Doctoral Programme in Civil, Environmental and Mechanical Engineering

Research subjects proposed for the 41st cycle – first call

A mandatory attachment of the application is a description of the research project (max 4 pages) relative to the research areas of the Doctoral Programme in Civil, Environmental and Mechanical Engineering on specific topics as described below.

Curriculum A - Civil and Environmental Engineering

- *Reference person:* Marco Tubino (UNITN/DICAM)

Participants: Guido Zolezzi (UNITN/DICAM), Niccolò Ragno (UNITN/DICAM)

A1 - scholarship on reserved topics

Funded by: MUR (Italian Ministry of University and Research) – Dipartimenti di Eccellenza (Departments of Excellence) Project - "Dipartimenti di Eccellenza 2023-2027 (Legge 232/2016)", CUP n. E63C22003880001".

Title: Sediment regime and evolutionary trajectories of riverine ecosystems

Project description: Rivers are among the most threatened ecosystems of the world and are impacted more and more by human activities. Rivers are strongly connected with other components of the earth system by exchanging water and sediment and by responding to alterations such as climate change, growth of vegetation, building of in-stream structures and gravel mining activities. This connectivity invariably leads to changing conditions on a multitude of temporal scales, from the daily scale (e.g., discharge variation due to precipitations or water releases), to the scales of decades or centuries (e.g., climate change, alterations of the sediment production in the basin). As a result, rivers are often out of equilibrium and follow morphodynamic trajectories, depending on intensity, duration, and nature of stressors. Their role as fundamental connecting agents of the evolving landscape is underpinned by the morphological dynamics, which results from the combined effect of processes acting at multiple scales, from the grain to the catchment. Channel geometry and patterns reflect the ongoing adjustment to fluctuating flow and sediment yields (bedload/suspended load) and, consequently, the balance of erosional and depositional processes. Sediment management in fluvial and tidal networks is of crucial importance for environmental, productive and safety reasons. The loss of sediment connectivity along river networks is recognized as a major cause of habitat degradation and biodiversity loss, while erosion/deposition processes may severely contribute to flood hazards. Specifically, in alpine regions, the impact of sediment deficits is responsible for riverbed incision and related habitat degradation. At the same time, increase in sediment load and transport is a major problem in regions with soil erosion due to intensive agriculture. Consequences of sediment deficits and impacts on the river are decrease in habitat heterogeneity, risk of river bank erosion and of damage to infrastructure, lack of spawning habitats for fish species and depauperate macroinvertebrate fauna, decrease in sediment turnover rates and river type-specific sediment quality, risk of channel avulsion during extreme events.

In the last 40 years our understanding of morphodynamics has been remarkably advanced through mathematical theories and predictive models, which have received strong validation from laboratory scale experiments and more recently also from field observations. Theoretical models can now benefit from the remarkable support of satellite information, which provides an unprecedented capability of performing quantitative analyses of the spatial distributions of river and deltas characteristics and evolutionary trajectories. The morphodynamic processes that determine the shape of the river have been mainly studied under the assumption that the river system is in dynamic equilibrium. Furthermore, most of the existing morphodynamic models refer to the reach scale, i.e. a hydro-morphologically homogeneous portion of the channel, though processes at this scale are clearly conditioned by those occurring at hierarchically higher scales. Disequilibrium between sediment supply and transport capacity and the presence of evolutionary trajectories, as well as the morphodynamical response to a variable flow regime, such as the hydrological cycle, are still to a large extent unexplored.

Research aims and methodology

Within the above framework, the aim of the project is to investigate non-equilibrium hydraulic and morphodynamic processes and the related habitat responses.

With reference to projects currently underway at the Department of Civil, Environmental and Mechanical Engineering, the candidate will be able to develop his/her research with reference to one of the following topics:

a) Develop suitable quantitative, process-based tools to assess sediment production and transport processes at the river network scale in Alpine basins and detect the potential for restoration accounting for the operational and structural constraints set by the anthropic stressors. The project methodology envisages the integration of mathematical modelling approaches with the collection and analysis of field data in target case studies. Modelling will focus on the development and testing of a nested, multi-scale approach, where a chain of models will be used from the catchment to the reach scale. The field component will integrate the analysis of existing datasets available at public environmental agencies with those of remotely sensed data and with the collection and analysis of in situ field data.

b) Develop suitable quantitative, process-based tools to assess the morphodynamical trajectories and flow and sediment distribution in multi-thread, anabranching river reaches, as well as in complex river networks in transitional environments undergoing sedimentation processes, and analyse the role of changes of the external controlling variables. This will be accomplished by using a combination of numerical modelling, physical modelling at the Hydraulic laboratory of the Department of Civil Environmental and Mechanical Engineering, where a large experimental facility is available, field measurements and monitoring and statistical data analysis and interpretation of results on the basis of theoretical and conceptual models. Effectively tackling these questions is made possible by two key factors: (i) the recent theoretical development on bifurcations/confluences morphodynamics; (ii) the availability of a specific case study.

The ideal candidate will have a background in Environmental Engineering, River Geomorphology or related fields. Candidates should also possess strong computer, scientific, and analytical expertise, have excellent communication (oral and written) skills, have the ability to work independently and as part of a team, self-motivation, adaptability, and a good attitude for critical thinking. Since foreseen activities include model development, the candidate is required to have computational proficiency (or the will to pursue it) preferably in Fortran, R/python/Matlab and GIS products.

Suggested references:

- Schmutz & Sendzimir eds (2018), *Riverine Ecosystem Management.*
- Cavalli et al. (2013), Geomorphology.
- Heckmann et al. (2018), Earth Science Review.
- Morel et al. (2023), Nat. Hazard Earth Syst. Sci.
- Redolfi et al. (2019), Earth Surface Processes and Landforms.
- Ragno et al. (2021), Water Resources Research.
- Barile et al. (2024), Earth Surface Dynamics.
- Ragno & Tubino (2025), Earth Surface Processes and Landforms.

- *Reference persons:* Daniele Casagrande (UNITN/DICAM), Ivan Giongo (UNITN/DICAM)

Participant: Ghasan Doudak (University of Ottawa, Canada)

A2 - scholarship on reserved topics

Funded by: MUR (Italian Ministry of University and Research) – Dipartimenti di Eccellenza (Departments of Excellence) Project - "Dipartimenti di Eccellenza 2023-2027 (Legge 232/2016)", CUP n. E63C22003880001".

Title: Development of optimized analysis and construction strategies for multi-storey cross laminated timber seismic force resisting systems

Introduction and objectives

Cross Laminated Timber (CLT) structural systems represent nowadays a valuable solution for the construction of multi-storey buildings in seismic prone areas. The high strength-to-mass ratio of CLT panels and the capability of dissipating energy in mechanical connections are some of the key factors responsible for the outstanding response offered by CLT seismic force resisting systems (SFRSs) [1,2].

In the last two decades, a great effort has been undertaken in the investigation of the seismic performance of CLT structural systems. A large number of experimental campaigns have been conducted at connection-, wall- and building level [3]. Several numerical studies have been performed to either evaluate the non-linear response of mass timber SFRSs [4] or promote specific design-oriented methodologies [5] supporting the revision process of design Standards.

Despite the tremendous advancements in the entire sector of timber construction, significant limitations and technological constraints still exist in the use of CLT structural systems in seismic prone areas. The inadequate performance of proprietary mechanical connections (i.e. hold-down) when subjected to high loads, the gaps in knowledge concerning the mutual interaction of structural components (e.g. wall and floor panels) as well as the scarce development of hybrid (e.g. steel-timber) structural solutions are some of the reasons the adoption of CLT structural systems is still restricted.

This research project aims at the development of optimized analysis and construction strategies for multi-storey CLT buildings in seismic prone areas. Two main research goals are defined to partially overcome some of the existing constraints and limitations:

1. exploring the performance at the building level by investigating the interaction between the structural timber elements in the response of CLT SFRSs as well as developing design-oriented methodologies for an optimized and realistic prediction of the seismic effects on structural components;
2. investigating innovative construction strategies and details to enhance the seismic response of CLT SFRSs through the adoption of steel-timber hybrid structural elements.

Research Content and Methods

The study will be developed in two main working tasks finalized at the achievement of the research goals.

WT1: Optimized design-oriented methodologies for the seismic analysis of multi-story CLT SFRSs

Most of existing design-oriented methodologies for the prediction of seismic response of CLT buildings reported in Standard documents or commonly included in commercial software packages are primarily based on simplified assumptions that do not consider the mutual effects of interacting structural panels (e.g. floor and wall panels, lintels and wall segments in walls with openings). For this reason, WT1 will explore the interactions between the structural CLT elements in order to develop design-oriented methodologies for a more realistic and optimized prediction of internal actions and seismic effects on structural components (i.e. connections and panels) in multi-story CLT structures [6,7]. As an example, through both parametric numerical analyses and experimental tests, more specifically WT1 will focus on either proposing design-oriented analytical methods for the analysis and design of multi-story shearwalls with openings and/or establishing a better understanding of the behavior of multi-story segmented shearwalls with specific attention to the floor-to-wall panel interaction.

WT2: Construction strategies aimed at enhancing the seismic response of mass timber SFRSs

WT2 will investigate construction strategies to overcome existing limitations related to the seismic performance of CLT buildings by means of the adoption of hybrid structural solutions. In particular, WT2 will be aimed at investigating the mechanical performance of innovative hybrid CLT-steel shearwalls to be adopted as SFRSs in mass timber buildings [8,9,10]. The activities in WT2 will be conducted through both numerical analyses and experimental tests potentially performed both at component- and system level. Construction details will be analyzed and developed.

Expected results

The expected outcomes of this research study can be summarized as in the following:

1. proposal of analytical design-oriented strategies and development of Standard provisions for the analysis and design of multi-storey CLT SFRFs made with either shearwalls with cut-out openings or multi-panel shearwalls;
2. advancement in knowledge in the adoption of hybrid CLT-steel shearwall structural systems.

The results of the research project will be included in two publications in high-ranked international journals and will be presented in at least one conference.

References

[1] Izzi, M., Casagrande, D., Bezzi, S., Pasca, D., Follesa, M., Tomasi, R. Seismic behaviour of Cross-Laminated Timber structures: A state-of-the-art review (2018) Engineering Structures, 170, pp. 42-52.

[2] Pei, S., Van De Lindt, J.W., Popovski, M., Berman, J.W., Dolan, J.D., Ricles, J., Sause, R., (...), Rammer, D.R.Cross-Laminated Timber for Seismic Regions: Progress and Challenges for Research and Implementation (2016) Journal of Structural Engineering (United States), 142 (4), art. no. E2514001.

[3] Gavric, I., Fragiacomo, M., Ceccotti, A. Cyclic behavior of CLT wall systems: Experimental tests and analytical prediction models (2015) Journal of Structural Engineering (United States), 141 (11), art. no. 04015034.

[4] Rinaldin, G., Fragiacomo, M. Non-linear simulation of shaking-table tests on 3- and 7-storey X-Lam timber buildings (2016) Engineering Structures, 113, pp. 133-148.

[5] Christovasilis, I.P., Riparbelli, L., Rinaldin, G., Tamagnone, G. Methods for practice-oriented linear analysis in seismic design of Cross Laminated Timber buildings (2020) Soil Dynamics and Earthquake Engineering, 128, art. no. 105869.

[6] Casagrande, D., Fanti, R., Doudak, G., Polastri, A. Experimental and numerical study on the mechanical behaviour of CLT shearwalls with openings Construction and Building Materials, 2021, 298, 123858

[7] Masroor, M., Tannert, T. Validation and application of analytical design approach for multi-storey platform-type CLT shear walls, Engineering Structures, 2025, 327, 119655

[8] Zhang X., Fairhurst M., Tannert T. (2015). Ductility estimation for a novel timber-steel hybrid system. J. Struct. Eng.

[9] Khajehpour M., Pan Y., Tannert T. (2021). Seismic Analysis of Hybrid Steel Moment Frame CLT Shear Walls Structures. J. Perform. Constr. Facil., 35.

[10] Dickof C., Stiemer S. F., Bezabeh M. A., Tesfamariam S. (2014). CLT–steel hybrid system: Ductility and overstrength values based on static pushover analysis. J. Perform. Constr. Facil., 28(6).

- *Reference person:* Marco Broccardo (UNITN/DICAM)

Participants: Davide Noè Gorini (UNITN/DICAM), Chiara Nardin (UNITN/DICAM), Alfio Viganò (Provincia Autonoma di Trento)

A3 - scholarship on reserved topics

Funded by: University of Trento - Department of Civil, Environmental and Mechanical Engineering within the project “Seismic Risk” CUP no. C65E24000330003 – PAT

Title: Next Generation of Exposure and Seismic Risk Maps for the Trentino region

This research project aims to develop a prototype for high-resolution seismic risk maps at the regional scale, integrating microzonation studies with advanced vulnerability and exposure assessments. The project develops a comprehensive framework that integrates state-of-the-art predictive models of seismic hazard, structural vulnerability including soil-structure interaction, and exposure data for improved risk estimations and more efficient mitigation strategies across the Trentino region. The research outcomes are structured into three key contributions:

1. **Local-Scale Seismic Hazard Assessment and Microzonation Integration**
   - Development of a methodological framework to incorporate microzonation studies into seismic hazard models. The integration will be fully probabilistic.
   - Comparison of national-scale hazard assessments with local microzonation data, enhancing accuracy and resolution in risk estimation.
2. **Seismic Vulnerability and Exposure Modeling of the Built Environment**
   - State-of-the-art vulnerability models based on advanced surrogate models, and integration of soil-structure interaction according to computationally efficient, thermodynamic-based macroelement representations.
   - Integration of national building datasets with Global Earthquake Modelling taxonomies to map structural vulnerabilities.
   - Identification of high-risk building typologies and strategic infrastructure, enabling targeted risk mitigation.
3. **Integrated Seismic Risk Mapping: A Case Study in Trentino**
   - Development of a GIS-based seismic risk assessment model that combines hazard, vulnerability, and exposure data.

- Validation through application to the Alto Garda region, demonstrating adaptability for broader regional and national applications.
- Through the systematic comparison with conventional microzonation models, identification of urban aggregates in which soil-structure interaction can have negligible, favourable or detrimental effects on seismic risk.

This project is a pioneering effort in Italy and at the forefront of international research, integrating high-resolution microzonation with exposure analysis to develop a replicable and scalable seismic risk assessment methodology. The findings enhance seismic risk management and align with European initiatives such as ESRM20 (European Seismic Risk Model).

- *Reference person:* Dr. Giacomo Bertoldi (Eurac Research)

Participants: Prof. Bruno Majone, Dr. Alice Crespi (Eurac Research), Dr. Stefano Terzi (Eurac Research), Dr. Andrea Galletti (Eurac Research)

A4 - scholarship on reserved topics

Funded by: University of Trento – Eurac Research

Title: Climate Scenarios for Future Water Availability in Alpine Regions

Climate change and human activities are reshaping water availability and demand in the Alps. Changes in precipitation and temperature patterns, higher water needs for mountain ecosystems in response to warming and increasing water demands from socio-economic activities are expected to threaten water security in the next future. In the upper Adige River catchment (Eastern Italian Alps), reduced snowfall and glacier melt have already shifted the streamflow regime, and impacts of the summer streamflow decrease have already been registered in downstream areas. Recent events, such as the 2021–2022 drought, generated tensions and disputes for sharing the available water from upstream to downstream. This situation highlighted the need for improving the understanding and modelling of climate change effects on current and future water availability.

This PhD project aims to comprehensively address the challenges related to the modelling of current and future water availability in the Alps by improving and integrating information on climate change, snow dynamics, and evapotranspiration processes into hydrological simulations with a focus on the upper Adige catchment (Trentino-South Tyrol). The overall research question behind is: “How do changes in climate drivers, cryosphere and evapotranspiration demand influence the hydrological regime of mountain catchments, from an upstream-to-downstream perspective?”

Specific tasks will include: 1) evaluation of climate data for hydrological modelling, analysis of climatic drivers and development of meaningful climate scenarios for a critical assessment of future water resources and impacts of water scarcity conditions; 2) assessment of evapotranspiration contributions to water availability by integrating climatic data and land-use scenarios and developing and testing specific modelling modules; 3) study of spatio-temporal snow dynamics, including snowmelt processes, for improving its representation in hydrological models; 4) the inclusion of such processes in a multi model framework for current and future scenarios.

Expected research outputs will include at least three peer-reviewed scientific publications in high-impact journals covering the specific objectives listed above.

This PhD project will be partly supported by the NextWater_ST project, funded by the Province of Bolzano and led by Eurac Research (a period of the doctoral activities is required to be spent at Eurac premises in Bolzano). The project aims to enhance the understanding of the dynamics between water availability and multi-sectoral water demand in South Tyrol under future changes to support water management.

Key references:

- Brunner, M. I., Götte, J., Schlemper, C., & Van Loon, A. F. (2023). Hydrological drought generation processes and severity are changing in the Alps. *Geophysical Research Letters*, 50, e2022GL101776. https://doi.org/10.1029/2022GL101776
- Bozzoli, M., Crespi, A., Matiu, M., Majone, B., Giovannini, L., Zardi, D., Brugnara, Y., Bozzo, A., Berro, D. C., Mercalli, L., & Bertoldi, G. (2024). Long-term snowfall trends and variability in the Alps. *International Journal of Climatology*, 44(13), 4571–4591. https://doi.org/10.1002/joc.8597
- Mastrotheodoros, T., Pappas, C., Molnar, P. *et al.* (2020). More green and less blue water in the Alps during warmer summers. *Nature Climate Change,* 10, 155–161. https://doi.org/10.1038/s41558-019-0676-5

- *Reference persons:* Bruno Majone (UNITN/DICAM), Diego Avesani (UNITN/DICAM)

Participant: Mattia Carlin (Hydro Dolomiti Energia Srl)

A5 - scholarship on reserved topics

Funded by: University of Trento – Hydro Dolomiti Energia Srl

Title: Seasonal forecasting of Snow Cover Dynamics in Complex Mountain Terrains: Integrating Snow Simulations with multivariate ML-Based Methods

In Alpine regions, accurate seasonal snow prediction is essential for water management, hydropower generation and agricultural planning. However, two major challenges hinder its reliability: seasonal weather forecasting systems exhibit systematic errors, limiting their applicability for reliable snowmelt prediction, while physically based snow models typically require a large number of input variables and can be overly complex, restricting their feasibility for real-time operations.

To overcome these limitations, this study proposes the development of an integrated modeling framework for seasonal snow prediction. The framework will combine Neural Network-Based Multivariate Distributional Regression, which overcomes the limitations of stationary statistical postprocessing approaches, for bias-adjustment and downscaling with a parsimonious distributed snow model, derived from an enhanced version of the temperature-index model TOPMELT 1.0 (Zaramella e al., 2019). This approach aims to balance computational efficiency with physical consistency, optimizing input requirements for practical applications in Alpine catchments. The framework will be specifically designed to address the challenges posed by complex topography and local climate variability.

The overarching goal is to predict the seasonal spatio-temporal dynamics of the snowpack (including snow cover and volume) with lead times ranging from 1 to 7 months, assessing its performance across different spatial and temporal scales. This study will address the following key research questions: (i) To what extent can seasonal weather forecasts in complex mountainous terrain be improved using Neural Network-Based Multivariate Distributional Regression (NN-MDR) for bias-adjustment and downscaling? (ii) To what extent can the accuracy of snow simulations be improved by a fully distributed enhanced temperature-index model that explicitly represents topography-driven snowmelt processes? (iii) How much can the combination of (i) and (ii) will improve the prediction of snow dynamics at the seasonal scale?

To address these research questions, the study will integrate the following methodological components: (a) Downscaling and bias-adjustment of meteorological variables from the SEAS5 (fifth-generation seasonal weather forecast system generated by the European Centre for Medium-Range Weather Forecasts) system through the implementation of a NN-MDR, serving as a post-processing tool to refine forecast accuracy; (b) Development of a fully distributed version of TOPMELT 1.0 to improve the simulation of snow dynamics; (c) evaluation of forecast accuracy and uncertainty reduction of the SEAS5-TOPMELT modelling chain with reference to the topographically complex region of Trentino-South Tyrol, possibly trying to extend the approach to the overall Italian Alpine domain.

The research project is developed in collaboration with Hydro Dolomiti Energia Srl, the main hydropower production company in Trentino region.

Suggested references (to be not considered as exhaustive for the topic)

- Crochemore, L., Ramos, M. H., & Pappenberger, F. (2016). Bias correcting precipitation forecasts to improve the skill of seasonal streamflow forecasts. Hydrology and Earth System Sciences, 20(9), 3601–3618. https://doi.org/10.5194/hess-20-3601-2016
- Rasp, S., & Lerch, S. (2018). Neural networks for postprocessing ensemble weather forecasts. Monthly Weather Review, 146(11), 3885–3900. https://doi.org/10.1175/MWR-D-18-0187.1
- Schulz, B., & Lerch, S. (2022). Machine Learning Methods for Postprocessing Ensemble Forecasts of Wind Gusts: A Systematic Comparison. Monthly Weather Review, 150(1), 235–237. https://doi.org/10.1175/MWR-D-21-0150.1
- Zaramella, M., Borga, M., Zoccatelli, D., & Carturan, L. (2019). TOPMELT 1.0: a topography-based distribution function approach to snowmelt simulation for hydrological modelling at basin scale. Geoscientific Model Development, 12, 5251–5265. https://doi.org/10.5194/gmd-12-5251-2019

Curriculum B - Mechanics, Materials, Chemistry and Energy

- *Reference person:* Vincenzo Trovato (UNITN/DICAM)

B1 - scholarship on reserved topics

Funded by: Eurac Research

Title: Revenue maximization for an integrated PV - BESS with optimal capacity repowering due to different types degradation. System-level and local-level applications

Project Description:

Battery Energy Storage Systems (BESS) are expected to contribute to mitigate the uncertainty and variability of renewable sources (e.g., photovoltaic energy). The might be installed in standalone configurations or integrate and co-operated with a renewable generator (e.g., PV farms). The BESS flexible operation may be able to support system stability and contribute to maintain supply/demand balance in scenarios where the level of renewable generation is higher/lower than expected.

Time-varying energy market prices may justify arbitrage operation of the BESS, with indirect benefit of flattened system demand and reduced need for high-emitting and cost-intensive peak generators. BESS may also contribute to the security of supply by participating to Capacity Markets (CM). Nonetheless, BESS are subject to energy capacity degradation as result of their charging/discharging operation. If this feature is not properly managed, the financial feasibility of a BESS project could be highly affected by an excessive degradation of the energy capacity, shortening the useful life of the asset or requiring unplanned, cost-intensive revamping actions.

Initial modelling and relevant evidence has been produced by the proposing research group. Nonetheless, driven by several feedback from scientific and industrial stakeholders, fundamental advancement in the modelling is requested to facilitate the application of the proposed algorithm in the financial assessment of real industrial BESS or BESS-PV project. The Ph.D. project is therefore made of six work-packages:

• **WP1**: **adoption of a non-deterministic framework**. The first novel feature of the proposed project regards the ability to describe and capture the intrinsic uncertainties associated to WEM prices and/or PV output and/or costs for cell replacement and/or parameters of the asset degradation.

• **WP2**: **a wide revenue-stacking paradigm for the BESS**. The objective of the BESS operation will need to acknowledge the economic value of contracting multiple services, operating in different energy and ancillary services markets

• **WP3**: **battery management algorithm**. The development of a battery management algorithm to command the operation of racks of battery cells is paramount in order to better exploit the energy capacity of single racks and distribute evenly the operational effort.

• **WP4**: **impact of temperature dynamics and calendar aging**. The energy/power operation of the cells of a BESS is also affected by the operating temperature of the cells and the ambient one. The Ph.D. project aims to perform a series of laboratory tests in order to validate different formulations of energy capacity degradation, matching them with actual simulation results.

• **WP5**: **Implementation and validation of the proposed methods and algorithms to actual case studies for industrial innovation**. The results of this WP are the essence of the Ph.D. program since they summarize all the milestones and developments above, enabling a true and effective knowledge transfer to Industrial partners, potentially leading to the definition of an actual business project for a BESS project.

Research Outcomes:
The main tasks facilitating the promotion of the results of the Ph.D. program are:

• The submission of scientific articles to high-impact international peer-reviewed journals. Where possible, the open access publication option will be chosen in order to support the dissemination of the research to the Industry and Institutions.

• Presentation of the results achieved at national and international conferences and to technical exhibitions.

• Organization of dissemination and exploitation events, such as seminars for researchers and workshops for industrial partners or other external relevant stakeholders.

• In partnership with the industrial sponsor, the digital communication campaign, including the opening of a project web site and the possible creation of an account on social networks (e.g. LinkedIn, Instagram).

A period of the doctoral activities is required to be spent at Eurac premises in Bolzano.

Curriculum C - Modelling and Simulation

- *Reference person:* Marco Salucci (UNITN/DICAM)

Participants: Andrea Massa (UNITN/DICAM), Giacomo Oliveri (UNITN/DICAM), Paolo Rocca (UNITN/DICAM)

C1 - scholarship on reserved topics

Funded by: MUR (Italian Ministry of University and Research) – Dipartimenti di Eccellenza (Departments of Excellence) Project - "Dipartimenti di Eccellenza 2023-2027 (Legge 232/2016)", CUP n. E63C22003880001".

Title: Physics-Informed Surrogate Models and Optimization Techniques for Next-Generation Wireless Structural Health Monitoring ecosystems

The increasing demand for safety and reliability in civil and environmental infrastructures requires advanced monitoring and diagnostic solutions. Wireless Structural Health Monitoring (WSHM) systems, leveraging electromagnetic (EM) sensing technologies, offer real-time data acquisition and analysis capabilities.

However, challenges remain in efficiently processing large datasets and extracting meaningful insights for proper decision-making. Indeed, the high-dimensionality and heterogeneity of collected data, the sensor noise, and the environmental interference can negatively impact the overall monitoring/assessment accuracy. Additionally, real- time analysis demands significant computational resources, making conventional physics-based models impractical for rapid evaluations. Therefore, developing efficient surrogate models (SMs) that retain physical fidelity while reducing computational complexity is essential. Moreover, optimization techniques can play a crucial role in addressing these challenges. For instance, by optimizing sensor placement and data acquisition strategies, it is possible to maximize the collected information while minimizing energy consumption and computational burden.

Furthermore, optimization methods can improve model calibration and parameter estimation, leading to more accurate diagnostics and predictions. Within this framework, the research initiatives carried out by the members of the ELEDIA@UniTN - DICAM team have been focused on the development of several artificial intelligence (AI)-based strategies leveraging both machine learning (ML) techniques and global (evolutionary-inspired) optimization algorithms to solve complex problems arising in many engineering contexts.

The objective of the PhD research activity will therefore be the development and integration of suitably-customized physics-informed SMs and optimization techniques to enhance the accuracy and efficiency of next generation WSHM systems.

This research aligns with the “Mechanics of Solids and Structural/Infrastructural Systems” thematic area of the DICAM-EXC Project 2023-2027 by addressing reliability and life-cycle assessment challenges in complex structures. Furthermore, it contributes to the DICAM goals by advancing research, fostering multidisciplinary education, and promoting knowledge transfer through innovative solutions.

To this end, the PhD Student will join a trans-disciplinary team of Researchers and Professors working on a wide variety of domains from EM to civil and environmental engineering. The research activity will be conducted under the supervision of the PI/Advisor and the members of the ELEDIA@UniTN - DICAM of the University of Trento.

The expected outcomes of this activity can be listed as follows:

1. Review and analysis of the literature on modern WSHM systems, with focus on AI-based strategies for enhanced accuracy and reliability;

2. Develop and properly integrate advanced physics-informed SMs and optimization techniques for real-time data collection, analysis, and decision-making.

3. Validate the proposed methodologies in civil and environmental monitoring applications, ensuring alignment with safety & security and logistics requirements. The above biological properties represent some of the research activities will be proposed within this project.

Suggested selected references:

[1] B. Majone, F. Viani, E. Filippi, A. Bellin, A. Massa, G. Toller, F. Robol, and M. Salucci, “Wireless sensor network deployment for monitoring soil moisture dynamics at the field scale,” Proc. Env. Sci., vol. 19, pp. 426-235, 2013.

[2] M. Salucci, N. Anselmi, G. Oliveri, P. Calmon, R. Miorelli, C. Reboud, and A. Massa, "Real-time NDT-NDE through an innovative adaptive partial least squares SVR inversion approach," IEEE Trans. Geosci. Remote Sens., vol. 54, no. 11, pp. 6818-6832, Nov. 2016.

[3] F. Viani, A. Polo, P. Garofalo, N. Anselmi, M. Salucci, and E. Giarola, "Evolutionary optimization applied to wireless smart lighting in energy-efficient museums," IEEE Sensors J., vol. 17, no. 5, pp. 1213-1214, Mar. 2017.

[4] F. Viani, M. Bertolli, M. Salucci, and A. Polo, "Low-cost wireless monitoring and decision support for water saving in agriculture," IEEE Sensors J., vol. 17, no. 13, pp. 4299-4309, Jul. 2017.

[5] A. Massa, G. Oliveri, M. Salucci, N. Anselmi, and P. Rocca, "Learning-by- examples techniques as applied to electromagnetics," J. Electromagn. Waves Appl., vol. 32, no. 4, pp. 516-541, 2018.

[6] M. Salucci, N. Anselmi, G. Oliveri, P. Rocca, S. Ahmed, P. Calmon, R. Miorelli, C. Reboud, and A. Massa, "A nonlinear kernel-based adaptive learning-by- examples method for robust NDE-NDT of conductive tubes," J. Electromagn. Waves Appl., pp. 1-28, 2019.

[7] A. Massa, D. Marcantonio, X. Chen, M. Li, and M. Salucci, "DNNs as applied to electromagnetics, antennas, and propagation - A review," IEEE Antennas Wireless Propag. Lett., vol. 18, no. 11, pp. 2225-2229, Nov. 2019.

[8] A. Massa and M. Salucci, "On the design of complex EM devices and systems through the system-by-design paradigm - A framework for dealing with the computational complexity," IEEE Trans. Antennas Propag., vol. 70, no. 2, pp. 1328-1343, Feb. 2022.

[9] M. Salucci, M. Arrebola, T. Shan, and M. Li, "Artificial intelligence: New frontiers in real-time inverse scattering and electromagnetic imaging," IEEE Trans. Antennas Propag., vol. 70, no. 8, pp. 6349-6364, Aug. 2022.

[10] M. Arrebola, M. Li and M. Salucci, "Guest editorial artificial intelligence: New frontiers in real-time inverse scattering and electromagnetic imaging," IEEE Trans. Antennas Propag., vol. 70, no. 8, pp. 6131-6134, Aug. 2022.

C2 - scholarship on reserved topics

Funded by: MUR (Italian Ministry of University and Research) – Dipartimenti di Eccellenza (Departments of Excellence) Project - "Dipartimenti di Eccellenza 2023-2027 (Legge 232/2016)", CUP n. E63C22003880001".

Please note: candidates interested in this scholarship can develop their research projects within **one of the following topics.**

Topic 1

Title: Next-generation Metafoundations for Enhanced Seismic Protection of Nuclear Power Plants considering Soil-Structure Interaction

Reference persons: Oreste S. Bursi, Davide Noè Gorini, James M. Ricles (Prof. of Structural Engineering, Lehigh University, Bethlehem, PA, USA, Editor-in-Chief, Engineering Structures, Elsevier Publ.))

Are you interested in pushing the boundaries of earthquake, geotechnical engineering and metamaterials? This PhD opportunity focuses on designing cutting-edge 3D seismic protection solutions for next generation Nuclear Power Plants (NPPs), including Small Modular Reactors (SMRs).

The path leverages the dynamic interaction of NPPs with the surrounding soil, altering the frequency/amplitude-dependent features of the overall response, to enhance seismic protection, with reference to an innovative metamaterial-based foundation typology. This technique is based on the use of shallow metafoundations, inspired by locally resonant metastructures, particularly prone to limit earthquake-induced effects under multi-component ground motion.

The goal of this thesis is to develop a thermodynamic-based framework for high-fidelity assessment and design of next-generation metafoundations guaranteeing valuable seismic protection of NPPs. This framework will exploit cardinal features relating to the dynamic response of the foundation soils i) to exalt the performance of metafoundations, and ii) to identify optimised/innovative metafoundation configurations.

The main outcomes of the thesis are summarised below.

1. Development of an interpretative soil-metafoundation-superstructure numerical model based on thermodynamic macroelements.

2. Understanding and standardization of dynamic soil-metafoundation interaction.

3. Topological optimization of metafoundations and tuning of the soil-NPP system.

4. Validation of the improved metafoundation system.

Suggested selected references:

[1] Gorini, D.N.. A unified thermodynamic-based macroelement for geotechnical systems, Computers and Geotechnics, 179, 106965, https://doi.org/10.1016/j.compgeo.2024.106965 (2025)

[2] Guner, T., Nardin, C., Bursi, O.S., Erlicher, S., Monteil, A.. Design standardisation and seismic protection of SMRs through modular metafoundations, Nuclear Engineering and Design, https://doi.org/10.1016/j.nucengdes.2024.113347 (2024)

[3] Gorini, D.N., Callisto, L.. A multiaxial inertial macroelement for deep foundations, Computers and Geotechnics 155, 105222, 105222, https://doi.org/10.1016/j.compgeo.2022. (2023)

[4] Guner, T., Bursi, O.S., Erlicher, S.. Optimization and performance of metafoundations for seismic isolation of small modular reactors, Computer-Aided Civil and Infrastructure Engineering, http://doi.org/10.1111/mice.12902 (2022)

[5] Malik, F.N., Gorini, D.N., Ricles, J.M., Rahnemoonfar, M.. Multi-Physics Framework for Seismic Real-Time Hybrid Simulation of Soil-Foundation-Structural Systems, Engineering Structures, doi 10.2139/ssrn.5076556 (2025)

[6] Abu-Kassab, Q., Marullo, T., Suleiman, M. T., Ricles, J.M., Sause, R.. Large-scale multidirectional soil-foundation-structure interaction testing of renewable energy systems, Ocean Engineering, 323, 120595, https://doi.org/10.1016/j.oceaneng.2025.120595 (2025)

[7] Al-Subaihawi, S., Ricles, J.M., Abu-Kassab, Q., Suleiman, M., Sause, R., Marullo, T.. Coupled aero-hydro-geotech real-time hybrid simulation of offshore wind turbine monopile structures, Engineering Structures 303, 117463, https://doi.org/10.1016/j.engstruct.2024.117463 (2024)

Topic 2

Title: Ultra-strong macroscopic 2D materials

Reference persons: Nicola M. Pugno (UNITN/DICAM), Rodney Ruoff (The IBS CMCM)

Despite extensive *microscale* studies, the macroscopic mechanical properties of 2D materials including graphene are underexplored.

Recently, with the pioneer Rod Ruoff and his team at CMCM, we reported the Young's modulus (E = 1.11 ± 0.04 TPa), tensile strength (σ = 27.40 ± 4.36 GPa), and failure strain (ε_f = 6.01 ± 0.92 %) of centimeter scale single-crystal monolayer graphene (SCG) 'dog bone' samples with edges aligned along the zigzag (zz) direction, supported by an ultra-thin polymer (polycarbonate) film (https://arxiv.org/abs/2411.01440). For samples with edges along the armchair (ac) direction, we obtain E = 1.01 ± 0.10 TPa, σ = 20.21 ± 3.22 GPa, ε_f = 3.69 ± 0.38 %, and for 'chiral' samples whose edges were between zz and ac, we obtain E= 0.75 ± 0.12 TPa, σ = 23.56 ± 3.42 GPa, and ε_f = 4.53 ± 0.40 %.

The SCG is grown on CMCM's single crystal Cu(111) foils by chemical vapor deposition (CVD). CMCM uses a home-built 'float-on-water' (FOW) tensile testing system for tensile loading measurements that also enabled in situ observation of initiation and propagation of cracks. Our quantized fracture mechanics (QFM) analysis predicts an edge defect size from several to tens of nanometers based on chirality and notch angle to rationalize the measured tensile strengths. Through Weibull analysis and given that the fatal defects are confined on the edges of 1-cm macroscale samples, we are able to project (forecast) a strength ranging from 13.7 to 18.4 GPa for an A4-size SCG according to its chirality. The exceptional mechanical performance of macroscale single crystal graphene (SCG) paves the way for its widespread use in a very wide variety of applications. Another 2D material, single crystal h-BN, could have comparable or even better mechanical properties.

It is exciting to note that the basic science (the fundamental tensile loading mechanics) of still larger macroscale (large area) SCG, and of cm-scale and larger SC n-layer G, and of *any* macroscale (cm-scale *and* larger) of SC-hBN films is yet to be measured and understood. We aim to lead in basic science in these areas especially in this scholarship modelling and simulations.

We basically aim to model and eventually realize macroscopic 2D materials that are much stronger than the current strongest commercial ones, that are carbon fibers (Toray T-1200 carbon fiber has the highest commercial product strength of about 8 GPa; accounting also for its low density, it has by far the highest specific strength -strength divided by mass density- of any commercial product on Earth today). Top level joint publications are envisioned.

- *Reference person:* Simona Bordoni (UNITN/DICAM)

Participants: Elena Tomasi (FBK), Gabriele Frank (FBK)

C3 - scholarship on reserved topics

Funded by: Fondazione Bruno Kessler (FBK)

Title: Investigating the physical consistency of high-resolution meteorological fields obtained with deep learning downscaling methods

High-resolution meteorological fields are essential for assessing local climate change impacts. In recent years, deep learning (DL) downscaling techniques have shown increasing potential in emulating dynamical downscaling, with advanced techniques capable of reconstructing fine-scale features and flow characteristics. These methods offer substantial computational advantages over numerical approaches, making them a viable, sustainable option, especially for applications to climate projections, which are usually coarse, long term, and scenario rich. However, despite these successes and advantages, the spatio-temporal physical consistency of DL-downscaled fields remains underexplored. This PhD research will investigate the consistency of high-resolution downscaled climate data (e.g. temperature, wind, precipitation) through theoretical and empirical approaches, enhancing credibility and enabling broader applications of DL-based approaches in climate science.

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Intellectual Property of Research Results. The intellectual property rights of research results generated by PhD students under scholarships within the UniTrento-FBK Agreement shall belong to FBK.

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Collaboration with UniTrento. If UniTrento academic staff contribute to research results obtained through PhD scholarships funded by FBK, the determination of IP shares will be defined through separate written agreements based on each party's contribution. PhD students are required to collaborate with UniTrento in all necessary activities related to the joint management of IP.

- Reference persons: Nicola Pugno (UNITN/DICAM), Barbara Mazzolai (IIT)

C4 - scholarship on reserved topics

Funded by: University of Trento – Istituto Italiano di Tecnologia (IIT).

Title: 3D nanoprinting of bioinspired multifunctional materials and structures

Evolution has brought to the development of fascinating biological structures. Nanofabrication technologies provide valuable tools to fabricate artificial biomimetic materials and structures with properties that imitate the natural ones.

This project aims at developing novel multifunctional biomimetic artifacts by merging nanofabricated materials and structures with tailored mechanical properties, fabricated by two photon lithography, with functional electrospun fibers and 3D printed multi-materials.

Several biological properties and functionalities will be investigated as models to develop artificial systems embedding sensing and actuation abilities. In particular, plants and soft invertebrates will be the focus of such research, as described in the following.

Due to their low density and impressive mechanical properties, plants provide examples of lightweight yet robust structures (e.g., bamboo, plant seeds). These characteristics are achieved thanks to a hierarchical structure that combines porous architectures with density gradients and hollow parts to increase the flexural stiffness while keeping a lightweight.

Invertebrates with a soft body, as, e.g., octopus, can squeeze and move in any spaces. The octopus can also bend and elongate its eight arms, while the skin adapts to each movement providing at the same time camouflage properties.

Camouflage is obtained by chromatophores activated by light, resulting in a skin that combines sensing and actuation properties.

The above biological properties represent some of the research activities will be proposed within this project.

In summary, the expected work spans from biological investigation to design, fabrication, and characterization of the resulting prototypes. The expected outputs are patents and publications on high impact journals on the field.