POLITECNICO DI MILANO

PhD in INGEGNERIA MECCANICA / MECHANICAL ENGINEERING - 41st cycle

THEMATIC Research Field: BIO-INSPIRED STRATEGIES FOR ADVANCED METAMATERIALS DESIGN AND FABRICATION

Monthly net income of PhDscholarship (max 36 months)
1500.0 In case of a change of the welfare rates during the three-year period, the amount could be modified.

Context of the research activity	
Motivation and objectives of the research in this field	Bone is a remarkable natural material, evolved over millions of years to achieve an exceptional balance between strength, toughness, and adaptability. Unlike conventional synthetic materials, which often face trade-offs between these properties, bone's hierarchical architecture—from nanoscale mineralized collagen fibrils to microscale trabecular networks—enables it to resist fractures, efficiently distribute loads, and adapt dynamically to mechanical stimuli. These unique features provide a powerful blueprint for engineering next-generation metamaterials with enhanced mechanical resilience, lightweight efficiency, and programmable failure mechanisms. This research aims to harness bone-inspired design principles to develop advanced metamaterials capable of outperforming traditional materials in critical applications such as biomedical implants, aerospace structures, and impact-resistant systems. By integrating AI-driven generative design, synchrotron imaging, and high-resolution additive manufacturing, the study will shape optimized architectures that replicate bone's energy dissipation, crack deflection, and self-adaptive capabilities. A key objective is to bridge the gap between biology and engineering, leveraging computational models and experimental validation to refine material performance at multiple scales. Beyond improving mechanical properties, this approach will contribute to the development of more sustainable and efficient materials, reducing the need for

	excessive raw materials while enhancing durability. Ultimately, this research will pave the way for a new class of bio-inspired metamaterials, unlocking innovative solutions for structural, biomedical, and high-performance engineering applications.
Methods and techniques that will be developed and used to carry out the research	**Methods and Techniques**This doctoral research integrates synchrotron imaging, computational modeling, and image analysis to investigate bone damage mechanisms and design novel bio-inspired metamaterials. **1. Biological Analysis and Imaging** To extract key structural and mechanical principles from bone, advanced imaging and characterization techniques are used: •X-ray Synchrotron Microtomography (SR-µCT): provides high-resolution 3D imaging of bone's microarchitecture, capturing features such as trabecular networks and crack propagation pathways. •Scanning Electron Microscopy (SEM): reveal nanoscale details, including collagen fibril organization and mineralization patterns. •In Situ Mechanical Testing: evaluates real-time mechanical response under load, allowing direct observation of failure mechanisms. 2. **Computational Modeling and Simulation** Numerical techniques help translate bone's structural principles into engineered metamaterial designs: •Finite Element Analysis (FEA): simulates mechanical behavior, stress distribution, and deformation patterns to optimize bio-inspired architectures. •Extended Finite Element Method (XFEM): models crack initiation and propagation, replicating bone's damage-resistant mechanisms. •Cohesive Zone Modeling (CZM): predicts interfacial failure and energy dissipation in layered or composite materials inspired by bone. •Multi-Scale Modeling: bridges nanoscale material properties with macroscale mechanical performance, ensuring that microstructural designs enhance overall toughness and durability.

	toughness and durability. 3. **Generative and AI-Driven Design** Advances in artificial intelligence and computational optimization allow for the rapid development of bio-inspired structures: •Machine Learning for Structural Optimization: AI-driven algorithms analyze bone microstructures and predict optimal metamaterial designs. •Topology Optimization: uses computational techniques to generate lightweight, high-strength structures by mimicking bone's density distribution and load adaptation. •Bio-Inspired Algorithmic Design: implements evolutionary algorithms and generative design strategies to create self-adaptive and damage-resistant materials. 4. **Advanced Additive Manufacturing &Fabrication** Cutting-edge fabrication techniques are essential for realizing complex bio-inspired structures: •Fused Deposition Modeling (FDM): print gradient or porous structures that mimic bone's anisotropic mechanical behavior. •Multi-Material 3D Printing: allows the combination of stiff and compliant materials to replicate bone's composite nature.
Educational objectives	This doctoral research provides interdisciplinary training in biomechanics, materials science, AI, and computational modeling. Key objectives include: •**Knowledge acquisition:** understanding bone damage mechanisms, synchrotron imaging, and AI-driven fracture modeling. •**Technical skills:** Mastering in situ mechanical testing, FEA, XFEM, CZM, AI-based data analysis, and digital fabrication. •**Interdisciplinary research competencies and collaborations:** developing a multi-scale models integrating experiments, simulations, and AI with different research groups.

	•**Communication &development:** publishing research, presenting at conferences, and gaining expertise in project management. This training prepares the candidate for careers in academia, research, and biomedical industries.
Job opportunities	Our last survey on MeccPhD Doctorates highlighteda 100% employment rate within the first year and a 35% higher salary, compared to Master of Science holders in the same field. This project has received funding from The European Innovation Council (EIC) within the framework of EIC Pathfinder Challenge: AEC digitalisation for a new triad of design, fabrication, and materials, Grant agreement ID: 101161602. Cooperating to this research are: 1. Trinity College Dublin, Ireland 2. Galeazzi Orthopedic Institute, Milan, Italy 3. Elettra synchrotron, Trieste, Italy Two positions are opened on this topic.
Composition of the research group	1 Full Professors 0 Associated Professors 1 Assistant Professors 8 PhD Students
Name of the research directors	Prof. L.M.Vergani, Ing. F.Buccino

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Additional support - Financial aid per PhD student per year (gross amount)	
Housing - Foreign Students	--
Housing - Out-of-town residents	--

Scholarship Increase for a period abroad	
Amount monthly	750.0 €
By number of months	6

Additional information: educational activity, teaching assistantship, computer availability, desk availability, any other information

Financial aid is available for all PhD candidates (purchase of study books and materials, funding for participation in courses, summer schools, workshops and conferences) for a total amount of euro 6.114,50.
Our candidates are strongly encouraged to spend a research period abroad, joining high-level research groups in the specific PhD research topic, selected in agreement with the Supervisor. An increase in the scholarship will be applied for periods up to 6 months (approx. 750 euro/month- net amount). Additionally, PhD candidates who spend at least 3 months abroad are eligible for an extra reimbursement of €3,000 to cover travel expenses.
Teaching assistantship: availability of funding in recognition of supporting teaching activitiesby the PhD candidate. There are various forms of financial aid for activities of support to theteaching practice. The PhD student is encouraged to take part in these activities, within the limits allowed by the regulations.