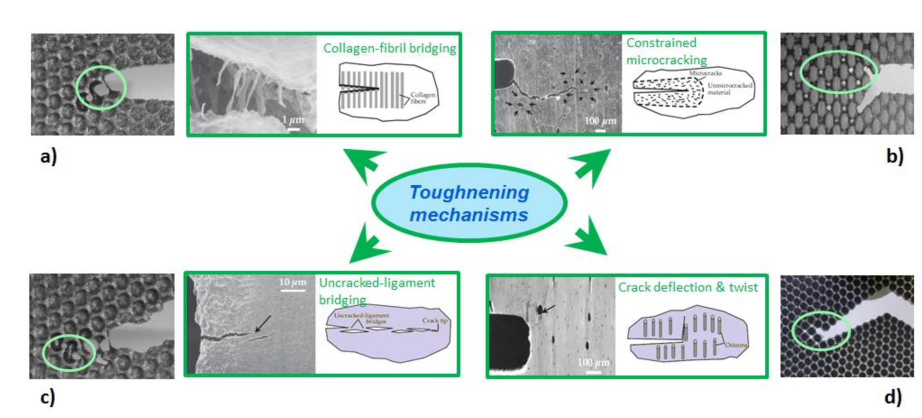


Results

- 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.

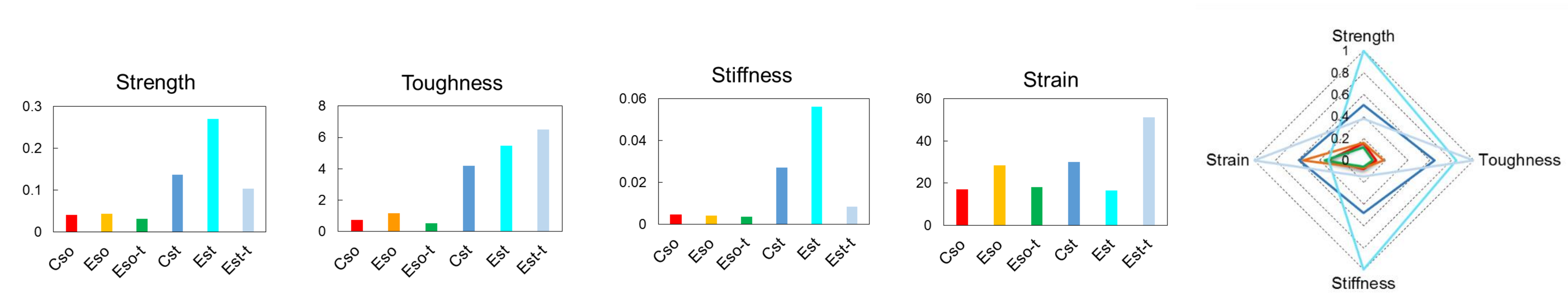
Small scale mechanisms

- Microvoids-microcracks in the resin
- Fibril bridging
- Uncracked ligament bridging

Large scale mechanisms

- Crack blunting
- Crack deflection
- Crack branching

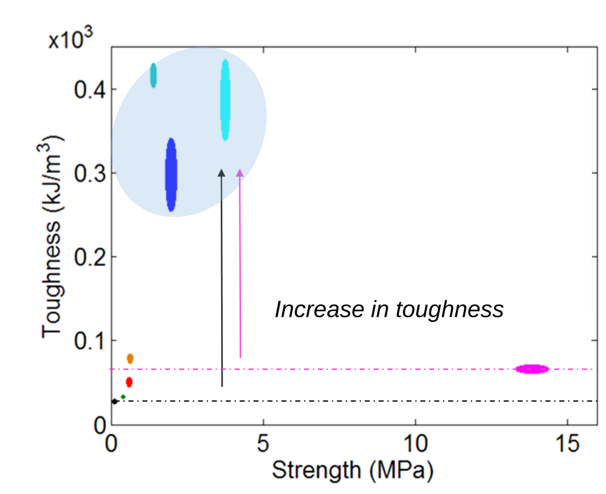
- Optimal combination of mechanical properties: increase in toughness and strain; good strength and stiffness performance



- **Cso**: circular osteon/soft matrix
- **Eso**: elliptical osteon/soft matrix
- **Eso-t**: elliptical osteon/soft matrix – transversal direction
- **Cst**: circular osteon/stiff matrix
- **Est**: elliptical osteon/stiff matrix
- **Est-t**: elliptical osteon/stiff matrix – transversal direction

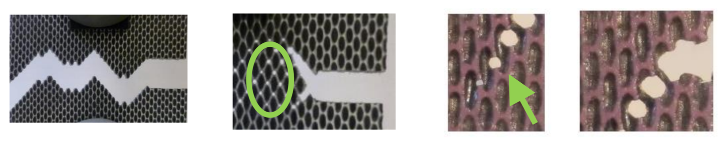
Amplification in toughness

- **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)
- The best performance is given by the Est composite type (elliptical inclusion-stiff matrix)

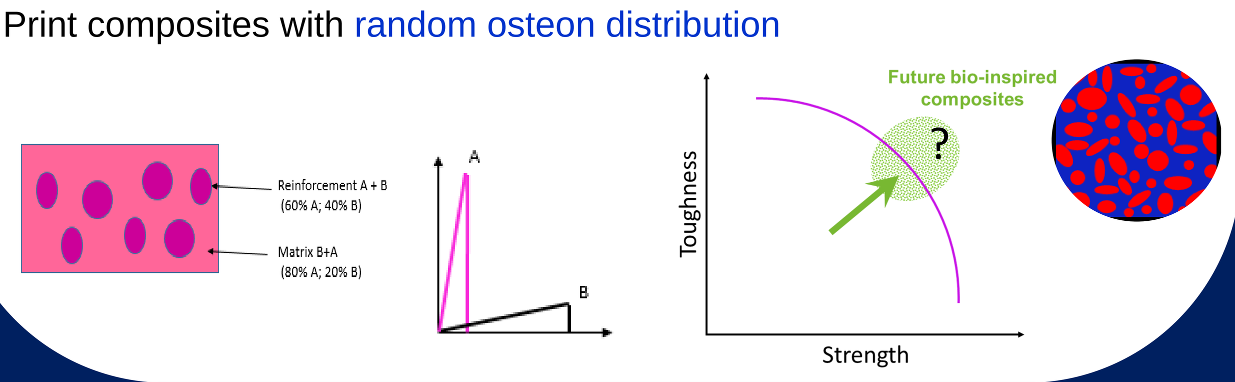


Remarks and future work

- 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 (i.e. dissipation mechanisms)
- Successful design:
  - Mimic the fundamental bone microscale toughening mechanisms
  - Increase in toughness with respect to the base materials (7-15 times)



- 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 material 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



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Acknowledgements

We acknowledge support from “Progetto Rocca” – MISTI Global seed funds. MJB, GG, LD and ZQ acknowledge support from NIH 5U01EB016422 and BASF-NORA.

We would like to thank the technicians, Luca Signorelli and Lorenzo Giudici (from Politecnico di Milano), for their help with experimental testing.