EU-DOCS for SmUCS

CO-SUPERVISED SUBJECT PROPOSAL FOR A DOCTORAL CONTRACT

Title of the thesis project: An AI-Driven Approach for Minimally Disruptive Repairs of Reinforced Concrete Maritime Ports in Response to Climate Change	
La Rochelle University Research Unit: LaSIE (Laboratoire des Sciences de l'Ingénieur pour l'Environnement)	**Partner university:** Rostock University (UROS), Germany **Cotutelle research unit:** Chair of Concrete Structures and Infrastructures Engineering
Name of the LRUniv supervisor: Emilio Bastidas-Arteaga Professor (PR2 - HDR)	**Name of the co-supervisor:** Panagiotis Spyridis Professor (full)
Non-academic partner: INROS LACKNER SE (Germany) - 2nd year of PhD (M21 to M23)	
Keywords *(6 max)*: resilience, coastal infrastructure, ports, bridges. reinforced concrete, maintenance, climate change.	

Scientific description of the research project

Reinforced concrete (RC) structures are vital components of coastal infrastructure underpinning the safety and prosperity of the adjacent nature and urban populations. However, these structures are increasingly threatened by chloride-induced corrosion, a major factor contributing to their deterioration, especially in marine environments[1,2]. Chloride ions penetrate concrete, leading to the corrosion of steel reinforcement bars, which compromises structural integrity and reduces the lifespan of these infrastructures. Chloride ingress is widely impacted by surrounding environmental conditions including climate change[3]. In addition, extreme events and sea level rise lead to an intensification of the loading regime of such structures and hence increased demands[4]. Finally, climate mitigation and environment protection objectives are compromised by the implementation of new constructions or extensive reconstruction activities[5].

This PhD topic focuses on the development of an innovative framework to enhance the resilience and sustainability of this coastal infrastructure in the face of climate change. The main objectives are:

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[1] Dimova, S., López, P., Sousa, M. L., Rianna, G., Bastidas-Arteaga, E., Nogal, M., Gervásio, H., Martorana, E., Reder, A. and Athanasopoulou, A. (2024). Impact of climate change on the corrosion of the European reinforced concrete building stock. Joint Research Centre.

[2] Nolan, S., Rossini, M., Knight, C., & Nanni, A. (2021). New directions for reinforced concrete coastal structures. Journal of Infrastructure Preservation and Resilience, 2, 1-12.

[3] Orcesi, A., O'Connor, A., Bastidas-Arteaga, E., Stewart, M.G., Imam, B., Kreislova, K., Schoefs, F., Markogiannaki, O., Wu, T., Li, Y. Salman, A. (2022). Investigating the effects of climate change on material properties and structural performance. Structural Engineering International, 32(4), 577-588.

[4] Orcesi, A., O'connor, A., Diamantidis, D., Sykora, M., Wu, T., Akiyama, M., Alhamid, A.K., Schmidt, F., Pregnolato, M., Li, Y., Salarieh, B. (2022). Investigating the effects of climate change on structural actions. Structural Engineering International, 32(4), 563-576.

[5] Pacheco-Torgal, F., Melchers, R. E., Shi, X., De Belie, N., Van Tittelboom, K., & Perez, A. S. (Eds.). (2017). Eco-efficient repair and rehabilitation of concrete infrastructures. Woodhead Publishing.

- To study, performing experimental and numerical research, the effectiveness of innovative repair techniques using an inventory of predesigned solutions with advanced composite materials, such as sprayable polymers, and preformed textile concretes that can be rapidly applied (minimally disruptive) to strengthen RC structures affected by chloride-induced corrosion and increased loads.
- To create an artificial intelligence (AI) -based modelling methodology for predictive maintenance, specifically tailored to coastal concrete infrastructures and enabling proactive management of structural health and performance.
- To establish a multi-criteria framework for evaluating repair strategies and lifetime assessment, focusing on robustness, resilience, sustainability, and minimal operational disruption for concrete structures in port systems, and extend this to other types of coastal concrete infrastructures (e.g., bridges, renewables, underwater tunnels).

This PhD topic involves several scientific challenges in the context of durability of RC structures located in coastal and maritime areas. First, it focuses on utilizing advanced modelling techniques at both material and structural scales to (i) accurately assess the extent of chloride-induced corrosion damage in RC structures, and (ii) evaluate the effectiveness of various repair and strengthening methods. Second, the research aims to investigate, by experimental and numerical studies, the long-term performance and environmental impact of composite materials used to repair/strength in harsh coastal environments, ensuring that these materials meet the durability requirements essential for sustainability. Third, a key challenge is to enhance the accuracy and reliability of physical and AI models through rigorous experimental validation, which is crucial for developing predictive tools that can be used to formulate maintenance, rehabilitation, and adaptation strategies for coastal infrastructure. Finally, this study will also address the challenge of the formulation of repair strategies (time and extent of repair) considering multiple criteria: costs, durability, and environmental impact.

To tackle the scientific challenges associated with this thesis, a comprehensive methodological approach will be employed. Laboratory experiments and small-scale on-site pilot studies will be conducted to evaluate the mechanical properties, durability, and overall performance of RC beams with and without being repaired/strengthened with composite materials under simulated environmental conditions that mimic coastal exposure. These experiments will be designed to assess both material and structural component scales, providing critical insights into the behaviour of composite materials in harsh coastal environments. In parallel, advanced numerical models will be developed to simulate the mechanical behaviour of repaired RC structures, considering various factors such as material degradation, repair techniques, and loading conditions. This simulation work will enhance understanding of how these structures perform over time. These models involve non-linear and coupled partial differential equations that should be solved in space and time as well as several sources of uncertainty[6]. Therefore, an AI-based surrogate model[7,8] will be developed to facilitate lifetime assessment, enabling the formulation of sustainable maintenance strategies that optimize the longevity and resilience of coastal infrastructure. Finally, this AI-based surrogate will be integrated in a framework for evaluating the effectiveness of repair strategies based on multiple criteria, including cost, durability, and environmental impact.

The first outcome of this PhD thesis will be the development, through comprehensive experimental and numerical research campaigns, of effective and sustainable repair methods that can be quickly implemented with minimal disruption to ongoing operations in infrastructure systems. The research will also result in the creation of reliable and validated physical and AI-based models capable of accurately predicting the performance of repaired structures under a variety of environmental conditions, including potential future climate change scenarios. This predictive capability, in particular for AI-based models, will be paramount in guiding maintenance and rehabilitation efforts. Furthermore, the establishment of a comprehensive framework for evaluating the effectiveness of repair strategies will provide a systematic approach to decision-making, incorporating multiple criteria such as cost, durability, and environmental impact. At the end, the developments of this PhD thesis will enhance the ability of stakeholders to select optimal repair solutions contributing to the resilience and sustainability

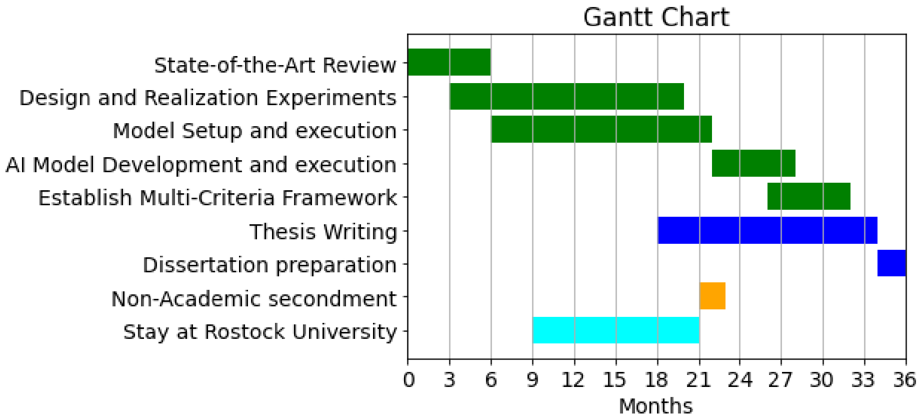
[6] Bastidas-Arteaga E, El Soueidy C-P, Amiri O, Nguyen P-T (2020). Polynomial Chaos Expansion for lifetime assessment and sensitivity analysis of reinforced concrete structures subjected to chloride ingress and climate change. *Structural Concrete*. 21(4):1396-1407

[7] Kudela, J., & Matousek, R. (2022). Recent advances and applications of surrogate models for finite element method computations: a review. *Soft Computing*, *26*(24), 13709-13733.

[8] Guo, H., Dong, Y., Bastidas-Arteaga, E., & Lei, X. (2024). Life-cycle performance prediction and interpretation for coastal and marine RC structures: An ensemble learning framework. *Structural Safety*, 110, 102496.

of concrete components in ports (like berths/quays, jetties, container yards and crane runways) and provide a scientific basis for maintenance activities in similarly susceptible coastal infrastructures (e.g. rail/road transportation, energy, and civil defence).

The following tasks will be conducted by the PhD Student according to the Gantt diagram below. The mobility activities, stay at Rostock University and non-academic secondment are also provided in the diagram.



T1 State-of-the-Art Review: This task will establish the current knowledge base and identify gaps for further research. The PhD student will conduct a comprehensive review of existing literature on chloride-induced corrosion damage (including mechanisms and modelling), repair and strengthening methods, multi-criteria lifetime assessment, probabilistic and AI methods, and climate change-related actions.

T2 Design and Realization Experiments: This task will start with the development of a detailed experimental design aimed at evaluating the mechanical properties, durability, and quality performance of composite materials and RC repaired components under simulated environmental conditions relevant to chloride exposure. This task will involve selecting appropriate materials, defining testing protocols, and outlining methodologies for data collection. Once the experimental design is validated, the PhD student will execute the experiments in the laboratory. He/she will collect and analyze data to assess the mechanical properties and performance of composite materials, and interpreting results to draw conclusions about their suitability for use in chloride-exposed environments.

T3 Model Setup and execution: Model setup concerns the creation of advanced numerical models to simulate the deterioration processes as well as the mechanical behaviour of repaired RC structures. This will require defining the parameters for degradation, repair methods, and loading conditions to accurately reflect real-world scenarios. Once the model setup is completed, the PhD student will execute the numerical simulations and analyse the results to understand the mechanical behaviour of the structures under different conditions, providing insights that will inform repair strategies. This stage also encompasses the validation of the model using the experimental observations collected in T2.

T4 AI Surrogate Model Development and execution: This task initiates with the development of an artificial intelligence surrogate (Artificial Neural Network) model designed for lifetime assessment under a changing climate. The inputs of this model are climate change predictions, material properties and repair features, and the outputs encompass durability and safety indicators. Validated models from T3 will be used to develop the database employed to develop the AI Surrogate. This task involves setting up the model framework, generating the database and, preparing it for implementation. Once the AI surrogate is built and validated, it will be used to assess the performance of maintenance strategies for chloride-exposed RC structures.

T5 Establish Multi-Criteria Framework: this task involves developing a structured approach to evaluate and compare the effectiveness of the solutions taking into account multiple criteria such as cost, durability, and environmental impact. A suitable multi-criteria decision-making method will be employed to evaluate these alternatives, followed by sensitivity analysis to test the robustness of the results. The findings will be documented and presented using visual tools, allowing for iterative refinement based on stakeholder feedback.

T6 Thesis Writing: This task will formally start in the middle of the PhD but we will encourage the PhD student to constantly advance in the writing of the manuscript. This task will involve articulating the research context, methodologies, results, and implications of the study. This stage will end two months before the defence.

T7 Dissertation preparation: Once the thesis is submitted to the committee, the PhD student will focus on the preparation of the oral defence.

Scientific alignment with EU-DOCs for SmUCS objectives

The PhD topic on the innovative repair and retrofit of reinforced concrete coastal infrastructure aligns with the EU-DOCS for SmUCS objectives by addressing critical challenges related to Smart Urban Coastal Sustainability. The focus on chloride-induced deterioration in RC structures is particularly relevant given the increasing vulnerability of coastal infrastructure to climate change and environmental degradation. By developing innovative, minimally disruptive repair techniques and AI-based assessment tools, this research directly contributes, by using smart solutions, to enhancing the resilience and sustainability of urban coastal areas, which is a primary goal of the SmUCS programme. Furthermore, the interdisciplinary approach required for this research, integrating materials science, civil engineering, data science, and environmental monitoring, embodies the EU-DOCS emphasis on collaborative efforts across diverse academic fields to tackle complex issues.

Additionally, the PhD project aligns with the EU-DOCS for SmUCS objectives through its commitment to international collaboration and the development of transversal skills. The cotutelle framework, enabling co-supervision by faculty from two institutions, promotes an international perspective that is crucial for addressing global coastal sustainability challenges. The incorporation of a three-month secondment with our non-academic partner further enhances the practical applicability of the research, allowing the PhD student to engage with real-world problems and develop solutions that are grounded in the needs of industry and society.

Societal and economic challenges and contributions

Ports are vital to the global economy, handling nearly 90% of the world's trade by volume[9]. They serve as critical trade and logistics hubs for the global supply chain, enabling the movement of goods that sustain industries and communities regionally but also worldwide. Typically, such infrastructure is tightly linked to large cities and urbanised areas, and in Europe, ports contribute to over 1.5 million direct jobs and up to 3 million when including indirect employment, driving regional GDP growth and fostering economic stability[7,10,11]: Seaports of Europe are gateways to other continents (74% of extra-EU goods shipping), but they are also important for intra-European trade and transport, with 37% of the intra-EU freight traffic and 385 million passengers pass by ports every year. Moreover, a 50% growth of cargo handled in EU ports is predicted by 2030. Beyond their logistical roles, ports are increasingly central to the global transition toward sustainability. They are evolving into pivotal points for energy conveyance, facilitating the installation of offshore wind farms and renewable tidal and wave power harvesting and acting as distribution nodes for alternative fuels such as LNG and hydrogen. As urbanization intensifies, with 40% of Europe's population living in coastal regions, ports also serve as fronts for urban growth and resilience, bridging local development with global trade networks. In this transformative era, ports are not just gateways for goods but also for the technologies and systems that will define a sustainable future[9]. But at the same time, sea ports and connected coastal infrastructure is particularly susceptible to climate change effects[12,13]: Climate change is expected to have more severe impacts in northern Europe, where Europe's top 20 cargo seaports are located. In total, 852 ports face the risk of inundation in 2080 and the number of seaports to be exposed to inundation levels higher than 1m is projected to increase by 80% from 2030 to 2080. The number of

[9] Chow, M., Sharma, A.I., Noronha, M., Koehring, M. (2023) Global Maritime Trends 2050. Economist Impact, comm by. Lloyd's Register Foundation and Lloyd's. Register

[10] Christodoulou A., Demirel H., Impacts of climate change on transport - A focus on airports, seaports and inland waterways, EUR 28896 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-97039-9, doi:10.2760/378464, JRC108865.

[11] EUKN (2021). Port Cities and Mega-Trends: Glocal Approaches to Sustainable Transitions. European Urban Knowledge Network (EUKN) Policy Lab for France.

[12] Valente, S., & Veloso-Gomes, F. (2020). Coastal climate adaptation in port-cities: adaptation deficits, barriers, and challenges ahead. Journal of Environmental Planning and Management, 63(3), 389-414.

[13] Verschuur, J., Koks, E. E., & Hall, J. W. (2023). Systemic risks from climate-related disruptions at ports. Nature Climate Change, 13(8), 804-806.

ports that face the risk of inundation is expected to increase by more than 50% from 2030 to 2080.

Despite their importance, the structural integrity of port infrastructure, particularly reinforced concrete elements face significant threats. These structures are exposed to harsh marine environments, leading to chloride-induced corrosion and deterioration, exacerbated by climate change impacts, in addition to direct climate actions such as extreme storms surge and wave shocks. The resulting maintenance costs, exceeding an estimated €12 billion annually in Europe, strain budgets, risk systemic disruptions to global supply chains and compromise the strive to implement the European Green Deal[10,14,15]. This project seeks to address these challenges through innovative solutions for repairing and retrofitting concrete structures in a minimally disruptive way to reduce the impact of the interventions. By leveraging advanced materials, predictive modelling, and AI-based technologies, the PhD project will enable rapid, minimally disruptive, cost-efficient, and sustainable maintenance/retrofitting interventions. These approaches not only extend the lifespan of critical infrastructure but also reduce environmental impacts, underpinning safety and availability of ports and relevant coastal structures for challenging future scenarios.

Partnership context

La **Rochelle Université** is a young, dynamic, and international higher education institution, founded in 1993. La Rochelle Université brand is associated with high-level research, which tends to focus on the distinctive societal challenge of Smart Urban Coastal Sustainability, and with student-centred teaching quality. Based on a multi-disciplinary foundation, our dynamism in research has enabled us to set up six of our own research units and three joint research units recognised by the CNRS, and to establish a position of national and international excellence in coastal engineering, environmental, energy and digital transitions. We developed a rich experience in multidisciplinary research, which enables us to actively contribute to the resolution of some of the major societal issues of the 21st century. The laboratory of LRU involved in the present project is the LaSIE (**Laboratory of Engineering Science for the Environment**) UMR CNRS 7356. The unit brings together a wide range of skills with integrated approaches from the atomic scale to the material, the built, and its environment at different time and space scales, with a continuum: from the development of mathematical tools to the applications, patent deposits, through models, numerical and experimental research.

The **University of Rostock,** established in 1419, is one of Germany's oldest academic institutions, recognized for its research in maritime systems, life sciences, and aging. Recently, the university introduced a civil engineering program focusing on rural and coastal environments as part of Mecklenburg-Vorpommern's BLU initiative. Within this program, the **Chair of Concrete Structures and Infrastructures** was created to address challenges in sustainable construction, innovative material applications, and efficient concrete design, aligning with regional needs and sustainability goals. The Chair is equipped with advanced probabilistic and surrogate non-linear analysis tools, an in-house structural laboratory and concreting facilities, and access to facilities at the Fraunhofer Institute and the Mecklenburg-Vorpommern Competence Centre for Building. These resources support research and development in concrete structures and infrastructure engineering. The Chair's capabilities are further enhanced by its collaboration with regional and national initiatives, as well as the active involvement of Prof. Spyridis, who serves on the Competence Centre's board.

Non-academic partner

INROS LACKNER SE, headquartered in Rostock, is a leading international engineering and consulting firm specializing in comprehensive infrastructure and construction solutions. The company offers a broad range of services, including planning, design, project management, and consulting across multiple sectors, including architecture, transportation, water management, and environmental engineering. With a strong emphasis on sustainable and innovative solutions, INROS LACKNER collaborates closely with clients worldwide to deliver tailored projects that meet technical, economic, and ecological requirements. Its interdisciplinary approach ensures high-quality outcomes that integrate cutting-edge technologies and proven expertise. The company places special focus on engaging young scientists and students in assisting roles, providing them with opportunities to develop

[14] Schroten, A., van Wijngaarden, L., Brambilla, M., Gatto, M., Maffii, S., Trosky, F., Kramer, H., Monden, R., Bertschmann, D., Killer, M. and Lambla, V. (2019). Overview of transport infrastructure expenditures and costs. *Publications Office of the European Union, Luxembourg*.

[15] Vousdoukas, Michalis I., Lorenzo Mentaschi, Jochen Hinkel, Philip J. Ward, Ignazio Mongelli, Juan-Carlos Ciscar, and Luc Feyen. "Economic motivation for raising coastal flood defenses in Europe." Nature communications 11, no. 1 (2020): 2119.

their talents and grow into future leading professionals. INROS LACKNER bears a distinguishing excellence in the field Maritime Engineering and Ports: Coastal Infrastructure. The company specializes in port facilities, sea defences, and waterfront developments, addressing complex challenges like climate resilience, tidal impacts, and sediment dynamics. Services include feasibility studies, structural engineering, and integrated environmental solutions, ensuring durable, sustainable, and efficient coastal infrastructure tailored to specific geographic and operational needs.